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Number 66

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The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks

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The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks

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Abstract

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Agriculture Handbook 66 (AH-66) represents a complete revision and major expansion of the 1986 edition. It has been reorganized and now includes 17 Chapters and 138 Commodity Summaries written by nearly a hundred experts in plant science and postharvest technology. This version, like the previous editions of AH-66 in 1954, 1968, 1977, and 1986, presents summaries of current storage requirements of fresh fruits, vegetables, cut flowers, and other horticultural crops. However, this highly expanded version also includes information on quality characteristics, maturity indices, grading, packaging, precooling, retail display, chilling sensitivity, ethylene production and sensitivity, respiration rates, physiological disorders, postharvest pathology, quarantine issues, and suitability as fresh-cut product. A large number of fruits and vegetables were added, as well as sections on food safety, nutritional quality, texture, and fresh-cut produce. The purpose of storing plant material is to lengthen the time it can be consumed or utilized. In doing so, it is critical to provide an environment that minimizes deterioration, maintains microbial safety, and retains other quality attributes. AH-66 provides guidelines and other important information for storing and handling horticultural commodities to accomplish this.

Keywords: carbon dioxide, chilling injury, cold storage, controlled atmosphere storage, cut flowers, ethylene, flavor, food safety, fresh-cut, fresh produce, fruit softening, heat load, 1-methylcyclopropene, microbial safety, minimally processed, modified-atmosphere packaging, potted plants, nutritional quality, nuts, orchids, packaging film, perishable, postharvest biology, precooling, respiration, sensory evaluation, shelf-life, texture.

The information contained in AH-66 has been assembled from material prepared by nearly a hundred authors from around the world. All of the information contained herein was peer reviewed and edited for scientific content. Every effort was made to provide the most accurate and current information available.

The contributors' professional affiliations and addresses were up-to-date at the time of submission of their chapters, and the editors made all reasonable efforts to update any changes received during the review and publishing process. However, due to the large number of contributors and countries represented, it is not inconceivable that some of the contributors may have changed organizations in the interim and thus are no longer at the addresses given in this handbook. In cases where the editors received specific address changes or death notices, all such updates are reflected in this volume.

While supplies last, printed copies of this publication may be obtained at no cost from the USDA-ARS Food Quality Laboratory, Building 002, Room 117, 10300 Baltimore Avenue, Beltsville, MD 20705-2350.

Copies of this publication may be purchased in various formats (microfiche, photocopy, CD, and print on demand) from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, (800) 553-6847, http//:www.ntis.gov.

This publication in its entirety is freely accessible on the Internet at http://www.ars.usda.gov/is/np/indexpubs.

ARS Mission

The Agricultural Research Service conducts research to develop and transfer solutions to agricultural problems of high national priority and provides information access and dissemination to—ensure high-quality, safe food and other agricultural products; assess the nutritional needs of Americans; sustain a competitive agricultural economy; enhance the natural resource base and the environment; and provide economic opportunities for rural citizens, communities, and society as a whole.

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Abbreviations

APHIS	Animal and Plant Health Inspection Service, USDA
ARS	Agricultural Research Service, USDA
BTU	British thermal unit
bu	bushel
$CaCl_2$	calcium chloride
CDC	Centers for Disease Control and Prevention
CO_2	carbon dioxide
cm	centimeter
cfu	colony forming units
CA	controlled atmosphere
CFM	cubic feet per minute
ed., eds.	editor; editors
EPA	Environmental Protection Agency
FDA	Food and Drug Administration, HHS
ft	feet
GC	gas chromatograph
GRAS	generally recognized as safe
h	hour
HAT	high temperature forced-air treatment
Hg	mercury
HHS	United States Department of Health and Human Services
HWB	hot water brushing
HWT	hot water treatment
in	inch
J	Joules
kg	kilogram
L	liter
MS	mass spectrometer
m	meter
mL	milliliter
MA	modified atmosphere
MAP	modified atmosphere packaging
µL	microliter
min	minute
mo	month
N	Newtons
N_2	nitrogen
nL	nanoliter
oz	ounce, Avoirdupois
O_2	oxygen
OTR	oxygen transmission rate
ppb	parts per billion
ppm	parts per million
%	percent
lb	pound, avoirdupois
RH	relative humidity
sec	second
T	short ton
STS	silver thiosulfate
NaOCl	sodium hypochlorite
SSC	soluble solids content
SO_2	sulfur dioxide
TA	total acidity
SSC	total soluble solids
U.S.	United States
USDA	United States Department of Agriculture
VHT	vapor heat treatment

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Introduction

This latest edition of Agriculture Handbook 66 (AH-66) represents a complete revision of the 1986 edition. It has been reorganized and now includes 17 chapters and 138 commodity summaries written by nearly a hundred experts in plant biology and postharvest technology. This version—like the previous editions of AH-66 in 1954, 1968, 1977, and 1986—presents summaries of current storage requirements of fresh fruits, vegetables, cut flowers, and other horticultural crops. However, this highly improved and expanded version also includes information on quality characteristics, maturity indices, grading, packaging, precooling, retail display, chilling sensitivity, ethylene production and sensitivity, respiration rates, physiological disorders, postharvest pathology, quarantine issues, and suitability as fresh-cut product. In addition, a large number of fruits and vegetables were added, as well as sections on food safety, nutritional quality, texture, and fresh-cut produce.

The purpose of storing plant material is to lengthen the time it can be stored and marketed prior to consumption or other use. In doing so, it is critical to provide an environment that minimizes deterioration and maintains microbial safety and quality. The primary intent of AH-66 is to provide guidelines for optimal handling and storage of produce in order to accomplish this.

AH-66 is intended as a general reference, and the recommendations should not be considered absolute, but rather as safe limits at which products can ordinarily be handled and stored. A draft version of the data presented in this volume is available at http://www.ba.ars.usda.gov/hb66. Updates to the online data will be made as they become available, and users are encouraged to periodically check for any new information.

Each contribution in this volume was peer reviewed by at least one individual knowledgeable in that particular area or commodity, as well as two editors. This review process helped to ensure that the information in this edition of AH-66 is as accurate and current as possible. The editors would like to express their sincere appreciation to all of the contributors and to the reviewers, who are listed in the Acknowledgments.

The original edition of AH-66, published in 1954, was written by R.C. Wright, D.H. Rose, and T.M. Whiteman, all from USDA Agricultural Research Service (ARS). Then, in 1968, the handbook was revised by J.M. Lutz and R.E. Hardenburg, also from USDA-ARS. A major revision by R.E. Hardenburg, A.E. Watada, and C.Y. Wang, at USDA-ARS Horticultural Crops Quality Laboratory (now Food Quality Laboratory) in Beltsville, MD, was published in 1986. In 1990, 10,000 copies of the 1986 edition were reprinted, of which few remain today. The volume has also been translated into several languages. It was clearly time for an extensive revision, both to bring the content up to date and to increase its availability.

Most temperatures are given in both ºC and ºF. Nevertheless, a “Temperature Conversion Chart” is included in this volume. Though temperatures are sometimes expressed to the first decimal place due to conversion, this does not mean that this level of accuracy is recommended, necessary, or possible in a commercial situation. Generally, storage temperatures can only be expected to be maintained within ±1 ºC. Also, see the “Metric Conversion Chart” for some common metric conversions. Respiration and ethylene production rates for many fruits and vegetables are also summarized in the sections “Respiration” and “Ethylene Effects.” A“Commodity Cross-Reference” index has been included to aid in finding the commodity summary for produce called by various names in different cultures and geographical locations.

“In this work, when it shall be found that much is omitted,let it not be forgotten that much likewise is performed.”

Dr. Samuel Johnson,
English lexicographer and essayist, 1775

Temperature Conversion Chart

°C = 5/9 (°F - 32)
°F = (9/5 × °C) + 32

°C	°F	°C	°F
-2	28.4	23	73.4
-1	30.2	24	75.2
0	32.0	25	77.0
1	33.8	26	78.8
2	35.6	27	80.6
3	37.4	28	82.4
4	39.2	29	84.2
5	41.0	30	86.0
6	42.8	31	87.8
7	44.6	32	89.6
8	46.4	33	91.4
9	48.2	34	93.2
10	50.0	35	95.0
11	51.8	36	96.8
12	53.6	37	98.6
13	55.4	38	100.4
14	57.2	39	102.2
15	59.0	40	104.4
16	60.8	45	113.0
17	62.6	50	122.0
18	64.4	55	131.0
19	66.2	60	140.0
20	68.0	65	149.0
21	69.8	70	158.0
22	71.6	75	167.0

Metric Conversion Chart

Mass
1.0 avoirdupois pound (lb) = 0.454 kilogram (kg) = 454 grams (g)
1.0 kilogram (kg) = 2.2 pounds (lb) = 35.2 avoirdupois ounces (oz) = 32.15 troy ounces
1.0 avoirdupois ounce (oz) = 0.9115 troy ounce = 0.0284 kilogram (kg) = 28.4 grams (g)
1 short ton (T) = 2,000 pounds (lb) = 907.2 kilograms (kg) = 0.893 long ton = 0.907 metric tonne

Length
1 inch (in) = 2.54 centimeters (cm)
1 centimeter (cm) = 0.394 inch (in)
1 foot (ft) = 30.48 centimeters (cm)
1 yard (yd) = 91.44 centimeters (cm) or 0.9144 meter (m)
1 meter (m) = 3.28 feet (ft) = 1.0936 yards (yd)
1 mile (mi) = 1.61 kilometers (km)
1 kilometer (km) = 0.621 mile (mi)

Volume
1 quart (qt) = 0.946 liter (L)
1 liter (L) = 1.057 quarts (qt)
1 cup (c) = 0.24 liter (L)
1 pint (pt) = 0.47 liter (L)
1 quart (qt) = 0.95 liter (L)
1 U.S. bushel (bu) = 35.24 liters (L)
1 liter (L) = 0.2838 bushel (bu)
1 U.S. gallon (gal) = 3.785 liters (L)
1 liter (L) = 0.2642 gallon (gal)
1 cubic foot (ft^3) = 28.32 liters (L)
1 cubic yard (yd^3) = 0.76 cubic meter (m^3)
1 liter (L) = 61.02 cubic inches (in^3)

Area
1 acre = 0.4047 hectare
1 hectare = 2.47 acres
1 square meter (m^2) = 1550 square inches (in^2) = 1.196 square yards (yd^2) = 10.76 square feet (ft^2)
1 square inch (in^2) = 6.45 square centimeters (cm^2)
1 square foot (ft^2) = 0.0929 square meter (m^2)

Energy/Work
1 joule (J) = 0.00094 British thermal units (BTU) = 1 watt per second ($W\ s^{-1}$)
1 British thermal unit (BTU) = 1,055 joules (J) = 0.252 kilocalorie (kcal)

Commodity Cross-Reference

To find...	See...
Abogado	Avocado
Alligator pear	Avocado
Alfalfa sprouts	Sprouts
Anon	Sapodilla
Apple cactus	Dragon fruit
Apple pear (misleading)	Asian pear
Araçá boi	Arazá
Avocat	Avocado
Basil	Annual culinary herbs
Bean sprouts	Sprouts
Beets	Beet
Belgian endive	Chicory
Bell pepper	Pepper
Bhendi	Okra
Bhindi	Okra
Boy-toyo	Bok choy
Cactus fruit	Prickly pear
Cactus pad	Nopalitos
Cactus pear	Prickly pear
Caimito	Sapodilla
Calabaza	Pumpkin
Calabrese	Broccoli
Canary melon	Honeydew melon
Cantelope	Netted melon
Casaba melon	Honeydew melon
Cassave	Cassava
Cay mang cut	Mangosteen
Chervil	Annual culinary herbs
Chico mamey	Sapodilla
Chico zapote	Sapodilla
Chiku	Sapodilla
Chile pepper	Pepper
Chinese apple	Pomegranate
Chinese chard	Bok choy
Chinese chive	Perennial culinary herbs
Chinese date plum	Persimmon
Chinese long bean	Bean
Chinese okra	Luffa
Chinese pear	Asian pear
Chive	Perennial culinary herbs
Ciku	Sapodilla
Claytonia	Salad greens
Cocoyam	Taro
Collards	Greens for cooking
Coriander	Annual culinary herbs
Corn salad	Salad greens

To find...	See...
Crenshaw melon	Honeydew melon
Custard apple	Avocado
Daikon	Radish
Dandelion	Salad greens
Dasheen	Taro
Date Plum	Persimmon
Dill	Annual culinary herbs
Dilly	Sapodilla
Duku	Longkong
Dulian	Durian
Duren	Durian
Duyin	Durian
Eddoe	Taro
Elderberry	Currant
Escarole	Endive and Escarole
Field salad	Salad greens
Filbert	Hazelnut
Fire dragon fruit	Dragon fruit
Flat bean	Bean
French bean	Bean
French sorrel	Salad greens
Garden sorrel	Salad greens
Gooseberry	Currant
Globe artichoke	Artichoke
Collard greens	Greens for Cooking
Gombo	Okra
Green bean	Bean
Green cabbage	Cabbage
Green onion	Onion
Grosse sapote	Sapodilla
Groundnut	Peanut
Gumbo	Okra
Hamburg parsley	Parsley
Husk tomato	Tomatillo
Japanese pear	Asian pear
Java plum	Wax apple
Kadu	Durian
Kale	Greens for cooking
Kang kong	Water convolvulus
Kong xin cai	Water convolvulus
La pitahaya rouge	Dragon fruit
Lady’s finger	Okra
Lamb’s lettuce	Salad greens
Langsat	Longkong
Lanson	Longkong
Lychee	Litchi
Long bean	Bean
Lucuma	Sapodilla

To find...	See...
Malanga	Taro
Malay apple	Wax apple
Mamey	Sapodilla
Mandioca	Cassava
Manggistan	Mangosteen
Mangis	Mangosteen
Mangkhut	Mangosteen
Mangostan	Mangosteen
Mangostanier	Mangosteen
Mangostao	Mangosteen
Manggustan	Mangosteen
Manioc	Cassava
Marjoram	Perennial culinary herbs
Marmalade fruit	Sapodilla
Matai	Waterchestnut
Melon, Honeydew melon	Honeydew melon
Melon, Netted	Netted melon
Mesetor	Mangosteen
Miner’s lettuce	Salad greens
Mongkhut	Mangosteen
Mung bean sprouts	Sprouts
Muskmelon	Netted melon
Mustard cabbage	Bok choy
Mustard greens	Greens for cooking
Nachi	Asian pear
Nasberry	Sapodilla
Néspero	Sapodilla
Noplaes	Nopalitos
Oregano	Perennial culinary herbs
Oriental pear	Asian pear
Oxheart cabbage	Cabbage
Oyster plant	Salsify
Pak-choy	Bok choy
Pake boong	Water convolvulvus
Pak-tsoi	Bok choy
Palta	Avocado
Paprika	Pepper
Peppermint	Perennial culinary herbs
Pichi	Arazá
Pitahaya	Dragon fruit
Pitaya roja	Dragon fruit
Pod bean	Bean
Quaio	Okra
Quingumbo	Okra
Rape	Greens for cooking
Red beet	Beet
Rian	Durian
Rocket salad	Salad greens

To find...	See...
Roquette	Salad greens
Rose apple	Wax apple
Rose water apple	Wax apple
Rosemary	Perennial culinary herbs
Round sorrel	Salad greens
Rucola	Salad greens
Rugula	Salad greens
Runner bean	Bean
Rupina caspi	Arazá
Sage	Perennial culinary herbs
Salad chervil	Annual culinary herbs
Salad pear	Asian pear
Sand apple	Asian pear
Sapota	Sapodilla
Sapote	Sapodilla
Saurieng	Durian
Savory	Annual culinary herbs
Savoy cabbage	Cabbage
Sementah	Mangosteen
Semetah	Mangosteen
Sha Li pear	Asian pear
Shalea pear	Asian pear
Shallot	Onion
Snap bean	Bean
Sororia	Arazá
Sorrel	Salad greens
Spearmint	Perennial culinary herbs
Spinach	Greens for cooking
Sponge gourd	Luffa
Spring onion	Onion
Sprouting broccoli	Broccoli
Star apple	Sapodilla
Star fruit	Carambola
Stinkvrucht	Durian
Stinky rose	Garlic
Strawberry pear	Dragon fruit
String bean	Bean
Sugar pea	Pea
Summer savory	Annual culinary herbs
Summer squash	Squash
Sunchokes	Jerusalem artichoke
Swedes	Rutabaga
Swedish turnips	Rutabaga
Sweetsop	Sapodilla
Sweet cherry	Cherry, sweet
Sweet pepper	Pepper
Table beet	Beet
Taisai	Bok choy

To find...	See...
Tamarindo	Tamarind
Tangerine	Mandarin and Tangerine
Tannier	Taro
Tarragon	Perennial culinary herbs
Thang loy	Dragon fruit
Thureen	Durian
Thurian	Durian
Thyme	Perennial culinary herbs
Tree tomato	Tamarillo
Turnip-rooted cabbage	Kohlrabi or Rutabaga
Turnip greens	Greens for cooking
Vegetable oyster	Salsify
Water cabbage	Water convolvulvus
White celery mustard	Bok choy
White sapote	Sapodilla
Whitloof	Chicory
Winter purslane	Salad greens
Winter spinach	Water convolvulvus
Yard-long bean	Bean
Yellow pitaya	Dragon fruit
Yellow wax bean	Bean
Yuca	Cassava
Zapote	Sapodilla
Zucchini	Squash

Respiration and Ethylene Production Rates

The values in table 1 are approximations or the average rates of a range; see individual sections on each commodity for more specific information and references. Values in parentheses after ethylene rates are the temperatures at which ethylene production was measured. For respiration data, to get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Table 1. Rates of respiration and ethylene production

Commodity	Respiration						C_2H_4 Production
	0 °C	5 °C	10 °C	15 °C	20 °C	25 °C	
	mg kg^{-1} h^{-1}						*µL kg^{-1} h^{-1}*
Apple							
Fall	3	6	9	15	20	nd[1]	varies greatly
Summer	5	8	17	25	31	nd	varies greatly
Apricot	6	nd	16	nd	40	nd	<0.1 (0 °C)
Arazá (ripe)	nd	nd	601	nd	1283	nd	nd
Artichoke	30	43	71	110	193	nd	<0.1
Asian Pear	5	nd	nd	nd	25	nd	varies greatly
Asparagus[2]	60	105	215	235	270	nd	2.6 (20 °C)
Atemoya	nd	nd	119	168	250	nd	200 (20 °C)
Avocado	nd	35	105	nd	190	nd	>100 (ripe; 20 °C)
Banana (ripe)	nd	nd	80	140[3]	280	nd	5.0 (15 °C)
Basil	36	nd	71	nd	167	nd	very low[7]
Beans							
Snap	20	34	58	92	130	nd	<0.05 (5 °C)
Long	40	46	92	202	220	nd	<0.05 (5 °C)
Beets	5	11	18	31	60	nd	<0.1 (0 °C)
Blackberry	19	36	62	75	115	nd	varies; 0.1 to 2.0
Blueberry	6	11	29	48	70	101	varies; 0.5 to 10.0
Bok Choy	6	11	20	39	56	nd	<0.2
Breadfruit	nd	nd	nd	329	nd	480	1.2
Broccoli	21	34	81	170	300	nd	<0.1 (20 °C)
Brussels sprouts	40	70	147	200	276	nd	<0.25 (7.5 °C)
Cabbage	5	11	18	28	42	62	<1.1 (20 °C)
Carambola	nd	15	22	27	65	nd	<3.0 (20 °C)
Carrot (topped)	15	20	31	40	25	nd	<0.1 (20 °C)
Cassava	nd	nd	nd	nd	nd	40	1.7 (25 °C)
Cauliflower	17	21	34	46	79	92	<1.0 (20 °C)
Celeriac	7	13	23	35	45	nd	<0.1 (20 °C)
Celery	15	20	31	40	71	nd	<0.1 (20 °C)
Cherimoya	nd	nd	119	182	300	nd	200 (20 °C)
Cherry, Sweet	8	22	28	46	65	nd	<0.1 (0 °C)
Chervil	12	nd	80	nd	170	nd	very low

Table 1. Rates of respiration and ethylene production—*Continued*

Commodity	Respiration						C_2H_4 Production
	0 °C	5 °C	10 °C	15 °C	20 °C	25 °C	
	mg kg⁻¹ h⁻¹						*µL kg⁻¹ h⁻¹*
Chicory	3	6	13	21	37	nd	<0.1 (0 °C)
Chinese Cabbage	10	12	18	26	39	nd	<0.1 (20 °C)
Chinese Chive	54	nd	99	nd	432	nd	very low
Chive	22	nd	110	nd	540	nd	very low
Coconut	nd	nd	nd	nd	nd	50	very low
Coriander	22	30	nd	nd	nd	nd	very low
Cranberry	4	5	8	nd	16	nd	0.6 (5 °C)
Cucumber	nd	nd	26	29	31	37	0.6 (20 °C)
Currant, Black	16	28	42	96	142	nd	nd
Dill	22	nd	103	324	nd	nd	<0.1 (20 °C)
Dragon Fruit	nd	nd	nd	nd	105	nd	<0.1
Durian	nd	nd	nd	nd	265[4]	nd	40 (ripe)
Eggplant							
American	nd	nd	nd	69[5]	nd	nd	0.4 (12.5 °C)
Japanese	nd	nd	nd	131[5]	nd	nd	0.4 (12.5 °C)
White egg	nd	nd	nd	113[5]	nd	nd	0.4 (12.5 °C)
Endive/Escarole	45	52	73	100	133	200	very low
Fennel	19[6]	nd	nd	nd	32	nd	4.3 (20 °C)
Fig	6	13	21	nd	50	nd	0.6 (0 °C)
Garlic							
Bulbs	8	16	24	22	20	nd	very low
Fresh peeled	24	35	85	nd	nd	nd	very low
Ginger	nd	nd	nd	nd	6[3]	nd	very low
Ginseng	6	nd	15	33	nd	95	very low
Gooseberry	7	12	23	52	81	nd	nd
Grape, American	3	5	8	16	33	39	<0.1 (20 °C)
Grape, Muscadine	10[6]	13	nd	nd	51	nd	<0.1 (20 °C)
Grape, Table	3	7	13	nd	27	nd	<0.1 (20 °C)
Grapefruit	nd	nd	nd	<10	nd	nd	<0.1 (20 °C)
Guava	nd	nd	34	nd	74	nd	10 (20 °C)
Honeydew Melon	nd	8	14	24	30	33	very low
Horseradish	8	14	25	32	40	nd	<1.0
Jerusalem Artichoke	10	12	19	50	nd	nd	nd
Jicama	6	11	14	nd	6	nd	very low
Kiwifruit (ripe)	3	6	12	nd	19	nd	75
Kohlrabi	10	16	31	46	nd	nd	<0.1 (20 °C)
Leek	15	25	60	96	110	115	<0.1
Lemon	nd	nd	11	19	24	nd	<0.1 (20 °C)
Lettuce							
Head	12	17	31	39	56	82	very low
Leaf	23	30	39	63	101	147	very low

Table 1. Rates of respiration and ethylene production—*Continued*

Commodity	Respiration						C_2H_4 Production
	0 °C	5 °C	10 °C	15 °C	20 °C	25 °C	
	mg kg⁻¹ h⁻¹						*µL kg⁻¹ h⁻¹*
Lime	nd	nd	,10	nd	nd	nd	<0.1 (20 °C)
Litchi	nd	13	24	nd	60	102	very low
Longan	nd	7	21	nd	42	nd	very low
Longkong	nd	nd	45[8]	nd	nd	nd	4.0
Loquat	11[9]	12	31	nd	80	nd	very low
Luffa	14	27	36	63	79	nd	<0.1 (20 °C)
Mamey Apple	nd	nd	nd	nd	nd	35	400.0 (27 °C)
Mandarin (Tangerine)	nd	6	8	16	25	nd	<0.1 (20 °C)
Mango	nd	16	35	58	113	nd	1.5 (20 °C)
Mangosteen	nd	nd	nd	nd	nd	21	0.03
Marjoram	28	nd	68	nd	nd	nd	very low
Mint	20	nd	76	nd	252	nd	very low
Mushroom	35	70	97	nd	264	nd	<0.1 (20 °C)
Nectarine (ripe)	5	nd	20	nd	87	nd	5.0 (0 °C)
Netted Melon	6	10	15	37	55	67	55.0
Nopalitos	nd	18	40	56	74	nd	very low
Okra	21[5]	40	91	146	261	345	0.5
Olive	nd	15	28	nd	60	nd	<0.5 (20 °C)
Onion	3	5	7	7	8	nd	<0.1 (20 °C)
Orange	4	6	8	18	28	nd	<0.1 (20 °C)
Oregano	22	nd	101	nd	176	nd	very low
Papaya (ripe)	nd	5	nd	19	80	nd	8.0
Parsley	30	60	114	150	199	274	very low
Parsnip	12	13	22	37	nd	nd	<0.1 (20 °C)
Passion Fruit	nd	44	59	141	262	nd	280.0 (20 °C)
Pea							
Garden	38	64	86	175	271	313	<0.1 (20 °C)
Edible Pod	39	64	89	176	273	nd	<0.1 (20 °C)
Peach (ripe)	5	nd	20	nd	87	nd	5.0 (0 °C)
Pepper	nd	7	12	27	34	nd	<0.2 (20 °C)
Persimmon	6	nd	nd	nd	22	nd	<0.5 (20 °C)
Pineapple	nd	2	6	13	24	nd	<1.0 (20 °C)
Plum (ripe)	3	nd	10	nd	20	nd	<5.0 (0 °C)
Pomegranate	nd	6	12	nd	24	nd	<0.1 (10 °C)
Potato (cured)	nd	12	16	17	22	nd	<0.1 (20 °C)
Prickly Pear	nd	nd	nd	nd	32	nd	0.2 (20 °C)
Radicchio	8	13[10]	23[11]	nd	nd	45	0.3 (6 °C)
Radish							
Topped	16	20	34	74	130	172	very low
Bunched with tops	6	10	16	32	51	75	very low
Rambutan (mature)	nd	nd	nd	nd	nd	70	very low

Table 1. Rates of respiration and ethylene production—*Continued*

Commodity	Respiration						C_2H_4 Production
	0 °C	5 °C	10 °C	15 °C	20 °C	25 °C	
	mg kg⁻¹ h⁻¹						*μL kg⁻¹ h⁻¹*
Raspberry	17[6]	23	35	42	125	nd	≤12.0 (20 °C)
Rhubarb	11	15	25	40	49	nd	nd
Rutabaga	5	10	14	26	37	nd	<0.1 (20 °C)
Sage	36	nd	103	nd	157	nd	very low
Salad Greens							
Rocket Salad	42	113	nd	nd	nd	nd	very low
Lamb's Lettuce	12	67[11]	81	nd	139	nd	very low
Salsify	25	43	49	nd	193	nd	very low
Sapodilla	nd	nd	nd	nd	nd	16	3.7 (20 °C)
Sapote	nd	nd	nd	nd	nd	nd	>100 (20 °C)
Southern Pea							
Whole Pods	24[6]	25	nd	nd	148	nd	nd
Shelled Peas	29[6]	nd	nd	nd	126	nd	nd
Spinach	21	45	110	179	230	nd	very low
Sprouts (mung bean)	23	42	96	nd	nd	nd	<0.1 (10 °C)
Squash, Summer	25	32	67	153	164	nd	<1.0 (20 °C)
Squash, Winter	nd	nd	99[5]	nd	nd	nd	very low
Star Apple	nd	nd	nd	nd	38	nd	0.1 (20 °C)
Strawberry	16	nd	75	nd	150	nd	<0.1 (20 °C)
Sweet Corn	41	63	105	159	261	359	very low
Swiss Chard	19[6]	nd	nd	nd	29	nd	0.14 (20 °C)
Tamarillo	nd	nd	nd	nd	27	nd	<0.1
Tarragon	40	nd	99	nd	234	nd	very low
Thyme	38	nd	82	nd	203	nd	very low
Tomatillo							
(mature green)	nd	13	16	nd	32	nd	10.0 (20 °C)
Tomato	nd	nd	15	22	35	43	10.0 (20 °C)
Truffles	28	35	45	nd	nd	nd	very low
Turnip	8	10	16	23	25	nd	very low
Waterchestnut	10	25	42	79	114	nd	nd
Water Convolvulus	nd	nd	nd	nd	nd	100	<2.0
Watercress	22	50	110	175	322	377	<1.0 (20 °C)
Watermelon	nd	4	8	nd	21	nd	<1.0 (20 °C)
Wax Apple	nd	nd	5	nd	10	nd	very little

[1] nd = Not determined.
[2] 1 day after harvest.
[3] At 13 °C.
[4] At 22 °C.
[5] At 12.5 °C.
[6] At 2 °C.
[7] Although not accurately measured, "very low" is considered to be <0.05 μL kg⁻¹ h⁻¹.
[8] At 9 °C.
[9] At 1 °C.
[10] At 6 °C.
[11] At 7.5 °C.

Precooling and Storage Facilities

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In-Field Temperature Management

Temperature management of perishable commodities begins with proper handling at harvest. Generally, produce should be harvested in the morning so that it will be at the coolest possible temperature during the delay between harvest and initial cooling. Exceptions to this recommendation are produce, such as some citrus fruit, that are damaged if they are handled when they are turgid in the morning (Eckert and Eaks 1989), or situations in which the produce is harvested in the late afternoon so that it can be transported to a local market during the cool night hours. Produce should be shaded to protect it from solar heat gain. Reduce the time between picking and initial cooling; this is particularly critical because fruits and vegetables transpire and respire at high rates at field temperatures (Maxie et al. 1959, Harvey and Harris 1986, d'Sousa and Ingle 1989, Robbins and Moore 1992).

Initial Cooling Methods

Produce is usually cooled to its long-term storage temperature in special facilities designed to rapidly remove produce heat.

Forced-air cooling is the most widely adaptable method and is commonly used for many fruits, fruit-type vegetables, and cut flowers (Parsons et al. 1970, 1972, Rij et al. 1979, Baird et al. 1988, Thompson et al. 1998).

Hydrocooling uses water as the cooling medium and is less widely used than forced-air cooling because some products do not tolerate water contact and because it requires the use of water-resistant packaging. It is commonly used for root-, stem-, and flower-type vegetables; melons; and some tree fruits (Pentzer et al. 1936, Toussaint 1955, Stewart and Lipton 1960, Bennett 1963, Perry and Perkins 1968, Mitchell 1971).

Vacuum- and water spray vacuum-cooling are usually reserved for crops, such as leafy vegetables, that release water vapor rapidly, allowing them to be quickly cooled (Barger 1963, Harvey 1963).

Package icing uses crushed ice to cool and maintain product temperature and is used for a very few commodities, mainly those whose purchasers have a strong traditional demand for this method. It is still common for broccoli.

Room cooling is accomplished by placing warm produce in a refrigerated room. Cooling times are at least 24 h and can be much longer if produce is not packaged correctly or if no provision is made to allow airflow past boxes. It is used for a few commodities, such as citrus and CA-stored apples, which can have acceptable, though not optimal, quality without use of rapid cooling.

Transport cooling in refrigerated ships and containers is used for products, such as bananas, in areas with no cooling infrastructure. Highway trailers have insufficient airflow to cool produce and should never be depended on for initial cooling.

Table 1 is a summary comparison of the six initial cooling methods.

Table 1. Comparison of typical product effects and cost for six common cooling methods

	Forced-air	Hydro	Vacuum	Water spray	Ice	Room
Typical cooling time (h)	1 to 10	0.1 to 1.0	0.3 to 2.0	0.3 to 2.0	0.1 to 0.3*	20 to 100
Product moisture loss (%)	0.1 to 2.0	0 to 0.5	2.0 to 4.0	No data	No data	0.1 to 2.0
Water contact with product	No	Yes	No	Yes	Yes, unless bagged	No
Potential for decay contamination	Low	High†	None	High†	Low	Low
Capital cost	Low	Low	Medium	Medium	High	Low‡
Energy efficiency	Low	High	High	Medium	Low	Low
Water-resistant packaging needed	No	Yes	No	Yes	Yes	No
Portable	Sometimes	Rarely done	Common	Common	Common	No
Feasibility of in-line cooling	Rarely done	Yes	No	No	Rarely done	No

Source: Thompson et al. 1998

*Top icing can take much longer.

†Recirculated water must be constantly sanitized to minimize accumulation of decay-causing pathogens.

‡Low if product is also stored in cooler as is done with apples; otherwise long cooling times make it an expensive system.

Forced-Air Cooling

Refrigerated air is used as the cooling medium with this system. It is forced through produce packed in boxes or pallet bins. A number of airflow systems are used, but the tunnel cooler is the most common (Thompson et al. 1998). Two rows of packages, bins, or palletized product are placed on either side of an air-return channel. A tarp is placed over the product and the channel, and a fan removes air from the channel, drawing air through the product. The product is cooled in batches. Cooling times range from 1 h for cut flowers to more than 6 h for larger fruit, packed in airflow-restricting materials such as bags or paper wraps.

The cold-wall system is adapted to cooling smaller quantities of produce (Thompson et al. 1998). Individual pallets or cartloads of packages are placed against a plenum wall. Usually the plenum has a slightly lower air pressure than the room, and air is pulled through the product. Some coolers, particularly for cut flowers, use a pressurized plenum and air is pushed through the product. Cold-wall systems do not use floor space as efficiently as tunnel coolers and require more management because each pallet is cooled individually.

The serpentine air system is designed for cooling produce in pallet bins (Thompson et al. 1998). Stacks of even numbers of bins are placed against a negative pressure plenum wall. Bottom openings for forklift tines are used for air supply and air return channels. Air flows vertically up or down through the product. The forklift openings are limited in dimension, which restricts airflow and causes slow cooling. This system is used for partially cooling product that will be packaged later and finish-cooled after packing and for cooling product in long-term storage. The system uses cold room volume very efficiently.

Cooling time in forced-air coolers is controlled by volumetric airflow rate and product diameter (Flockens and Meffert 1972, Gan and Woods 1989). Coolers often operate with 1 L kg^{-1} sec^{1} of produce, with a typical range of 0.5 to 2.0 L kg^{-1} sec^{-1} (1 L kg^{-1} sec^{-1} equals approximately 1 CFM lb^{-1}). At 1 L kg^{-1} sec^{-1}, grapes with a small minimum diameter will cool in about 2 h, while cantaloupes with a much larger diameter require more than 5 h. Boxes should have about 5% sidewall vent area to accommodate airflow without excessive pressure drop across the box (Wang and Tupin 1968, Mitchell et al. 1971). Internal packaging materials should be selected to restrict airflow as little as possible.

Forced-air cooling causes some moisture loss. Loss may not be detectable for produce items with a low transpiration coefficient, like citrus fruits, or it may equal several percent of initial weight for produce with a high transpiration coefficient (Sastry and Baird 1978). Moisture loss is linearly related to difference between initial and final product temperatures. High initial produce temperatures cause higher moisture loss than lower temperatures when cooling starts. Moisture loss can be reduced at the expense of longer cooling times by wrapping product in plastic or packing it in bags.

Details of fan selection, air plenum design, refrigeration sizing, product cooling times, and operational guidelines can be found in Thompson et al. (1998). Forced-air coolers are the least energy efficient type of cooler but are widely used because they are adaptable to a wide range of products and packaging systems (Thompson et al. 2002). Small units can be installed in many existing cold storage facilities.

Hydrocooling

Cooling is accomplished with this technique by moving cold water around produce with a shower system or by immersing produce directly in cold water. Shower coolers distribute water using a perforated metal pan that is flooded with cold water from the refrigeration evaporator (Thompson et al. 1998). Shower-type coolers can be built with a moving conveyor for continuous flow operation, or they can be operated in a batch mode. Immersion coolers are suited for produce that sinks in water (Thompson et al. 1998). They usually cool more slowly than shower coolers because water flows at slower rates past the product.

Water is a better heat-transfer medium than air, and consequently hydrocoolers cool produce much faster than forced-air coolers. In well designed shower coolers, small diameter produce, like cherries, cools in less than 10 min. Large diameter products like melons cool in 45 to 60 min (Stewart and Lipton 1960, Stewart and Couey 1963, Thompson et al. 1998). Immersion coolers usually have longer cooling times than shower coolers because water speed past produce is slower.

Packages for hydrocooled produce must allow vertical water flow and tolerate water contact. Plastic or wood containers work well in hydrocoolers. Corrugated fiberboard must be wax-dipped to withstand water contact.

Hydrocoolers cause no moisture loss in cooling. In fact, they can rehydrate slightly wilted produce. Hydrocooler water spreads plant decay organisms and thus must be obtained from a clean source and treated (usually with hypochlorous acid from sodium hypochlorite or gaseous chlorine) to minimize the levels of decay organisms (Thompson et al. 1998).

Calculations of hydrocooler size, refrigeration capacity, water flow needs, and typical product cooling times can be found in Thompson et al. (1998). Hydrocoolers can be fairly energy efficient and are the least expensive cooling method to purchase (Thompson 1992).

Package Icing

Packing a product with crushed or flaked ice can quickly cool it and provides a source of cooling during subsequent handling. It also maintains high humidity around the product, reducing moisture loss. Its disadvantages are that it has high capital and operating costs, requires a package that will withstand constant water contact, and usually adds a great amount of weight to the package. In addition, meltwater can damage neighboring produce in a shipment of mixed commodities. Cut flowers are sometimes cooled initially with a forced-air system, and a small amount of ice in a sealed package is secured in the container. This greatly reduces the amount of ice needed and eliminates meltwater damage, while providing some temperature control during subsequent transit and handling.

Vacuum Cooling

This method achieves cooling by causing water to rapidly evaporate from a product. Water loss of about 1% causes 6 °C (11 °F) product cooling (Barger 1963). Product is placed in a steel vessel and vacuum pumps reduce pressure in the vessel from 760 mm Hg to 4.6 mm Hg (Thompson et al. (1998). Water boils at a pressure of 20 to 30 mm Hg depending on temperature. This causes rapid moisture evaporation and produce cooling. At the end of the cooling cycle, pressure equals 4.6 mm Hg and water boils at 0 °C (32 °F). If the product is held at this pressure long enough, it will cool to 0 °C (32 °F). For produce that releases moisture rapidly, like leafy green vegetables, cooling can be accomplished in 20 to 30 min, even when the product is wrapped in plastic film (Cheyney et al. 1979). The produce loses 2 to 4% of its weight during cooling, depending on its initial temperature. Spraying the produce with water before cooling minimizes product moisture loss. Some coolers are fitted with water spray systems that are activated during the cooling cycle.

Procedures for estimating vacuum pump capacity, refrigeration capacity, and condensing coil design can be found in Wang and Gitlin (undated). Use Thompson et al. (1998) and assume a -9 to -7 °C (15 to 20 °F) refrigerant evaporating temperature to estimate compressor horsepower. Vacuum coolers are very energy efficient (Thompson et al. 1987) and are cost competitive if well utilized (Thompson 1992).

Marine Transport Cooling

Perishable products should be cooled before being loaded into a refrigerated transport vehicle. However, some production areas do not have cooling facilities, and transport cooling is the only feasible option. Citrus and bananas in the tropics are often cooled during marine transport. Refrigerated containers and ships supply refrigerated air through a floor plenum. Fastest possible cooling is obtained by using packages that allow vertical airflow and by loading the cargo so that refrigerated air is forced through the product. Boxes should have top and bottom vents, and interior packaging materials should not block air flow. The load or dunnage material must cover the entire floor to prevent refrigerated air from traveling up though spaces between pallet loads and bypassing the load. Proper packaging and loading will allow product to cool in 1 to 2 days (Heap 1998). Improper practices will prevent the load from cooling and the product will arrive at destination too warm and in poor quality.

Cooling Time Calculations

Rate of cooling is directly related to the temperature difference between the cooling medium and the product. Initially, when the product is warm, temperature drops quite rapidly; later, the rate slows as product temperature drops. The product is considered “half cool” when its temperature drops to half the difference between its initial temperature and the cooling medium temperature. After another half-cooling period, the product is considered “three-quarters” cool. Product is usually finished cooling at “seven-eighths” or “fifteen-sixteenths” cool. Cooling time predictions can be done with equations presented in Thompson et al. (1998) or with a graphical method like that in Sargent et al. (1988).

Cold Storage

Building Design and Layout

The floor area needed for refrigerated storage can be calculated by determining the maximum amount of product the facility will be expected to handle in units of volume (m^3 or ft^3) divided by the storage height. Storage height is usually about 2 m, the height of a pallet load. Product height can be increased by adding pallet racks or, if boxes are strong enough, by stacking pallets up to three high. Pallet bins are sometimes stacked to a height of over 3 m. Add to this area space for corridors and space for lift truck movement.

Airflow Design

Adequate airflow is needed to distribute refrigerated air throughout the facility to maintain uniform air temperatures. Most cold storage is designed to have an air flow capacity of 0.3 $m^3\ min^{-1}\ tonne^{-1}$ of product (100 $ft^3\ min^{-1}\ ton^{1}$). In long-term storage, the product will reach setpoint temperature within a few days to about 1 week after the facility is filled. Airflow can then be reduced to about 20 to 40% of the design capacity and still maintain adequate temperature uniformity. This can be done by intermittent operation of fans or by keeping the fans constantly on but reducing their speed with an electronic speed control system. Slow air speeds reduce moisture loss from the product (Kroca and Hellickson 1993).

Airflow must be distributed uniformly throughout the coldroom to minimize temperature variability. For product in pallet loads, one of three systems is commonly used (Thompson et al. 1998). All three require placement of pallets in lanes separated by 10 to 15 cm (4 to 6 in). In rooms where the air must travel more than 15 m (50 ft), air is distributed through ceiling ducts or a plenum and returns to evaporators through a long opening in a plenum wall. Another system distributes air into the pallet lanes, and the air returns across the ceiling. Pallet bin storage can use the same systems, or air can be distributed through forklift openings or with a serpentine airflow system, as is used in some forced-air coolers.

Refrigeration Load

Determining the refrigeration capacity needed for a facility is based on estimating heat input to the cold storage from the following: uncooled product; product respiration; heat conduction through walls, floors, and roof; air infiltration through doors; lights; motors; equipment; and personnel. However these estimates cannot be done exactly. Over the life of a facility, it may be used for different products, the amount of product may change, and equipment performance deteriorates over time. Coldroom designers make estimates based on methods presented in Stoecker (1998) or ASHRAE (1999) and then add perhaps 20 to 30% extra capacity as a cushion. As a rule of thumb, refrigerated produce storage requires 10 to 14 kW of refrigeration capacity per 1,000 m^3 of storage volume and refrigerated shipping docks require 14 to 25 kW per 1,000 m^3 (Stoecker 1998).

Refrigeration Equipment

Most cold storage uses vapor recompression, also called mechanical refrigeration. A few facilities use absorption refrigeration, though this is only cost effective if there is an inexpensive source of low-temperature heat available. Detailed discussions of equipment selection and design are given in Stoecker (1998) and ASHRAE (1999).

The key design constraints for produce storage is uniformly maintaining desired temperature and relative humidity (RH). Uniform temperature is maintained by adequate refrigeration capacity, uniform air distribution, minimal temperature difference between the evaporator coil and the air temperature, and a precise temperature control system. High RH is needed to reduce product moisture loss. Most fresh produce requires 85 to 95% RH, while dried commodities, such as onion and ginger, need a low RH. High RH is obtained by minimizing temperature variation in the room and by operating the evaporator coil at a temperature close to the setpoint temperature of the room. This is done by installing a coil with a high surface area and by using a control system that maintains the refrigerant at its highest possible temperature.

Humidifiers may be needed to add moisture to paper or wood packaging materials; otherwise, packaging will absorb water from the product. Alternatively, the product can be packed in plastic packages that do not absorb water or in plastic bags that slow moisture loss. Plastic materials with minimum amounts of venting retard moisture loss from the produce (Crisosto et al. 1994) and may allow the cold storage to be held at a lower humidity. Products with low transpiration coefficients lose water slowly (Sastry and Baird 1978) and may not need special provision for high RH storage, especially if they are not stored for a long time.

Alternative Refrigeration Options

In areas with limited capital for investment in refrigeration, there are other options besides using mechanical refrigeration for temperature control, though none of them provide the optimum conditions that refrigeration does (Thompson 1999). Evaporative cooling drops air temperature to within a few degrees of the wet bulb temperature of the outside air and is sometimes used in dry climates. In these same climates, the nighttime air temperature tends to be lower and product can be ventilated with cool night air. Soil temperature at 2 m (6 ft) below the surface is equal to the average annual air temperature. Storage facilities can be built underground to take advantage of these lower temperatures. Well water is also usually equal to average annual air temperature and can sometimes be used to cool products. Using ice formed in winter and storing products at high altitudes are also occasionally used to provide cool storage temperatures. Unfortunately, few of the above options work well in humid, tropical climates.

Ethylene Control

Certain types of produce are sensitive to damage from ethylene; thus it is necessary to minimize ethylene level in their storage environment. Unless outside temperatures are very low or very high, ventilation is an inexpensive method of reducing ethylene levels. Ethylene can also be absorbed on commercially available potassium permanganate pellets. A few products, especially floral and ornamental crops, can be chemically treated to make them insensitive to ethylene damage.

Controlled Atmosphere Facilities

Storage rooms can be built for controlled atmosphere (CA) storage for about 5% additional cost if they are properly designed initially. The extra cost is for sealing joints between walls, ceilings, and floors and for installing gas-tight doors. Tilt-up concrete, metal panels, urethane foam, and plywood have all been successfully used as gas barriers. These storage rooms also need equipment for monitoring and controlling gas levels (Waelti and Bartsch 1990).

References

ASHRAE [American Society of Heating, Refrigerating, and Air-Conditioning Engineers]. 1999. ASHRAE Handbook Series (4 books). ASHRAE, Atlanta, GA.

Baird, C.D., J.J. Gaffney, and M.T. Talbot. 1988. Design criteria for efficient and cost-effective forced-air cooling systems for fruits and vegetables. ASHRAE Trans. 94:1434-1454.

Barger, W.R. 1963. Vacuum cooling: a comparison of cooling different vegetables. Marketing Research Report 600, U.S. Department of Agriculture, Washington, DC.

Bennett, A.H. 1963. Thermal characteristics of peaches as related to hydro-cooling. Technical Bull. 1292, U.S. Department of Agriculture, Washington, DC.

Cheyney, C.C., R.F. Kasmire, and L.L. Morris. 1979. Vacuum cooling of wrapped lettuce. Calif. Agric. 33:18-19.

Crisosto, C.H., J.L Smilanick, N.K. Dokoozlian, and D.A. Luvisi. 1994. Maintaining Table Grape Postharvest Quality for Long Distance Markets, International Symposium on Table Grape Production, American Society for Enology and Viticulture, Anaheim, CA.

d'Sousa, M.C., and M. Ingle. 1989. Effect of delayed cooling on the poststorage flesh firmness of apples. J. Food Sci. 54:493-494.

Eckert, J.L., and I.L. Eaks. 1989. Postharvest disorders and diseases of citrus fruits. *In* W. Ruther, ed, The Citrus Industry, Vol. 5, pp. 179-260, Department of Agriculture and Natural Resources, Pub. no. 3326, University of California, Davis, CA.

Flockens, I.H., and H.F.T. Meffert. 1972. Biophysical properties of horticultural products as related to loss of moisture during cooling down. J. Sci. Food Agric. 23:285-298.

Gan, G., and J.L. Woods. 1989. A deep bed simulation of vegetable cooling. *In* V.A. Dodd and P.M. Grace, eds, Land and Water Use, pp. 2301-2308. Balkema, Rotterdam, The Netherlands.

Harvey, J.M., and C.M. Harris. 1986. In-storage softening of kiwifruit: effects of delayed cooling. Int. J. Refrig. 9:352-355.

Harvey, J.M. 1963. Improved techniques for vacuum cooling vegetables. ASHRAE J. 5:41-44.

Heap, R. 1998. Transport of foodstuffs by sea. *In* R. Heap, M. Kierstan, and G. Ford, eds., Food Transportation, pp. 75-96. Blackie Academic and Professional, London, UK.

Kroca, R.W., and M.L. Hellickson. 1993. Energy savings in evaporator fan-cycled apple storages. Appl. Eng. Agric. 9:553-560.

Maxie, E.C., F.G. Mitchell, and A. Greathead. 1959. Studies on strawberry quality. Calif. Agric., Feb. 1:16.

Mitchell, F.G., R.A. Parsons, and G. Mayer. 1971. Cooling trials with plastic tray pack nectarines in various containers. Calif. Agric. 25(9):13-15.

Parsons, R.A., F.G. Mitchell, and G. Mayer. 1970. Forced-air cooling of palletized fresh fruit. Paper 70-875, ASAE, St. Joseph, MI.

Parsons, R.A. 1972. Forced-air cooling of fruit in bulk bins. SP-01-72:38-41, American Society of Agricultural Engineers, St. Joseph, MI.

Perry, R., and R. Perkins. 1968. Hydro-cooling sweet corn. Paper 68-800, American Society of Agricultural Engineers, St. Joseph, MI.

Pentzer, W.T., R.L. Perry, G.C. Hanna, et al. 1936. Precooling and Shipping California Asparagus. University of California Agricultural Experiment Station Bulletin 600, Univ. of California, Davis, CA.

Rij, R. E., J.F. Thompson, and D. S. Farnham. 1979. Handling, precooling, and temperature management of cut flower crops for truck transportation. USDA-SEA Adv. Agric. Technol. AAT-W-5. June.

Robbins, J., and P.P. Moore. 1992. Fruit quality of stored fresh red raspberries after a delay in cooling. HortTechnology 2(4):468-470.

Sargent, S.A., M.T. Talbot, and J.K. Brecht. 1988. Evaluating precooling methods for vegetable packinghouse operations. Proceedings of the Florida State Horticulture Society 101:175-182.

Sastry, S.K., and C.D. Baird. 1978. Transpiration rates of certain fruits and vegetables. ASHRAE Trans. 84(2):237-255.

Stewart, K.S., and H.M. Couey. 1963. Hydro-cooling vegetables—a practical guide to predicting final temperatures and cooling times. Mkt. Res. Rpt. 637, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Stewart, J.K., and W.J. Lipton. 1960. Factors influencing heat loss in cantaloupes during hydro-cooling. Marketing Research Report 421, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Stoecker, W.F. 1998. Industrial Refrigeration Handbook. McGraw-Hill, New York, NY.

Thompson, J.F. 1999. Cold-storage systems. *In* F.W. Bakker-Arkema, ed., CIGR Handbook of Agricultural Engineering, vol. IV, pp. 339-361. ASAE, St. Joseph, MI.

Thompson, J.F., F.G. Mitchell, and R.F. Kasmire. 2002. Cooling horticultural commodities. *In* A.A.Kader, ed., Postharvest Technology of Horticultural Crops, pp. 97-112. DANR Pub. no. 3311, University of California, Davis, CA.

Thompson, J.F., F.G. Mitchell., T.R. Rumsey, et al. 1998. Commercial cooling of fruits, vegetables, and flowers. DANR Pub. no. 21567, University of California, Davis, CA.

Toussaint, W.D., T.T. Hatlow, and G. Abshier. 1955. Hydro-cooling peaches in the North Carolina sandhills. Env. Infor. Ser. no. 320, North Carolina Agricultural Experiment Station, North Carolina State University, Raleigh, NC.

Wang, J.K., and K. Tunpun. 1968. Forced-air cooling of tomatoes in cartons. Trans. Am. Soc. Agric. Eng. 12:804-806.

Waelti, H., and J.A. Bartsch. 1990. CA storage facilities. *In* M. Calderon and R. Barkai-Golan, eds., Food Preservation by Modified Atmospheres, pp. 373-389. CRC Press, Boca Raton, FL.

Heat Load Calculation

Some factors need to be considered in determining refrigeration required for a cold-storage plant. Examples are simplified to illustrate steps necessary to calculate heat load of a refrigerated storage area during cooling and normal storage operation. More information on load calculations can be found in Patchen (1971), Ryall and Lipton (1979), ASHRAE (1981), and Bartsch and Blanpied (1984). The information presented here is adapted from pages 14 to 16 of the previous USDA Agriculture Handbook Number 66 (Hardenberg et al. 1986). Examples are shown in metric units for pears in storage at -1.1 ºC (30 ºF). To convert respiration rate of fruits and vegetables expressed in mg CO_2 kg^{-1} h^{-1} to heat production in kJ, multiply mg CO_2 kg^{-1} h^{-1} by 61 to get kcal $tonne^{-1}$ day^{-1} (1 kcal = 4,186 kJ).

Conditions	**Example**
Storage size	15×15×4.5 m
Outside surface area (including floor)	720 m^2
Inside dimensions	14.7×14.7×4.2 m
Volume	908 m^3
Insulation	7.6 cm of polyurethane with a conductivity value (k) = 1.3 kJ per m^2 per cm thickness per ºC; coefficient of transmission (U) = 1.1 kJ h^{-1} m^{-2} $ºC^{-1}$
Ambient conditions at harvest	30 ºC and 50% RH
Fruit temperature	at harvest, 21 ºC; in storage, -1.1 ºC
Storage capacity	600 bins at 500 kg fruit per bin = 300,000 kg of fruit
Bin weight	63.5 kg; total weight of bins = 38,100 kg
Loading weight and time	200 bins (100,000 kg fruit per day); 3 days to fill
Cooling rate	1st day, 21 to 4.5 ºC; 2nd day, 4.5 to -1.1 ºC
Air changes from door openings:	
during cooling	6 per day
during storage	1.8 per day
Specific heat	pears, 0.86; wood bins, 0.5
Heat load to lower air:	
from 30 to -1.1 ºC (50% RH)	74.5 kJ m^{-3}
from 7.2 to -1.1 ºC (70% RH)	15.3 kJ m^{-3}
Miscellaneous heat loads	lights, 2,400 W per h (3.6 kJ W^{-1}) fans at 3,112 kJ per HP electric forklifts, 36,920 kJ each for 8 h workers, 1,000 kJ per h per person

A. Load during cooling and filling storage: temperature difference (TD) from 30 ºC to -1.1 ºC = 31.1 ºC, assuming 31.1 ºC TD on all surfaces:

	kJ per 24 h
1. Building-transmission load: area (720 m^2) × U (1.1 kJ) × TD (31.1 ºC) × h (24) =	591,149
2. Air-change load from doors: vol (908 m^3) × heat load (74.5 kJ) × air changes (6) =	405,876
3. Product cooling (field heat removal):	
First day	
Fruit (100,000 kg) × specific heat (0.86) × TD (21 to 4.5 ºC) × kJ factor (4.186) =	5,939,934
Bin weight (12,700 kg) × specific heat (0.5) × TD (21 to 4.5 ºC) × kJ factor (4.186) =	438,588
Second day	
Fruit weight (100,000 kg) × specific heat (0.86) × TD (4.5 to -1.1 ºC) × kJ factor (4.186) =	2,015,977
Bin weight (12,700 kg) × specific heat (0.5) × TD (4.5 to -1.1 ºC) × kJ factor (4.186) =	148,854
4. Heat of respiration during cooling (vital heat):	
First day	
Average temperature of 13 ºC; respiration rate of 12,206 kJ per tonne per 24 h; tons of fruit (100) × rate (12,206) =	1,220,600
Second day	
Average temperature of 1.7 ºC; respiration rate of 1,741 kJ per tonne per 24 h; tonnes of fruit (100) × rate (1,741) =	174,100
Maximum heat accumulated in storage before cooling completed: total fruit weight of 300,000 kg - 2 day loading weight of 200,000 kg = 100,000 kg (100 tonnes); respiration rate at -1.1 ºC is 812 kJ per tonne per 24 h; tonnes of fruit (100) × respiration rate (812) =	81,200
5. Miscellaneous heat loads:	
Lights: W (2,400) × kJ per W (3.6) × h (8) =	69,120
Fans: HP (3) × kJ per HP (3,112) × h (24) =	224,064
Forklifts: 2 × 36,920 kJ per forklift for 8 h =	73,840
Labor: workers (2) × kJ per h (1,000) × h (8) =	16,000

Total heat load during cooling:

Building transmission	519,149
Air change	405,876
Product cooling	8,543,353
Production respiration	1,475,900
Miscellaneous	383,024
Subtotal	11,399,302
Add 10% to be cautious	1,139,930
Total required refrigeration	12,539,232

Assuming refrigeration equipment operates 18 h per day: 12,539,232 ÷ 18 h = 696,624 kJ h^{-1}. Since a tonne of refrigeration absorbs 12,660 kJ per 24 h: 696,624 ÷ 12,660 = 55 tonnes of peak refrigeration capacity is required.

B. Load during normal storage operation (average outside ambient conditions, 7.2 ºC at 70% RH; storage temperature, -1.1 ºC; TD = 7.2 º to -1.1 ºC = 8.3 ºC).

	kJ per 24 h
1. Building-transmission load: area (720 m^2) × U (1.1 kJ) × TD (8.3 ºC) × h (24) =	157,766
2. Air-change load from doors: vol (908 m^3) × heat load (15.3 kJ) × air changes (1.8) =	25,006

Product load (respiration, no cooling):
3. Respiration rate at -1.1 ºC is 812 kJ per tonne per 24 h; tonne fruit (300) × rate (812) = 243,600

4. Miscellaneous head loads:

Lights: W (2,400) × kJ per W (3.6) × h (4) =	34,560
Fans: HP (3) × kJ per HP (3,112) × h (24) =	224,064
Labor: people (1) × kJ per h (1,000) × h (4) =	4,000

Total load during storage:

Building transmission		157,766
Air change		25,006
Product load (respiration)		243,600
Miscellaneous		262,624
	Subtotal	688,996
	Add 10% to be cautious	68,899
	Total required refrigeration	757,895

Assuming refrigeration equipment operates 18 hours per day: 757,895 ÷ 18 h = 42,105 kJ h^{-1} and 42,105 ÷ 12,660 = 3.3 tonnes of refrigeration capacity is needed during normal storage.

References

ASHRAE [American Society of Heating, Refrigerating and Air Conditioning Engineers]. 1981. American Society of Heating, Refrigeration and Air Conditioning Engineers Handbook 1982 Applications. ASHRAE, Atlanta, GA.

Bartsch, J.A., and G.D. Blanpied. 1984. Refrigeration and controlled atmosphere storage for horticultural crops. NRAES no. 22, Northeast Region Agricultural Engineer Service, Cornell University, Ithaca, NY.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, pp. 14-16. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Patchen, G.O. 1971. Storage for apples and pears. Marketing Research Report 924, U.S. Department of Agriculture, Washington, DC.

Ryall, A.L., and W.J. Lipton. 1979. Vegetables and melons. *In* Handling, Transportation and Storage of Fruits and Vegetables, 2nd ed., vol. 1. AVI Pub. Co., Westport, CT.

Controlled Atmosphere Storage

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Introduction

Controlled atmosphere (CA) storage involves maintaining an atmospheric composition that is different from air composition (about 78% N_2, 21% O_2, and 0.03% CO_2); generally, O_2 below 8% and CO_2 above 1% are used. Atmosphere modification should be considered as a supplement to maintenance of optimum ranges of temperature and RH for each commodity in preserving quality and safety of fresh fruits, ornamentals, vegetables, and their products throughout postharvest handling. This chapter gives an overview of responses to CA; specific CA considerations are given in individual commodity summaries.

Biological Basis of CA Effects

Exposure of fresh horticultural crops to low O_2 and/or elevated CO_2 atmospheres within the range tolerated by each commodity reduces their respiration and ethylene production rates; however, outside this range respiration and ethylene production rates can be stimulated, indicating a stress response. This stress can contribute to incidence of physiological disorders and increased susceptibility to decay. Elevated CO_2-induced stresses are additive to and sometimes synergistic with stresses caused by low O_2, physical or chemical injuries, and exposure to temperatures, RH, and/or C_2H_4 concentrations outside the optimum range for the commodity.

The shift from aerobic to anaerobic respiration depends on fruit maturity and ripeness stage (gas diffusion characteristics), temperature, and duration of exposure to stress-inducing concentrations of O_2 and/or CO_2. Up to a point, fruits and vegetables are able to recover from the detrimental effects of low O_2 and high CO_2 stresses (fermentative metabolism) and resume normal respiratory metabolism upon transfer to air. Plant tissues have the capacity for recovery from the stresses caused by brief exposure to fungistatic atmospheres (>10% CO_2) or insecticidal atmospheres (<1% O_2 and/or 40 to 80% CO_2). Postclimacteric fruits are less tolerant and have lower capacity for recovery following exposure to reduced O_2 or elevated CO_2 levels than preclimacteric fruits. The speed and extent of recovery depend on duration and levels of stresses and underlying, metabolically driven cellular repair.

Elevated-CO_2 atmospheres inhibit activity of ACC synthase (key regulatory site of ethylene biosynthesis), while ACC oxidase activity is stimulated at low CO_2 and inhibited at high CO_2 concentrations and/or low O_2 levels. Ethylene action is inhibited by elevated CO_2 atmospheres. Optimum atmospheric compositions retard chlorophyll loss (green color), biosynthesis of carotenoids (yellow and orange colors) and anthocyanins (red and blue colors), and biosynthesis and oxidation of phenolic compounds (brown color). Controlled atmospheres slow down the activity of cell wall degrading enzymes involved in softening and enzymes involved in lignification, leading to toughening of vegetables. Low O_2 and/or high CO_2 atmospheres influence flavor by reducing loss of acidity, starch to sugar conversion, sugar interconversions, and biosynthesis of flavor volatiles. When produce is kept in an optimum atmosphere, ascorbic acid and other vitamins are retained, resulting in better nutritional quality.

Severe stress CA conditions decrease cytoplasmic pH and ATP levels and reduce pyruvate dehydrogenase activity, while pyruvate decarboxylase, alcohol dehydrogenase, and lactate dehydrogenase are induced or activated. This causes accumulation of acetaldehyde, ethanol, ethyl acetate, and/or lactate, which may be detrimental to the commodities if they are exposed to stress CA conditions beyond their tolerance. Specific responses to CA depend on cultivar, maturity and ripeness stage, storage temperature and duration, and in some cases ethylene concentrations.

N_2 is an inert component of CA. Replacing N_2 with argon or helium may increase diffusivity of O_2, CO_2, and C_2H_4, but they have no direct effect on plant tissues and are more expensive than N_2 as a CA component.

Super-atmospheric levels of O_2 up to about 80% may accelerate ethylene-induced degreening of nonclimacteric commodities and ripening of climacteric fruits, respiration and ethylene production rates, and incidence of some physiological disorders (such as scald on apples and russet spotting on lettuce). At levels above 80% O_2, some commodities and postharvest pathogens suffer from O_2 toxicity. Use of super-atmospheric O_2 levels in CA will likely be limited to situations in which they reduce the negative effects of fungistatic, elevated CO_2 atmospheres on commodities that are sensitive to CO_2-induced injury.

Beneficial Effects of CA (Optimum Composition for the Commodity)—A Summary

- Retardation of senescence (including ripening) and associated biochemical and physiological changes, particularly slowing down rates of respiration, ethylene production, softening, and compositional changes.
- Reduction of sensitivity to ethylene action at O_2 levels <8% and/or CO_2 levels >1%.
- Alleviation of certain physiological disorders such as chilling injury of avocado and some storage disorders, including scald of apples.
- CA can have a direct or indirect effect on postharvest pathogens (bacteria and fungi) and consequently decay incidence and severity. For example, CO_2 at 10 to 15% significantly inhibits development of botrytis rot on strawberries, cherries, and other perishables.
- Low O_2 (<1%) and/or elevated CO_2 (40 to 60%) can be a useful tool for insect control in some fresh and dried fruits, flowers, and vegetables and in dried nuts and grains.

Detrimental Effects of CA (Above or Below Optimum Composition for the Commodity)—A Summary

- Initiation and/or aggravation of certain physiological disorders such as internal browning in apples and pears, brown stain of lettuce, and chilling injury of some commodities.
- Irregular ripening of fruits, such as banana, mango, pear, and tomato, can result from exposure to O_2 levels below 2% and/or CO_2 levels above 5% for >1 mo.
- Development of off flavors and off odors at very low O_2 concentrations (as a result of anaerobic respiration) and very high CO_2 levels (as a result of fermentative metabolism).
- Increased susceptibility to decay when the fruit is physiologically injured by too low O_2 or too high CO_2 concentrations.

Commercial Application of CA Storage

Several refinements in CA storage have been made in recent years to improve quality maintenance. These include creating nitrogen by separation from compressed air using molecular sieve beds or membrane systems, low-O_2 (1.0 to 1.5%) storage, low-ethylene (<1 $\mu L\ L^{-1}$) CA storage, rapid-CA (rapid establishment of optimal levels of O_2 and CO_2), and programmed- (or sequential-) CA storage—for example, storage in 1% O_2 for 2 to 6 weeks followed by storage in 2 to 3% O_2 for the remainder of the storage period. Other developments, which may expand use of atmospheric modification during transport and distribution, include improved technologies for establishing, monitoring, and maintaining CA using edible coatings or polymeric films with appropriate gas permeability to create a desired atmospheric composition around and within the commodity. Modified atmosphere packaging (MAP) is widely used in marketing fresh-cut produce.

Applications of CA to cut flowers are very limited because decay caused by *Botrytis cinerea* is often a limiting factor to postharvest life, and fungistatic CO_2 levels damage flower petals and/or associated stem and leaves. Also, it is less expensive to treat flowers with anti-ethylene chemicals than to use CA to minimize ethylene action.

Commercial use of CA storage is greatest on apples and pears worldwide, less on cabbages, sweet onions, kiwifruits, avocados, persimmons, pomegranates, and nuts and dried fruits and vegetables (table 1). Atmospheric modification during long-distance transport is used with apples, asparagus, avocados, bananas, broccoli, cane berries, cherries, figs, kiwifruits, mangos, melons, nectarines, peaches, pears, plums, and strawberries. Continued technological developments in the future to provide CA during transport and storage at a reasonable cost (positive benefit/cost ratio) are essential to greater applications on fresh horticultural commodities and their products.

Table 1. Classification of horticultural crops according to their CA storage potential at optimum temperatures and RH.

Storage duration	Commodities
Months	
>12	Almond, Brazil nut, cashew, filbert, macadamia, pecan, pistachio, walnut, dried fruits and vegetables
6 to 12	Some cultivars of apples and European pears
3 to 6	Cabbage, Chinese cabbage, kiwifruit, persimmon, pomegranate, some cultivars of Asian pears
1 to 3	Avocado, banana, cherry, grape (no SO_2), mango, olive, onion (sweet cultivars), some cultivars of nectarine, peach and plum, tomato (mature-green)
<1	Asparagus, broccoli, cane berries, fig, lettuce, muskmelons, papaya, pineapple, strawberry, sweet corn, fresh-cut fruits and vegetables, some cut flowers

Additional Reading and Reference Material

Calderon, M., and R. Barkai-Golan, eds. 1990. Food Preservation by Modified Atmospheres. CRC Press, Boca Raton, FL.

El-Goorani, M.A., and N.F. Sommer. 1981. Effects of modified atmospheres on postharvest pathogens of fruits and vegetables. Hort. Rev. 3:412-461.

Gorny, J., ed. 1997. Fresh-Cut Fruits and Vegetables and MAP, CA'97 Proceedings, vol. 5. Postharvest Hort. Ser. no. 19, University of California, Davis, CA.

Kader, A.A. 1986. Biochemical and physiological basis for effects of controlled and modified atmospheres on fruits and vegetables. Food Technol. 405:99-100, 102-104.

Kader, A.A., ed. 1997. Fruits Other Than Apples and Pears, CA'97 Proceedings, vol. 3. Postharvest Hort. Ser. no. 17, University of California, Davis CA.

Kader, A.A., D. Zagory, and E.L. Kerbel. 1989. Modified atmosphere packaging of fruits and vegetables. CRC Crit. Rev. Food Sci. Nutr. 28:1-30.

Mitcham, E.J., ed. 1997. Apples and Pears, CA'97 Proceedings, vol. 2. Postharvest Hort. Ser. no. 16, University of California, Davis, CA.

Raghavan, G.S.V., P. Alvo, Y. Gairepy, and C. Vigneault. 1996. Refrigerated and controlled modified atmosphere storage. *In* L.P. Somogyi et al., eds, Processing Fruits: Science and Technology, vol. 1, Biology, Principles and Applications, pp. 135-167. Technomic Pub. Co., Lancaster, PA.

Saltveit, M.E., ed. 1997. Vegetables and Ornamentals, CA'97 Proceedings, vol. 4. Postharvest Hort. Ser. no. 18, University of California, Davis, CA.

Thompson, A.K. 1998. Controlled Atmosphere Storage of Fruits and Vegetables. CAB International, Wallingford, U.K.

Thompson, J.F., and E.J. Mitcham, eds. 1997. Technology and Disinfestation Studies, CA'97 Proceedings, vol. 1. Postharvest Hort. Ser. no. 15, University of California, Davis, CA.

Vigneault, C., V.G.S. Raghavan, and R. Prange. 1994. Techniques for controlled atmosphere storage of fruit and vegetables. Tech. Bull 1993-18E, Agriculture Canada, Kentville, N.S.

Wang, C.Y. 1990. Physiological and biochemical effects of controlled atmosphere on fruits and vegetables. *In* M. Calderon and R. Barkai-Golan, eds, Food Preservation by Modified Atmospheres, pp. 197-223. CRC Press, Boca Raton, FL.

Weichmann, J. 1986. The effect of controlled atmosphere storage on the sensory and nutritional quality of fruits and vegetables. Hort. Rev. 8:101-127.

Yahia, E.M. 1998. Modified and controlled atmosphere for tropical fruits. Hort. Rev. 22:123-183.

Zagory, D., and A.A. Kader. 1989. Quality maintenance in fresh fruits and vegetables by controlled atmospheres. *In* J.J. Jen, ed., Quality Factors of Fruits and Vegetables: Chemistry and Technology, pp. 174-188. American Chemical Society, Washington, DC

Temperature Preconditioning

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Introduction

Temperature preconditioning of fruits and vegetables has been practiced for more than 70 years, since Baker (1939, 1952) described heat treatments for disinfestation of fruit flies in citrus. There is renewed interest in high temperature as a postharvest treatment for control of both insect pests and fungal pathogens in fresh produce. In part, this is because of the deregistration of a number of compounds that, until recently, have been used for effective control of postharvest disorders. In addition, there is increased consumer demand for produce that has had minimal, or ideally no, chemical treatment.

Heat has fungicidal as well as insecticidal action, but heat regimes that are optimal for insect control may not be optimal for disease control; in some cases they may even be detrimental. A thermal treatment that is developed for fungus or insect control should not damage the commodity being treated. In fact, in many cases high temperature manipulation before storage may have beneficial effects on the commodity treated. These benefits include slowing the ripening of climacteric fruit and vegetables, enhancing sweetness of produce by increasing the amount of sugars or decreasing acidity, and prevention of storage disorders such as superficial scald on apples and chilling injury on subtropical fruits and vegetables (Lurie 1998).

Temperature conditioning before storage may also mean an incubation period spent at either ambient temperature of 16 to 25 °C (61 to 77 °F) or at a temperature below ambient but above that which might produce chilling injury: 5 to 12 °C (41 to 54 °F), depending on the commodity. This type of temperature manipulation is often referred to as a "curing" period and is used with crops such as potatoes, onions, and carrots. Its purpose is generally to increase resistance of the commodity to pathogen invasion, though it may also increase resistance to low-temperature injury in citrus.

In this chapter we discuss temperature preconditioning treatments according to their purpose; that is, pathogen, insect, or chilling injury control. Most of the methods listed here, however, are still experimental and have yet to be accepted for routine commercial practice.

Commercial Treatments

The greatest number of temperature manipulations used commercially are based on high-temperature treatments (vapor heat or hot forced-air) for insect disinfestation. Temperature regimes are developed specifically for each commodity and insect pest. The accepted procedures for produce entering the United States are described in the Plant Protection and Quarantine Treatment Manual from USDA, Animal and Plant Health Inspection Service (APHIS). The manual is routinely updated (APHIS 1998). The latest edition of the manual should be consulted for approved treatments for particular commodities or pests.

An example of commercial temperature conditioning for pest control is Mexican-grown mangos, which may be infested with a variety of fruit fly larvae or eggs. Officially authorized treatments are high-temperature, forced-air treatment (HAT) or a hot water dip treatment (HWT) before storage and shipment. In HAT, fruit are heated until their centers reaches 48 °C (118 °F). HWT conditions depend on fruit size and can vary from 45 to 90 min in water, where the fruit interior reaches 46 °C (115 °F).

Vapor-heat (VHT) differs from high-temperature, forced-air in that moisture accumulates on the surface of the fruit. The water droplets transfer heat more efficiently than air, allowing the fruit to heat quickly; but there may also be increased physical injury to the fruit. Papayas grown in Hawaii are vapor-heat-treated before being exported to Japan.

Citrus can be disinfested by HAT at 44 °C (111 °F) for 100 min, with an additional 90 min spent raising the temperature to 44°C. The usual disinfestation method, however, is to hold the fruit at low temperature of 0 to 2 °C (32 to 36 °F) for 10 to 16 days before raising the temperature to the normal storage temperature of 6 to 11°C (43 to 52 °F), depending on cultivar. Since citrus is sensitive to chilling, fruit are generally held at 20 °C (68 °F) or 16 °C (61 °F) for 3 to 5 days before placing at low temperature. This curing treatment decreases fruit susceptibility to chilling injury resulting from the subsequent disinfestation treatment.

Insect Disinfestation

The development and implementation of heat treatments for insect disinfestation have been reviewed thoroughly (Couey 1989, Paull 1993). Table 1 includes treatment regimes that have been reported in the past 20 years. More than half the treatments are designed to kill fruit fly eggs or larvae, because their presence requires strict quarantine in most fruit-importing countries. The most recently developed methods include heat treatments in combination with low-O_2 or high-CO_2 atmospheres.

Antifungal Treatments

Curing is used commercially to increase resistance to pathogen invasion. Potatoes are cured at 12 °C (54 °F) for 10 to 12 days before storage at 4 to 9 °C (39 to 48 °F), depending on cultivar and on whether they are designated for industry or home consumption. Sweet potatoes are also cured at 30 °C (86 °F) for 5 days before storage at 12 °C (54 °F). In both cases the curing period allows for wound healing and deposition of cell wall material to create a physical barrier to pathogens. Kiwifruit also benefit from a curing period. If held at 10 °C (50 °F) before storage at low temperatures, they develop fewer rots after storage. Onions can be stored longer if held at 28 °C (82 °F) for 3 days before storage.

The two commercial applications of high-temperature antifungal treatments are HWT for papayas (Akamine and Arisumi 1953), which has been used for almost 50 years, and a hot-water brush treatment (HWB) (Fallik 1996a, 1999, Prusky et al. 1997). The brush system is in use on packing lines for export of corn, mangos, peppers, and some citrus from Israel. The machine sprays hot water at 50 to 65 °C (122 to 149 °F) on produce as it moves along on brush rollers. The major benefit appears to be removal of spores and dirt, though hot water combined with brushing also causes surface cracks to be filled in by the natural wax of the commodity, as well as eliciting resistance to pathogens in some cases.

The state of temperature conditioning treatments against fungal pathogens was reviewed by Barkai-Golan and Phillips (1991) and Coates and Johnson (1993). The majority of the regimes listed in table 2 were developed in the past 10 years. Dips in hot fungicide solution have been used since the 1950s for pathogen control. As various fungicides lose their registration or as pathogens develop resistance, there is increased interest in heat-treating produce in combination with compounds that are generally recognized as safe (GRAS), such as calcium chloride or sodium carbonate (table 2).

Physiological Benefits of Conditioning Treatments

Most thermal treatments have been developed as lethal regimes for insects or fungi. Some of these regimes, however, also have prophylactic effects against physiological disorders such as chilling injury (CI). Prevention of CI allows the commodity to be stored longer at lower temperatures, which in turn permits export in ships rather than more costly air freight. In addition, a preshipping heat treatment can allow for low-temperature disinfestations of commodities, such as citrus, by improving the resistance of fruit to CI generally incurred during this treatment.

Other heat treatments have been developed specifically to maintain postharvest quality, such as increased firmness of apples or decreased yellowing of broccoli, or to protect against other abiotic stresses, such as irradiation disinfestation treatments (table 3). The physiological mechanisms of these treatments were previously reviewed by Lurie (1998).

Table 1. Thermal treatment of horticultural commodities for insect disinfestation

Insect	Latin name	Fruit	Regime*	Temperature/Time	Reference
Fruit flies					
Caribbean fruit fly	*Anastrepha suspensa*	grapefruit	HAT		Sharp & Gould 1994
		mango	HAT	52 °C/125 min	Miller et al. 1991
		orange	HAT		Sharp & McGuire 1996
Mediterranean fruit fly	*Ceratitis capitata*	avocado	HAT	40 °C/24 h	Jang 1996
		mango	VHT	47 °C/15 min	Heather et al. 1997
		papaya	HAT	47 °C at pulp for 3.5 h	Armstrong et al. 1995
Melon fruit fly	*Dacus cucurbitae* *Bactrocera cucurbitae*	avocado	HAT	40 °C/24 h	Jang 1996
		cucumber	HAT then HWT	32 °C/24 h then 45-46 °C/50-60 min	Chan & Linse 1989
		papaya	HAT	4C °C at pulp for 3.5 h	Armstrong et al. 1995
		zucchini	VHT		Jacobi et al. 1996
Mexican fruit fly	*Anastrepha ludens* *Bactrocera cucumis*	grapefruit	HAT & CA	44 °C/2 h in 1% O_2	Shellie et al. 1997
		zucchini	VHT	45 °C/30 min	Jacobi et al. 1996
Oriental fruit fly	*Dacus dorsalis* *Bactrocera dorsalis*	cucumber	HAT then HWT	32 °C/24 h then 45-46 °C/50-60 min	Chan & Linse 1989
		papaya	HAT	47 °C at pulp for 3.5 h	Armstrong et al. 1995
Papaya fruit fly	*Bactrocera payapae*	mango	VHT	47 °C/15 min	Heather et al. 1997
Queensland fruit fly	*Bactrocera tyroni*	avocado	HWT & benomyl	46 °C/3 min then 1 °C/7 days	Jessup 1994
		litchi	VHT	45 °C/30 min	Jacobi et al. 1993
		mango	VHT	47 °C/10 min	Heather et al. 1997 Jacobi et al. 1995
			HWT then VHT	53 °C/15 min then 47°C/15 min	Jacobi & Giles 1997

Table 1. Thermal treatment of horticultural commodities for insect disinfestation—*Continued*

Insect	Latin name	Fruit	Regime*	Temperature/Time	Reference
Other insects					
Coddling moth	*Cydia pomonella*	apple	HAT or VHT	44 °C/120 min then 0 °C/4 weeks	Neven et al. 1996
		cherry	HAT & CA	47 °C/44 min in 1% O_2; 15% CO_2	Neven & Mitcham 1996 Neven & Drake 2000
		pear	HAT or VHT	44 °C/120 min then 0°C/4 weeks	Neven et al. 1996
			HAT & CA	30 °C/ 30 h in 0.3% O_2	Chervin et al. 1997
Fuller's rose beetle	*Asynonychus godmani*	lemon	HWT	52 °C/8 min	Soderstrom et al. 1993
Leafroller	*Cnephasia jactatana*	apple	HAT & CA	40 °C/10 h in 0.4% O_2 45 °C/5 h in 0.4% O_2	Whiting et al. 1999
	Ctenopseustis obliquana	kiwifruit	HAT & CA	40 °C/5-7 h in 0.4% O_2 40 °C/6 h in 2% O_2; 5% CO_2	Whiting et al. 1997 Hoy & Whiting 1998
Light brown apple moth	*Epiphyas postvittana*	apple	HAT & CA	40 °C/17-20 h in 1.2% O_2; 1% CO_2	Lay-Yee et al. 1997 Dentener et al. 2000
			HWT & ethanol	45 °C/13 min in 50% ethanol	Hoy & Whiting 1998
		kiwifruit	HAT & CA		
		pear	HAT & CA	30 °C/30 h in 0.3% O_2	Chervin et al. 1997
Longtailed mealybug	*Pseudococcus longispinus*	persimmon	HWT	48 °C/26 min or 50 °C/22 min	Lester et al. 1995
			HAT		Dentener et al. 1996, 1997

Table 1. Thermal treatment of horticultural commodities for insect disinfestation—*Continued*

Insect	Latin name	Fruit	Regime*	Temperature/Time	Reference
New Zealand flower thrips	*Thrips obscuratus*	apricot nectarine peach	HWT	48 °C/3 min then 50 °C/2 min	McLaren et al. 1997
Obscure mealybug	*Pseudococcus affinis*	apple	HAT & CA	40 °C/10 h in 0.4% O_2 45 °C/5 h in 0.4% O_2	Whiting & Hoy 1997
Oriental fruit moth	*Grapholita molesta*	pear	HAT & CA	30 °C/30 h in 0.3% O_2	Chervin et al. 1997
Two spotted spider mite	*Tetranychus urticae*	apples	HWT & ethanol	45 °C/13 min in 50% ethanol	Dentener et al. 1998
		kiwifruit	HAT & CA	44 °C/211 min	Lay-Yee & Whiting 1996
		persimmon	HWT	47 °C/67 min	Lester et al. 1997
White peach scale	*Pseudaulacaspis pentagona*	papaya	VHT	47 °C/4 h	Follet & Gabbard 1999

* HAT: high-temperature forced-air treatment
VHT: vapor-heat treatment
HWT: hot-water treatment
CA: controlled atmosphere

Table 2. Thermal treatment of horticultural commodities for eradication of and protection from fungal pathogens

Fungus	Common name	Crop	Regime*	Temperature/Time	Reference
Alternaria alternata	Black spot	carrot	HWB	100 °C/3 sec	Afek et al. 1999
		mango	HWB	60-70 °C/15-20 sec	Prusky et al. 1999
	Black mold	pepper	HWT	50 °C/3 min	Fallik et al. 1996b
Botrytis cinerea	Grey mold	apple	HAT & $CaCl_2$	38 °C/4 days and $CaCl_2$ dip	Klein et al. 1997
		pepper	HWT	50 °C/3 min	Fallik et al. 1996b
		strawberry	HWT	45 °C/15 min	Garcia et al. 1996
		tomato	HWT	50 °C/2 min	Barkai-Golan et al. 1993
			HAT	38 °C/2 days	Fallik et al. 1993
Botryodiplodia theobromae	Stem and surface rots	papaya	HAT	49 °C/20 min 32 °C/30 min then 49 °C/20 min	Nishijima et al. 1992
Chalara paradoxa	Crown rot	banana	HWT	45 °C/20 min or 50 °C/10 min	Reyes et al. 1998
Colletotrichum gloeosporioides	Anthracnose	mango	VHT	46-48 °C/24 sec to 8 min	Coates et al. 1993
			HWT		McGuire 1991
			HAT	51.5 °C/125 min	Miller et al. 1991
Diplodia natalensis	Stem end rot	mango	HAT	51.5 °C/125 min	Miller et al. 1991
			HWT		McGuire 1991
Mycospharella spp.	Stem and surface rots	papaya	HAT	49 °C/20 min 42 °C/30 min then 49°C/20 min	Nishijima et al. 1992
Penicillium digitatum	Green mold	grapefruit	HAT	46 °C/6 h	Shellie 1998
			HWB	59-62 °C/15 sec	Porat et al. 2000

Table 2. Thermal treatment of horticultural commodities for eradication of and protection from fungal pathogens—*Continued*

Fungus	Common name	Crop	Regime*	Temperature/Time	Reference
		lemon	HAT	36 °C/3 days	Kim et al. 1991
			HWT & Na_2CO_3	45 °C/150 sec in 2% Na_2CO_3	Smilanick et al. 1997
		orange	HWT	53 °C/3 min	Schirra et al. 1997
			HWT & Na_2CO_3	41-43 °C/1-2 min in 6% Na_2CO_3	Smilanick et al. 1997
Penicillium expansum	Blue mold	apple	HAT & $CaCl_2$	38 °C/4 days in 4% $CaCl_2$	Sams et al. 1993
			HAT	38°C/4 days	Fallik et al. 1996c
Penicillium italicum	Blue mold	cactus pear	HAT or HWT	38 °C/24 h or 55 °C/5 min	Schirra et al. 1996
Penicillium spp.		lemon	HWT & imazalil	50 °C/3 min + imazalil	Schirra et al. 1997
Rhizopus stolonifer		tomato	HWT	50 °C/2 min	Barkai-Golan et al. 1993

* HWB: hot water brushing
HWT: hot water treatment
HAT: high-temperature forced-air treatment
VHT: vapor heat treatment

Table 3. Physiological benefits of thermal treatments for horticultural crops

Chilling injury

Crop	**Phenomenon/ Appearance**	**Regime***	**Temperature/Time**	**Reference**
Apple	scald	HAT	38 °C/4 days or 42 °C/2 days	Lurie et al. 1990
Avocado	skin browning	HAT then HWT	38 °C/3-10 h then 40 °C/30 min	Woolf et al. 1995
	internal browning, pitting	HWT	38 °C/60 min	Florissen et al. 1996
		HWT		Woolf et al. 1997
Cactus pear	rind pitting, brown staining	HAT or HWT	38 °C/24 h or 55 °C/5 min	Schirra et al. 1996
Citrus	rind pitting	HAT	34-36 °C/48-72 h	Ben -Yehoshua et al. 1987
				Gonzalez-Aguilare et al. 1998
		HWT	50-54 °C/3 min	Schirra & D'Hallewin 1997
			53 °C/2-3 min	Rodov et al. 1995
		HWB	59-62 °C/15-30 sec	Porat et al. 1999
Mango	pitting	HAT	38 °C/2 days	McCollum et al. 1993
			54 °C/20 min	Jacobi et al. 1995
Persimmon	gel formation	HWT	47 °C/90-120 min; 50 °C/30-45 min; 52 °C/20-30 min	Lay-Yee et al. 1997
		HAT		Woolf et al. 1997
Green pepper	pitting	HAT	40 °C/20 h	Mencarelli et al. 1993
Cucumber	pitting	HWT	42 °C/30 min	McCullum et al. 1995
Tomato	pitting	HAT	38 °C/2-3 days	Lurie & Klein 1991
		HWT	48 °C/2 min	Lurie et al. 1997
			42 °C/60 min	McDonald et al. 1998, 1999
Zucchini	pitting	HWT	42 °C/30 min	Wang 1994

Table 3. Physiological benefits of thermal treatments for horticultural crops—*Continued*

Improved postharvest quality

Commodity	Parameter/Attribute	Regime*	Temperature/Time	Reference
Apple	increased firmness	HAT	38 °C/4 days; 42 °C/2 days	Klein & Lurie 1992
Asparagus	inhibited curvature	HWT	47 ºC/2-5 min	Paull & Chen 1999
Broccoli	decreased yellowing	HWT	50 °C/2 min	Forney 1995
			45 °C/10 min; 47 °C/7.5 min	Tian et al. 1996, 1997
Collard	decreased yellowing	HAT	45 °C/30 min	Wang 1998
Green onions	inhibited elongation	HWT	55 °C/2 min	Hong et al. 2000
Guava	decreased softening and yellowing	HWT	46 °C/35 min	McGuire 1997
Kale	decreased yellowing	HAT	40 °C/60 min	Wang 1998
Potato	inhibited sprouting	HWT		Rangann et al. 1998

* HWT: hot water treatment
HAT: high-temperature forced-air treatment

References

Afek, U., J. Orenstein, and E. Nuriel. 1999. Steam treatment to prevent carrot decay during storage. Crop Protection 18:639-642.

Akamine, E.K., and T. Arisumi. 1953. Control of postharvest storage decay of fruits of papaya (*Carica papaya* L.) with special reference to the effect of hot water. Proc. Amer. Soc. Hort. Sci. 61:270-274.

APHIS [U.S. Department of Agriculture, Animal and Plant Health Inspection Service]. 1998. Plant Protection and Quarantine Manual. U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Hyattsville, MD.

Armstrong, J., B. Hu, and S. Brown. 1995. Single-temperature forced hot-air quarantine treatment to control fruit flies (Diptera: Tephritidae) in papaya. J. Econ. Entomol. 88:678-682.

Baker, A.G. 1939. The basis for treatment of products where fruit flies are involved as a condition for entry into the United States. Circular 551, U.S. Department of Agriculture, Washington, DC.

Baker, A.G. 1952. The vapor-heat process. *In* A. Stefferud, ed., Insects. The Yearbook of Agriculture 1952, pp. 401-403. U.S. Department of Agriculture, Washington, DC.

Barkai-Golan, R., and D.J. Phillips. 1991. Postharvest heat treatment of fresh fruits and vegetables for decay control. Plant Dis. 75:1085-1089.

Barkai-Golan, R., R. Padova, I. Ross, et al. 1993. Combined hot water and radiation treatments to control decay of tomato fruits. Sci. Hort. 56:101-105.

Ben-Yehoshua, S., B. Shapiro, and R. Moran. 1987. Individual seal-packaging enables the use of curing at high temperatures to reduce decay and heat injury of citrus fruits. HortScience 22:777-783.

Chan, H.T., and E. Linse. 1989. Conditioning cucumbers for quarantine heat treatments. HortScience 24:985-989.

Chervin, C., S. Kulkarni, S. Kreidl, et al. 1997. A high temperature/low oxygen pulse improves cold storage disinfestation. Postharv. Biol. Technol. 10:239-245.

Coates, L.M., and G.I. Johnson. 1993. Effective disease control in heat-disinfected fruit. Postharv. News Info. 4:35N-40N.

Coates, L.M., G. I. Johnson, and A. Cooke. 1993. Postharvest disease control in mangoes using high humidity hot air and fungicide treatments. Ann. Appl. Biol. 123:441-448.

Couey, H.M. 1989. Heat treatment for control of postharvest diseases and insect pests of fruits. HortScience 24:198-201.

Dentener, P.R., S. M. Alexander, P.J. Lester, et al. 1996. Hot air treatment for disinfestation of lightbrown apple moth and longtailed mealy bug on persimmons. Postharv. Biol. Technol. 8:143-152.

Dentener, P.R., K.V. Bennett, L.E. Hoy, et al. 1997. Postharvest disinfestation of lightbrown apple moth and longtailed mealybug on persimmons using heat and cold. Postharv. Biol. Technol. 12:255-264.

Dentener, P.R., S.E. Lewthwaite, J.H. Maindonald, and P.G. Connolly. 1998. Mortality of twospotted spider mite (Acari: Tetranychidae) after exposure to ethanol at elevated temperatures. J. Econ. Entomol. 91:767-772.

Dentener, P.R., S.E. Lewthwaite, K.V. Bennett, et al. 2000. Effect of temperature and treatment conditions on the mortality of *Epiphyas postvittana* (Lepidoptera: Tortricidae) exposed to ethanol. J. Econ. Entomol. 93:519-525.

Fallik, E., J. D. Klein, S. Grinberg, et al. 1993. Effect of postharvest heat treatment of tomatoes on fruit ripening and decay caused by *Botrytis cinerea*. Plant Dis. 77:985-988.

Fallik, E., Y. Aharoni, O. Yekutieli, et al. 1996a. A method for simultaneously cleaning and disinfecting agricultural produce. Israel Patent Application No. 116965.

Fallik, E., S. Grinberg, S. Alkalai, and S. Lurie. 1996b. The effectiveness of postharvest hot water dipping on the control of gray and black molds in sweet red pepper *(Capsicum annuum)*. Plant Pathol. 45:644-649.

Fallik, E., S. Grinberg, M. Gambourg, et al. 1996c. Prestorage heat treatment reduces pathogenicity of *Penicillium expansum* in apple fruit. Plant Pathol. 45:92-97.

Fallik, E., S. Grinberg, S. Alkalai, et al. 1999. A unique rapid hot water treatment to improve storage quality of sweet pepper. Postharv. Biol. Technol. 15:25-32.

Florissen, P., J.S. Ekman, C. Blumenthal, et al. 1996. The effects of short heat treatments on the induction of chilling injury in avocado fruit (*Persea americana* Mill). Postharv. Biol. Technol. 8:129-141.

Follet, P.A., and Z. Gabbard. 1999. Efficacy of the papaya vapor heat quarantine treatment against white peach scale in Hawaii. HortTechnology 9:506.

Forney, C.F. 1995. Hot water dips extend shelf-life of fresh broccoli. HortScience 30:1054-1057.

Garcia, J.M., C. Aguilera, and A.M. Jimenez. 1996. Grey mold in and quality of strawberry fruit following postharvest heat treatment. HortScience 31:255-257.

Gonzalez-Aguilar, G.A., L. Zacarias, and M.T. Lafuente. 1998. Ripening affects high-temperature-induced polyamines and their changes during cold storage of hybrid Fortune mandarins. J. Agric. Fd. Chem. 46:3503-3508.

Hallman, G.J., J.J. Gaffney, and J.L. Sharp. 1990. Vapor heat treatment for grapefruit infested with Caribbean fruit fly (Diptera: Tephritidae). J. Econ. Entomol. 83:1475-1478.

Heather, N.W., R.J. Corcoran, and R.A. Kopittke. 1997. Hot air disinfestation of Australian ‘Kensington’ mangoes against two fruit flies (Diptera: Tephritidae). Postharv. Biol. Technol. 10:99-105.

Hong, G., G. Peiser, and M.I. Cantwell. 2000. Use of controlled atmospheres and heat treatment to maintain quality of intact and minimally processed green onions. Postharv. Biol. Technol. 20:53-61.

Hoy, L.E., and D. C. Whiting. 1998. Mortality responses of three leafroller (Lepidoptera: Tortricidae) species on kiwifruit to a high-temperature controlled atmosphere treatment. N.Z. J. Crop Hort. Sci. 26:11-15.

Jacobi, K.K., Wong, L.S., and J.E. Giles. 1993. Lychee (*Lichi chinensis* Sonn.) fruit quality following vapour heat treatment and cool storage. Postharv. Biol. Technol. 3:111-119.

Jacobi, K.K., J. Giles, E. MacRae, and T. Wegrzyn. 1995a. Conditioning ‘Kensington’ mango with hot air alleviates hot water disinfestation injuries. HortScience 30:562-565.

Jacobi, K.K., L.S. Wong, and J.E. Giles. 1996. Postharvest quality of zucchini (*Cucurbita pepo* L.) following high humidity hot air disinfestation treatments and cool storage. Postharv. Biol. Technol. 7:309-316.

Jacobi, K.K., and J.E. Giles. 1997. Quality of ‘Kensington’ mango (*Mangifera indica* Linn.) fruit following combined vapor heat disinfestation and hot water disease control. Postharv. Biol. Technol. 12:285-292.

Jang, E.B. 1996. Systems approach to quarantine security: postharvest application of sequential mortality in the Hawaiian grown ‘Sharwil’ avocado system. J. Econ. Entomol. 89:950-956.

Jessup, A.J. 1994. Quarantine disinfestation of ‘Hass’ avocados against *Bactrocera tryoni* (Diptera: Tephritidae) with a hot fungicide dip followed by cold storage. J. Econ. Entomol. 87:127-130.

Kim, J.J., S. Ben-Yehoshua, B. Shapiro, et al. 1991. Accumulation of scoparone in heat-treated lemon fruit inoculated with *Penicillium digitatum* Sacc. Plant Physiol. 97:880-885.

Klein, J.D., and S. Lurie. 1992. Prestorage heating of apple fruit for enhanced postharvest quality: interaction of time and temperature. HortScience 27:326-328.

Klein, J., W. Conway, B. Whitaker, and C. Sams. 1997. *Botrytis cinerea* decay in apples is inhibited by postharvest heat and calcium treatments. J. Amer. Soc. Hort. Sci. 122:91-94.

Lay-Yee, M., and D.C. Whiting. 1996. Response of ‘Hayward’ kiwifruit to high-temperature controlled atmosphere treatments for control of two-spotted spider mite *(Tetranychus urticae)*. Postharv. Biol. Technol. 7:73-81.

Lay-Yee, M., S. Ball, S.K. Forbes, and A.B. Woolf. 1997a. Hot water treatment for insect disinfestation and reduction of chilling sensitivity of ‘Fuyu’ persimmon. Postharv. Biol. Technol. 10:81-89.

Lay-Yee, M., D.C. Whiting, and K.J. Rose. 1997b. Response of ‘Royal Gala’ and ‘Granny Smith’ apples to high-temperature controlled atmosphere treatments for control of *Epiphyas postvittana* and *Nysius huttoni*. Postharv. Biol. Technol. 12:127-136.

Lester, P.L., P.R. Dentener, R.J. Petry, and S.M. Alexander. 1995. Hot-water immersion for disinfestation of lightbrown apple moth *(Epiphyas postvittana)* and longtailed mealy bug *(Pseudococcus longispinus)* on persimmons. Postharv. Biol. Technol. 6:349-356.

Lester, P.J., P.R. Dentener, K.V. Bennett, and P.G. Connolly. 1997. Postharvest disinfestations of diapausing and nondiapausing twospotted spider mite *(Tetranychus urticae)* on persimmons: hot water immersion and coolstorage. Entom. Exper. Appl. 83:189-193.

Lurie, S. 1998. Postharvest heat treatments. Postharv. Biol. Technol. 14:257-269.

Lurie, S., and J.D. Klein. 1991. Acquisition of low temperature tolerance in tomatoes by exposure to high temperature stress. J. Amer. Soc. Hort. Sci. 116:1007-1012.

Lurie, S., J.D. Klein, and R. Ben-Arie. 1990. Postharvest heat treatment as a possible means of reducing superficial scald of apples. J. Hort. Sci. 65:503-509.

Lurie, S. M. Laamim, Z. Lapsker, and E. Fallik. 1997. Heat treatments to decrease chilling injury in tomato fruit. Effects on lipids, pericarp lesions and fungal growth. Physiol. Plant. 100:297-302.

McCollum, T.G., S. D’Aquino, and R.E. McDonald. 1993. Heat treatment inhibits mango chilling injury. HortScience 28:197-198.

McCollum, G., H. Doostdar, R. Mayer, and R. McDonald. 1995. Immersion of cucumber in heated water alters chilling-induced physiological changes. Postharv. Biol. Technol. 6:55-64.

McDonald, R.E., T.G. McCollum, and E.A. Baldwin. 1998. Heat treatment of mature-green tomatoes: differential effects of ethylene and partial ripening. J. Amer. Soc. Hort. Sci. 123:457-462.

McDonald, R.E., T.G. McCollum, and E.A. Baldwin. 1999. Temperature of water heat treatments influences tomato fruit quality following low-temperature storage. Postharv. Biol. Technol. 16:147-155.

McGuire, R.G. 1991. Concomitant decay reductions when mangoes are treated with heat to control infestations of Caribbean fruit fly. Plant Dis. 75:946-949.

McGuire, R.G. 1997. Market quality of guavas after hot-water quarantine treatment and application of carnauba wax coating. HortScience 32:271-274.

McLaren, G.F., R.M. McDonald, J.A. Fraser, et al. 1997. Disinfestation of New Zealand flower thrips from stonefruit using hot water. Acta Hort. 464:524.

Mencarelli, F., B. Ceccantoni, A. Bolini, and G. Anelli. 1993. Influence of heat treatment on the physiological response of sweet pepper kept at chilling temperature. Acta Hort. 343:238-243.

Miller, W.R., R.E. McDonald, and J.L. Sharp. 1991. Quality changes during storage and ripening of 'Tommy Atkins' mangos treated with heated forced air. HortScience 26:395-397.

Neven, L., and E. Mitcham. 1996. CATTS: controlled atmosphere/temperature treatment system. A novel tool for the development of quarantine treatments. Amer. Entomol. 42:56-59.

Neven, L.G., and S.R. Drake. 2000. Comparison of alternative postharvest quarantine treatments for sweet cherries. Postharv. Biol. Technol. 20:107-114.

Neven, L.G., L.M. Rehfield, and K.C. Shellie. 1996. Moist and vapor forced air treatments of apples and pears: effects on the mortality of fifth instar codling moth (Lepidoptera: Tortricidae). J. Econ. Entomol. 89:700-704.

Nishijima, K.A., K. Miura, J.W. Armstrong, et al. 1992. Effect of forced, hot-air treatment of papaya fruit on fruit quality and incidence of postharvest diseases. Plant Dis. 76:723-727.

Nishijima, K., H. Chan, S. Sanxter, and E. Linse. 1995. Reduced heat shock period of 'Sharwil' avocado for cold tolerance in quarantine cold treatment. HortScience 30:1052-1053.

Paull, R.E. 1994. Response of tropical horticultural commodities to insect disinfestation treatments. HortScience 29:988-996.

Paull, R.E., and N.J. Chen. 1999. Heat treatment prevents postharvest geotropic curvature of asparagus spears (*Asparagus officinallis* L.). Postharv. Biol. Technol. 16:37-41.

Porat, R., A. Daus, B. Weiss, et al. 2000. Reduction of postharvest decay in organic citrus fruit by a short hot water brushing treatment. Postharv. Biol. Technol. 18:151-157.

Porat, R., D. Pavoncello, J. Peretz, et al. 1999. Effects of various heat treatments on the induction of cold tolerance and on the postharvest qualities of 'Star Ruby' grapefruit. J. Amer. Soc. Hort. Sci. 124:184-188.

Prusky, D., Y. Fuchs, I. Kobiler, et al. 1999. Effect of hot water brushing, prochloraz treatment and waxing on incidence of black spot decay caused by *Alternaria alternata* in mango fruits. Postharv. Biol. Technol. 15:165-174.

Ranagann, B., G.S.V. Raghavan, and A.C. Kushalappa. 1998. Hot water dipping to enhance storability of potatoes. Postharv. Biol. Technol. 13:215-223.

Reyes, M.E.Q., W. Nishijima, and R.E. Paull. 1998. Control of crown rot in 'Santa Catarine Prata' and 'Williams' banana with hot water treatment. Postharvest Biol. Technol. 14:71-75.

Rodov, V., S. Ben-Yehoshua, R. Albagli, and D.Q. Fang. 1995. Reducing chilling injury and decay of stored citrus fruit by hot water dips. Postharv. Biol. Technol. 5:119-127.

Sams, C.E., W.S. Conway, J.A. Abbott, et al. 1993. Firmness and decay of apples following postharvest pressure infiltration of calcium and heat treatment. J. Amer. Soc. Hort. Sci. 118:623-627.

Schirra, M., and G. D'Hallewin. 1997. Storage performance of Fortune mandarins following hot water dips. Postharv. Biol. Technol. 10:229-238.

Schirra, M., G. Barbera, S. D'Aquino, T. La Mantia, and R.E. McDonald. 1996. Hot dips and high-temperature conditioning to improve shelf quality of late-crop cactus pear fruit. Trop. Sci. 36:159-165.

Schirra, M., M. Agabbio, S. D'Aquino, and T.G. McCollum. 1997. Postharvest heat conditioning effects on early ripening 'Gialla' cactus pear fruit. HortScience 32:702-704.

Schirra, M., P. Cabras, A. Angioni, et al. 1997. Effect of heated solutions on decay control and residues of imazalil in lemons. J. Agric. Fd Chem. 45:4127-4130.

Sharp, J.L., and W.P. Gould. 1994. Control of Caribbean fruit fly (Diptera: Tephritidae) in grapefruit by forced hot air and hydro-cooling. J. Econ. Entomol. 87:131-133.

Sharp, J.L., and R.G. McGuire. 1996. Control of Caribbean fruit fly (Diptera: Tephritidae) in navel orange by forced hot air. J. Econ. Entomol. 89:1181-1185.

Shellie, K.C., R.L. Mangan, and S.J. Ingle. 1997. Tolerance of grapefruit and Mexican fruit fly larvae to heated controlled atmospheres. Postharv. Biol. Technol. 10:179-186.

Shellie, K.C. 1998. Reduction of green mold on grapefruit after hot forced-air quarantine treatment. Plant Dis. 82:380-382.

Smilanick, J.L., D.A. Margosan, and D.J. Henson. 1995. Evaluation of heated solutions of sulfur dioxide, ethanol, and hydrogen peroxide to control postharvest green mold of lemons. Plant Dis. 79:742-747.

Smilanick, J.L., B.E. Mackey, R. Reese, et al. 1997. Influence of concentration of soda ash, temperature, and immersion period on the control of postharvest green mold of oranges. Plant Dis. 80:230-234.

Sonderstrom, E.L., D.G. Brandl, and B.E. Mackay. 1993. High temperature for control of *Asynonychus godmani* (Coleoptera: Curculionidae) eggs on lemon fruit. J. Econ. Entomol. 86:1773-1780.

Tian, M.S., A.B. Woolf, J.H. Bowen, and I.B. Ferguson. 1996. Changes in color and chlorophyll fluorescence of broccoli florets following hot water treatment. J. Amer. Soc. Hort. Sci. 121:310-313.

Tian, M.S., T. Islam, D.G. Stevenson, and D.E. Irving. 1997. Color, ethylene production, respiration, and compositional changes in broccoli dipped in hot water. J. Amer. Soc. Hort. Sci. 122:112-116.

Wang, C.Y. 1994. Combined treatment of heat shock and low temperature conditioning reduces chilling injury in zucchini squash. Postharv. Biol. Technol. 4:65-73.

Wang, C.Y. 1998. Heat treatment affects postharvest quality of kale and collard, but not of brussels sprouts. HortScience 33:881-883.

Whiting, D.C., and L.E. Hoy. 1997. High temperature controlled atmosphere and air treatments to control obscure mealybug (Hemiptera: Pseudococcidae) on apples. J. Econ. Entomol. 90:546-550.

Whiting, D.C., L.E. Jamieson, K.J. Spooner, and M. Lay-Yee. 1999. Combination of high-temperature controlled atmosphere and cold storage as a quarantine treatment against *Ctenopseustis obliquana* and *Epiphyas postvittana* on 'Royal Gala' apples. Postharv. Biol. Technol. 16:119-126.

Woolf, A.B., C.B. Watkins, J.H. Bowen, et al. 1995. Reducing external chilling injury in stored 'Hass' avocados with dry heat treatments. J. Amer. Soc. Hort. Sci. 120:1050-1056.

Woolf, A.B., and M. Lay-Yee. 1997. Pretreatments at 38 °C of 'Hass' avocado confer thermotolerance to 50 °C hot water treatments. HortScience 32:705-708.

Woolf, A.B., S. Ball, K. Spooner, et al. 1997. Reduction of chilling injury in the sweet persimmon 'Fuyu' during storage by dry air heat treatments. Postharv. Biol. Technol. 11:155-164.

Modified Atmosphere Packaging

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Introduction

Modified-atmosphere packaging (MAP) of fresh fruits and vegetables refers to the technique of sealing actively respiring produce in polymeric film packages to modify the O_2 and CO_2 levels within the package atmosphere. It is often desirable to generate an atmosphere low in O_2 and/or high in CO_2 to influence the metabolism of the product being packaged or the activity of decay-causing organisms to increase storability and/or shelf-life. For some products, modifying both O_2 and CO_2 may be desirable; indeed, altering the O_2 level automatically alters CO_2 level. In addition to atmosphere modification, MAP vastly improves moisture retention, which can have a greater influence on preserving quality than O_2 and CO_2 levels. Furthermore, packaging isolates the product from the external environment and helps to ensure conditions that, if not sterile, at least reduce exposure to pathogens and contaminants.

MAP was first evaluated in the mid to late 1940s for its ability to reduce O_2 levels sufficiently to slow the ripening of apple fruit. The primary limitation of MAP application in the early studies was technical in nature—specifically, the lack of consistent control of O_2 levels in the package. Since then, the types and properties of polymers have increased to provide a wider range of gas permeability, tensile strength, flexibility, printability, and clarity. As a result, successful modified atmosphere (MA) packaging systems have been developed for a number of commodities.

It is important to recognize that while atmosphere modification can improve the storability of some fruits and vegetables, it has the potential to induce undesirable effects. Fermentation and off flavors may develop if decreased O_2 levels cannot sustain aerobic respiration (Kays 1997). Similarly, injury will occur if CO_2 exceeds tolerable levels. Ranges of nondamaging O_2 and CO_2 levels have been published for a number of fruits and vegetables (Kader 1997a, Kupferman 1997, Richardson and Kupferman 1997, Saltveit 1997, Beaudry 1999, 2000), minimally processed products (Gorny 1997), and flowers and ornamentals (Reid 1997). Horticultural crops differ in their tolerance for O_2 (table 1) and CO_2 (table 2).). The range of O_2 and CO_2 levels for fruits (figure 1) and vegetables (figure 2) can overlap or be distinct.

Table 1. O_2 limits below which injury can occur for selected horticultural crops held at typical storage temperatures

O_2	Commodities
%	
<0.5	Chopped greenleaf*, redleaf*, romaine* and iceberg lettuce*; spinach; sliced pear; broccoli*; mushroom
1.0	Broccoli florets, chopped butterhead lettuce, sliced apple, brussels sprouts, cantaloupe, cucumber, crisphead lettuce, onion bulbs, apricot, avocado, banana*, cherimoya, atemoya, sweet cherry, cranberry, grape, kiwifruit*, litchi, nectarine, peach, plum, rambutan, sweetsop
1.5	Most apples*, most pears*
2.0	Shredded and cut carrots, artichoke, cabbage*, cauliflower, celery, bell and chili peppers, sweet corn, tomato, blackberry, durian, fig, mango, olive, papaya, pineapple, pomegranate, raspberry, strawberry
2.5	Shredded cabbage, blueberry
3.0	Cubed or sliced cantaloup, low-permeability apples* and pears*, grapefruit, persimmon
4.0	Sliced mushrooms
5.0	Green snap beans, lemon, lime, orange
10.0	Asparagus
14.0	Orange sections

Source: Gorny 1997, Kader 1997a, Kupferman 1997, Richardson and Kupferman 1997, Saltveit 1997, and Beaudry 2000

* Considered to have very good to excellent potential to respond to low O_2.

Table 2. CO_2 partial pressures above which injury will occur for selected horticultural crops

CO_2	Commodities
kPa	
2	Lettuce (crisphead), pear
3	Artichoke, tomato
5	Apple (most cultivars), apricot, cauliflower, cucumber, grape, nashi, olive, orange, peach (clingstone), potato, pepper (bell)
7	Banana, bean (green snap), kiwifruit
8	Papaya
10	Asparagus, brussels sprouts, cabbage, celery, grapefruit, lemon, lime, mango, nectarine, peach (freestone), persimmon, pineapple, sweet corn
15	Avocado, broccoli, lychee, plum, pomegranate, sweetsop
20	Cantaloupe (muskmelon), durian, mushroom, rambutan
25	Blackberry, blueberry, fig, raspberry, strawberry
30	Cherimoya

Source: modified from Herner 1987, Kader 1997a, and Saltveit 1997

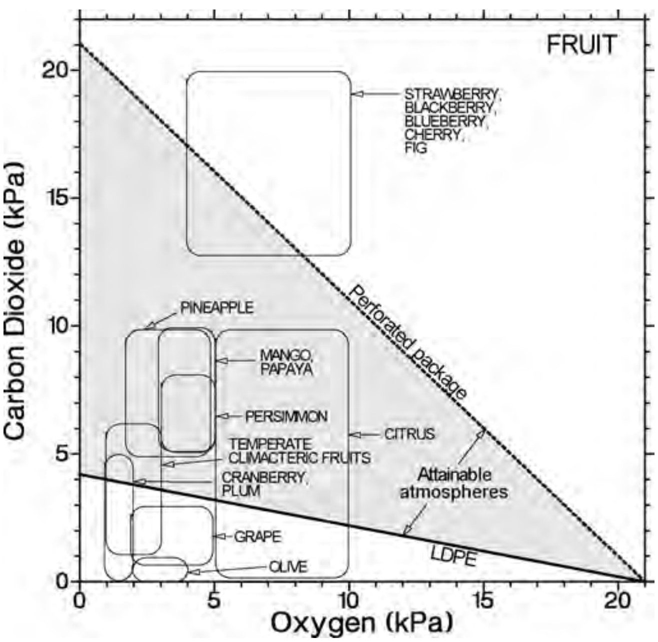

Figure 1. Recommended O_2 and CO_2 combinations for the storage of fruit. The chart depicts atmospheres theoretically attainable by MAP by film permeation alone (low-density polyethylene, LDPE, lower boundary) and via perforations alone (upper, dashed line) or their combination (shaded area). Data are adapted from Kader (1997) and reprinted with permission from Beaudry (1999). Copyright 1999 by Elsevier Science.

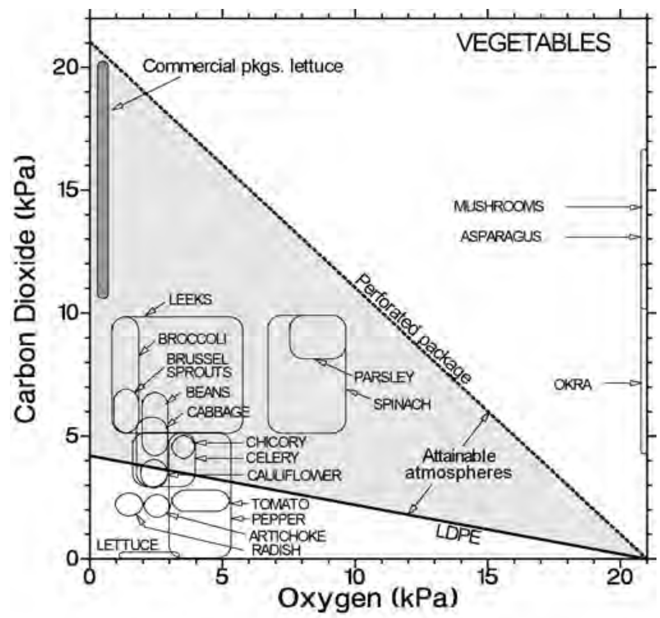

Figure 2. Recommended O_2 and CO_2 combinations for the storage of vegetables. The chart depicts atmospheres theoretically attainable by MAP using low-density polyethylene (LDPE, lower boundary) and perforated packages (upper, dashed line); redrawn from Mannapperuma et al. (1989). The shaded area represents atmospheres observed in commercial MA packages of mixed lettuce-based salads (Cameron et al. 1995). Reprinted with permission from Beaudry (1999). Copyright 1999 by Elsevier Science.

The composition of the atmosphere within a package results from the interaction of a number of factors that include the permeability characteristics of the package, the respiratory behavior of the plant material, and the environment. The films making up the package are selected to have specific permeability characteristics, and changes in these characteristics over time, temperature, and humidity follow known physical laws. The environment can be controlled to provide specific conditions. In contrast to these known and controllable factors are the often unknown and uncontrollable responses of the plant material. Plant species and cultivar, cultural practices, stage of development, manner of harvest, tissue type, and postharvest handling—all of these factors contribute and influence the response of the material to the generated atmosphere. The scope of plant responses can be further modified by initial gas flush of the package before sealing and inclusion of chemical treatments to slow unwanted processes or reduce decay. Each of these components of the packaging process can be examined separately to better illustrate how each contributes to packaging strategies.

Package Parameters

Atmosphere modification in MAP requires actively respiring plant tissue and a barrier through which gas exchange is restricted. The reduced O_2 and increased CO_2 resulting from tissue respiration create gradients across the film barrier that provide the driving force for gas movement into and out of the package. The levels of O_2 and CO_2 within a package depend on the interaction between commodity respiration and the permeability properties of the packaging film or microperforations (Beaudry et al. 1992, Kader et al. 1997a).

There are two strategies for creating film. The first employs continuous films that control movement of O_2 and CO_2 into or out of the package. The second uses perforated films with small holes, or microperforations, as the primary route of gas exchange.

Continuous Films: The movement of O_2 and CO_2 is usually directly proportional to the difference in gas concentration across the film. Steady-state (constant) O_2 and CO_2 levels are achieved in the package when the O_2 uptake and CO_2 production by the product are equal to that permeating through the film, a situation that exists only when the respiratory rate is constant.

Perforated Films: The rate of gas movement through a perforated film is the sum of gas diffusion through the perforation and gas permeation through the polymeric film. Generally, total gas flow through the perforations is much greater than gas movement through the film. Gas transmission through microperforations has been modeled (Fishman et al. 1996). The rate of gas exchange through perforations in a film is so much greater than through continuous films that a 1-mm perforation in a 0.0025 mm (1 mil) thick low-density polyethylene (LDPE) film has nearly the same gas flux as a half a square meter area of the film. As might be surmised, perforated packages are more suitable for produce having a high O_2 demand.

Gas Exchange Properties of Continuous and Perforated Films

The relative permeability of the package to O_2 and CO_2 differs substantially between continuous and perforated films and results in considerable differences in gas exchange behavior. In packages composed of continuous films, the permeability of the package to CO_2 is usually 2 to 8 times that of O_2 permeability. If the rate of O_2 uptake by the product is roughly the same as its production of CO_2 (the normal case unless fermentation is taking place), the CO_2 gradient will be much lower than the O_2 gradient. For example, low-density polyethylene (LDPE) has permeability to CO_2 that is four times that of O_2. In a LDPE package having a 10% O_2 steady-state atmosphere, the CO_2 level could be calculated as (21 - 10%)/4, or 2.75% CO_2. (Air contains 78% N_2, 21% O_2, and 0.03% CO_2.) For perforated films, the permeability to CO_2 is only 0.77 times that of O_2. As a result, in a package relying on perforations for gas exchange, CO_2 levels climb to roughly the same extent that O_2 levels decline (that is, the gradients are nearly equal) such that the sum of O_2 and CO_2 concentrations is usually in the range of 18 to 20%. For any given O_2 level, therefore, the perforated package will have a considerably higher level of CO_2 compared with the continuous film package. To extend the example above, if a package were designed to have a 10% O_2 steady-state atmosphere using perforations as the route of gas exchange, the CO_2 level would be 0.77 × (21 - 10%), or 8.8%, which is about 3-fold greater than in the continuous film package. The relative elevation of CO_2 in perforated film packages may be critically important in package design, if CO_2 is needed to help control decay or degreening.

MAP relying on a combination of perforation and permeation has features of both systems, with attainable combinations of O_2 and CO_2 being between those of packages relying on permeation and those relying on perforations (Mannapperuma et al. 1989, Beaudry 1999) (figures 1 and 2). The temperature sensitivity for permeation, and the permeability of O_2 and CO_2, is somewhere between those for perforated packages and continuous film packages.

Temperature is extremely important in package design, and continuous and perforated films differ in their response to temperature changes. The O_2 and CO_2 permeability of continuous films increases with temperature, while the diffusion of gases through perforations is extremely insensitive to temperature changes. For instance, O_2 permeation through LDPE can increase 200% from 0 to 15 °C, but the exchange of O_2 through perforations will increase only 11% across this temperature range.

Depending on the rates of respiration and transmission through the package, atmosphere modification can be achieved rapidly or relatively slowly. At low temperatures, atmosphere modification can take several days, such that some package systems would not achieve steady-state conditions before the end of their shelf-life. In many cases, purging the package atmosphere with CO_2, N_2, or a combination of gases is often desirable during filling and sealing to rapidly obtain the maximum benefits of MAP.

Respiratory Parameters

The maximal rate of respiration for most fruit and vegetable products undergoes a 4- to 6-fold increase from 0 to 15 °C (Beaudry et al. 1992, Cameron et al. 1994,1995, Lakakul et al. 1999). This means that product respiration increases at 2 or 3 times the rate of LDPE permeability and 30 times the rate of perforation permeability with increasing temperature. When respiratory demand for O_2 increases faster than O_2 permeation as temperature increases, O_2 levels decline and may pose a risk to product quality, limiting the usefulness of MAP in some situations.

Safe levels of O_2 and CO_2 are important for package design. A lower O_2 limit has been associated with onset of fermentation and accumulation of ethanol and acetaldehyde (Beaudry et al. 1992). Fermentation is linked to the development of off flavors and tissue damage. Effect of temperature on lower O_2 limit has been measured for a number of commodities including whole apple, apple slices, blueberry, and raspberry. In each case, lower O_2 limit increased with temperature. Lower O_2 limits vary from 0.15 to 5% (table 1) and are influenced by temperature, commodity, and cultivar (Beaudry and Gran 1993).

Integrating Package, Product, and Environment

Mathematical models can integrate the film permeability to O_2, to CO_2, and to H_2O and the respiratory response of the commodity to O_2 (and in some cases to CO_2), along with its lower O_2 limit and upper CO_2 limit (Beaudry et al. 1992, Cameron et al. 1994, Fishman et al. 1996, Hertog et al. 1998, Lakakul et al. 1999). These models enable the reasonably accurate prediction of package performance; that is, O_2-, CO_2-, and H_2O-

content in the package headspace under a variety of environmental conditions prior to construction of the package. Additionally, they permit the identification of limiting features of the film, package design, and product and environment conditions. Models typically include temperature dependency but can also be developed to predict effects of package volume, resistance to heat flow, and developmental changes in product physiology on headspace gases.

Predicting and Controlling O_2 and CO_2 Content

A model can be developed to predict the steady-state concentration of O_2 in the package headspace. Steady-state models incorporating temperature effects on respiration and permeability have been published for many commodities. In addition, more complex dynamic models have been developed to account for temporal changes in package volume, product respiration, and the humidity and temperature of the environment (Fishman et al. 1996, Hertog et al. 1998).

Package performance can be depicted in a number of ways. Perhaps the most instructive format is describing the effects of temperature on package O_2 levels. For example, a package was designed to produce low O_2 and high CO_2 levels for 100 g of apple slices at 0 °C (Lakakul et al. 1999). The practical O_2 limit was set 3-fold higher than the fermentation threshold to prevent variation in respiration and permeability from causing a reduction in package O_2 below the lower limit. If the package relied on perforations for gas exchange, it would undergo a rapid decline in O_2 by the time the package reached 6 °C (43 ºF). Films with higher temperature sensitivity would be less prone to risk fermentation. In this example, packages were designed to maintain aerobic O_2 levels at 15 °C, the highest temperature to which they would be exposed. The performance of the packages can then be predicted at lower temperatures likely to be encountered during storage. A package O_2 model can also be used to predict very specific package criteria. For instance, the 100 g of apple slices described above were in a container with a film area of 120 cm^2. Film thickness and composition with different permeability characteristics could be selected to protect against fermentation.

A package model can also be used to clarify the nature of the mismatch between the temperature sensitivity of O_2 uptake and O_2 flux through the film and denote methods to ameliorate this problem. One method would be to choose a film with permeability changes for O_2 similar to that of the respiration of the product, so if temperature increases, respiration and permeability of the film increase an equivalent amount.

Another solution to the MAP temperature problem is to develop a package system that senses either the environment or the physiological status of the enclosed product and responds by increasing the permeability to O_2 (Cameron et al. 1993). Such "sense-and-respond" packaging is technically difficult to develop, and progress has only been conceptual at this time (Smyth et al. 1999). A third approach is to design packages to function at the highest temperatures typically encountered in the distribution and retail cool chain and, as far as possible, maintain control over the temperature of the packaged product, thereby adapting to the limitations imposed by the film. Most companies using MAP have adopted this simple solution. Generally, the lowest temperature feasible is maintained, since temperature has a much more significant influence on preserving quality than the application of low O_2 (Kays 1997).

Variation in the respiration rate of the product and the variation in film or pore permeability can influence package design. Variation in product respiration and package permeability has been measured for broccoli, and the effect on package O_2 modeled (Cameron et al. 1993). Cameron et al. (1993) concluded that there is an estimable risk of the package O_2 falling sufficiently low to promote fermentation in any product. Packages should be designed to generate O_2 levels well above the lower limit to ensure aerobic conditions.

Products such as broccoli, mushrooms, and leeks have very high rates of respiration, and most continuous films do not have the capacity to provide enough O_2 to avoid fermentation. Accordingly, there is commercial interest in developing films with high gas transmission rates. Films that have improved rates of gas transmission by virtue of their polymeric nature are often blends of two or three different polymers, whith each polymer performing a specific function such as strength, transparency, and improved gas transmission. Similarly, films can be laminated to achieve needed properties.

The plastic polymer can also be mixed with an inert inorganic material such as $CaCO_3$ and SiO_2 to generate micoporous films. Gas permeabilities can be manipulated by adjusting the filler content, particle size of the filler, and degree of stretching. The average pore size ranges from 0.14 to 1.4 µm in diameter (Mizutani, 1989). Films using microperforations can attain very high gas transmission rates. The diameter of microperforation generally ranges from 40 to 200 µm; and, by altering the size and thickness of microperforations, gas permeability through a package can be altered to meet well-defined product requirements. Microperforated films have also been used to extend storage of strawberries and nectarines (Meyers 1985) and apple (Watkins et al. 1988).

Water Vapor

Plant tissues tend to lose moisture when RH is below 99 to 99.5%. Generally, water loss results in visible wilting or wrinkling of the surface of most commodities when it exceeds 4 to 6% of total fresh weight (Kays 1997). Fortunately, most MAP films are relatively impermeable to water. The RH is very near saturation in most continuous or perforated film packages. A saturated atmosphere at 20 ºC (68 ºF) has only 2.1% H_2O, and most external environments are at 30 to 60% RH, yielding a water vapor gradient of about 1%. The O_2 gradient can be several-fold higher. Because of the small driving force and the rapid rate of release of water vapor from the product, perforations have a much greater effect on the O_2 level than on RH. Fishman et al. (1996) calculated that perforating a continuous film increased O_2 flow 40-fold more than it increased H_2O flow. Only four perforations were required to achieve near-ambient O_2 levels, while 40 perforations only reduced RH to 95%

Condensation on the inner surface of the film is a common problem with MAP. A drop of only 0.2 °C in the film temperature can result in condensation in a package with an internal RH of 99% at 10 °C. Cold-storage rooms have temperature swings of several degrees, so condensation is possible in almost any MAP. Fortunately, there are film surface treatments that result in droplet dispersion, so the condensing water forms a thin, uniform layer that is virtually invisible. Condensation could also be reduced in MAPs for a few commodities, such as tomato, that tolerate low humidity by including materials in the package that reduce RH. Salts enclosed in permeable sachets can reduce humidity in MAPs of tomato fruit (Shirazi and Cameron 1992). The possibility of using films with very high water permeability has been examined using mathematical models (Cameron et al. 1995). However, since the external humidity would be critical in maintaining the proper package RH, this approach would encounter difficulty in maintaining a specific humidity level in shipping and storage environments.

Temperature Management

Product temperature affects storability more than any other factor. Precooling and temperature maintenance during handling and shipping are critical in preserving quality. Temperature also significantly affects film permeability and thereby the O_2 and CO_2 content of the package. The elevated rate of respiration at high temperature could be used to rapidly establish the desired package atmosphere, but this would only be useful in the few situations in which it would be more important to rapidly establish the atmosphere than to slow physiological processes—for example, to reduce cut-surface browning. Cameron et al. (1995) calculated that, at 25 ºC (77 ºF), a package of blueberry fruit could attain a steady-state atmosphere in less than 2 days, whereas it required approximately 20 days at 0 °C (32 ºF).

The temperature of the produce in the package is managed by circulating cool air around the outside of the package. The film and the headspace atmosphere are barriers to heat movement, prevent rapid cooling, and reduce the effectiveness of refrigeration. A "safe radius" for the distance from the center of the package to the circulated air can be calculated based on the heat of respiration and the rate at which heat can be removed by the cooler air (Sharp et al. 1993). For instance, the center of a package of broccoli must have a radius of less than 14 cm to keep it within 1 °C of the refrigerated air. Slower-respiring pear would function as well with a larger package having an effective radius of 50 cm.

Plant Responses to MAP

Some of the most important factors that affect shelf-life of fresh horticultural products are ripening and senescence, decay, and cut-surface browning. The effect of MA on these factors has been well characterized. The application of MA to affect these limiting factors can be restricted for some crops by adverse or nonbeneficial physiological responses; for example, induction of fermentation. Fresh product quality can be maximized more effectively by good temperature management than by atmosphere modification.

Ripening and Senescence

Low O_2 and elevated CO_2 can significantly reduce the rates of ripening and senescence primarily by reducing the synthesis and perception of ethylene (Burg and Burg 1967, Abeles et al. 1992). Changes in respiration and starch, sugars, chlorophyll, and cell wall constituents during ripening and/or senescence can be reduced and, in some cases, nearly arrested by eliminating ethylene action through the use of low O_2/high CO_2 atmospheres.

Chlorophyll loss, a desirable trait for many climacteric fruits, results in quality loss for many vegetables. Chlorophyll degradation during the senescence of green vegetables can be inhibited by low O_2 and elevated CO_2, a response that in some cases is partly mediated by ethylene, as with broccoli (Ku and Wills 1999).

While low O_2 and elevated CO_2 atmospheres are commonly used to minimize ethylene-dependent responses attendant to ripening in CA rooms, this goal may not be fully compatible with MAP. The problem with the incorporation of MAP for ripening control is not one of efficacy, but rather one of logistics. Modified atmospheres are most effective at reducing ripening prior to the onset of ripening, rather than at a later stage. However, packaged products are usually intended for immediate consumption and an unripe product is not immediately edible or is of lesser quality than the ripe product. Thus, the advantage of improved shelf-life by retarding ripening runs counter to the needs of the consumer when retail MAP systems are used. Nevertheless, MAP can reduce the rate of ripening of some commodities such as tomato even during its later stages (Yang and Chinnan 1988). More potential for using MAP to control ripening may exist at the packinghouse or distributor level, as in the case of overseas shipment of apples (Watkins et al. 1998), rather than at the retail level.

Decay

Decay control is a particularly important problem for many crops. Levels of >10% CO_2 effectively slow or stop the growth of numerous decay organisms (Brown 1922). Low O_2 has a very limited effect on decay organism activity or survival at levels above the fermentation threshold of most commodities. While not all horticultural commodities can withstand CO_2 levels sufficient to inhibit fungal activity, a number of highly perishable commodities are not adversely affected (table 2). Notable among these are strawberry, blueberry, blackberry, raspberry, and cherry, which can be stored successfully under a CO_2 atmosphere of 10 to 20%.

Packaging strategies to enhance CO_2 include initial purging with high levels of CO_2. This strategy relies on continued respiration to replace CO_2 lost from the package and is in commercial use for many berry crops. The choice of film type markedly alters the CO_2 content of a package. In particular, perforated and continuous films differ in their discrimination between O_2 and CO_2. Perforated films will generate a higher partial pressure of CO_2 for a given concentration of O_2 in the package. Perforated packages can accumulate CO_2 to levels within the fungistatic range. For example, a perforated package that generates 1% O_2 could accumulate a 15% CO_2 atmosphere.

While high RH reduces water loss, it also aggravates decay development. Strategies to reduce humidity in packages using salt sachets for the purpose of limiting decay have been explored (Shirazi and Cameron 1992). A number of effective chemical additives can be used at various points during processing and packaging to reduce decay.

Cut-Surface Browning

Mostly, low-O_2 MAP is used to reduce the browning of cut surfaces on lightly processed products such as lettuce and salad mixes. Atmosphere modification is often used in conjunction with processing aids to retard brown color development. Smyth et al. (1998) demonstrated that O_2 levels below 2% but above the fermentation threshold of about 0.5% reduced the rate of browning in lettuce. The partial pressure of O_2 in commercial packages of lettuce and salad products is often below the fermentation threshold (Cameron et al. 1995, Peiser et al. 1997). However, the fermentation of lettuce, if not severe, results in very few off flavors (Smyth et al. 1998).

Negative Responses

Respiration is reduced as O_2 becomes limiting, but there is usually a limit to which O_2 can be reduced. The lower O_2 limit is frequently considered to be the level of O_2 that induces fermentation. This fermentation threshold is not always the lower O_2 limit in commercial practice, however, because lower O_2 levels may confer benefits that outweigh the loss in flavor or other quality parameters. Ethanol, acetaldehyde, ethyl acetate, and lactate are products of fermentation that can contribute to the development of off flavors as well as physical injury (Kays 1997, Mattheis and Fellman 2000).

Production of compounds that contribute to the characteristic aromas of many fruit, such as apples, bananas, pears, peaches, and strawberries, can be adversely affected by low O_2 and elevated CO_2 (Song et al. 1998, Mattheis and Fellman 2000). Synthesis of aroma compounds are generally suppressed by high CO_2 and low O_2, in part by their action on ethylene perception but also via action of O_2 on oxidative processes, including respiration required for substrate production. Most products that suffered moderate suppression of aroma volatile production due to low-O_2 storage atmospheres will eventually develop characteristic flavors. However, low-O_2 MAP may suppress aroma production so consumers perceive reduced quality upon opening the container.

Conclusion

A number of critical points need to be considered in package design and application:

- Not all plant materials benefit from MAP. Those that do may differ in their responses to the atmospheres generated.
- Consideration should be given to the factor most limiting to the delivery of a product to the consumer, and the packaging strategy should be developed accordingly.
- Reduction of water loss by packaging has a marked influence on storability. Elevated humidity prevents desiccation but can also enhance decay.
- Temperature control is of critical importance and, by itself, has a greater impact than atmosphere modification for most products. Temperature should be near the storage/shipping temperature as soon as possible after packaging except in those cases for which a slightly elevated temperature is needed to assist in rapid atmosphere generation.
- Heat transmission from product through the package, carton, and pallet stack needs to be considered in the development of handling procedures.

- If a package is designed to produce low-O_2 or high-CO_2 levels at low temperatures, temperatures more than a few degrees above the target temperature should be avoided, or low-O_2 injury may result.
- Package modeling can improve understanding of how package, plant, and environmental factors interact and can be useful in package design.

References

Abeles, F.B., P.W. Morgan, and M.E. Saltveit Jr. 1992. Ethylene in Plant Biology, 2nd ed. Academic Press, San Diego, CA.

Beaudry, R.M. 2000. Responses of horticultural commodities to low oxygen: limits to the expanded use of modified atmosphere packaging. HortTechnology 10:491-500.

Beaudry, R.M. 1999. Effect of O_2 and CO_2 partial pressure on selected phenomena affecting fruit and vegetable quality. Postharvest Biol. Technol. 15:293-303.

Beaudry, R.M., A.C. Cameron, A. Shirazi, and D.L. Dostal-Lange. 1992. Modified-atmosphere packaging of blueberry fruit: effect of temperature on package O_2 and CO_2. J. Amer. Soc. Hort. Sci. 117:436-441.

Beaudry, R.M., and C.D. Gran. 1993. Using a modified-atmosphere packaging approach to answer some postharvest questions: factors affecting the lower oxygen limit. Acta Hort. 362:203-212.

Brown, W. 1922. On the germination and growth of fungi at various temperatures and in various concentrations of oxygen and carbon dioxide. Ann. Bot. 36:257-283.

Burg, S.P., and E.A. Burg. 1967. Molecular requirements for the biological activity of ethylene. Plant Physiol. 42: 114-152.

Cameron, A.C., R.M. Beaudry, N.H. Banks, and M.V. Yelanich. 1994. Modified-atmosphere packaging of blueberry fruit: Modeling respiration and package oxygen partial pressures as a function of temperature. J. Amer. Soc. Hort. Sci. 119:534-539.

Cameron, A.C., B.D. Patterson, P.C. Talasila, and D.W. Joles. 1993. Modeling the risk in modified atmosphere packaging: a case for sense-and-respond packaging. *In* G. Blanpied, J. Bartsch, and J. Hicks, eds., Proceedings of the 6th International Controlled Atmosphere Research Conference, pp. 95-102. NRAES-71, Cornell University, Ithaca, NY.

Cameron, A.C., P.C. Talasila, and D.J. Joles. 1995. Predicting the film permeability needs for modified atmosphere packaging of lightly processed fruits and vegetables. HortScience 30:25-34.

Fishman, S., V. Rodov, and S. Ben-Yehoshua. 1996. Mathematical model for perforation effect on oxygen and water vapor dynamics in modified-atmosphere packages. J. Food Sci. 61:956-961.

Gorny, J.R. 1997. A summary of CA and MA requirements and recommendations for fresh-cut (minimally-processed) fruits and vegetables. *In* J. Gorny, ed., Fresh-Cut Fruits and Vegetables and MAP, CA'97 Proceedings, vol. 5, pp. 30-66. Postharvest Hort. Ser. no. 19, University of California, Davis, CA.

Herner, R.C. 1987. High CO_2 effects on plant organs. *In* J. Weichman, ed., Postharvest Physiology of Vegetables, pp. 239-253. Marcel Dekker, New York, NY.

Hertog, M.L.A.T.M., H.W. Peppelenbos, R.G. Evelo, and L.M.M. Tijskens. 1998. A dynamic and generic model of gas exchange of respiring produce: the effects of oxygen, carbon dioxide and temperature. Postharvest Biol. Technol. 14:335-349.

Kader, A.A. 1997a. A summary of CA requirements and recommendations for fruits other than apples and pears. *In* A. Kader, ed., Fruits Other Than Apples and Pears, CA'97 Proceedings, vol. 2, pp. 1-36. Postharvest Hort. Ser. no. 17, University of California, Davis, CA.

Kader, A.A. 1997b. Biological bases of O_2 and CO_2 effects on postharvest life of horticultural perishables. *In* M.E. Saltveit, ed., Vegetables and Ornamentals, CA'97 Proceedings, vol. 4, pp. 160-163. Postharvest Hort. Ser. no. 18, University of California, Davis, CA.

Kader, A.A., D. Zagory, and E.L. Kerbel. 1989. Modified atmosphere packaging of fruits and vegetables. Crit. Rev. Food Sci. 28:1-30.

Kays, S.J. 1997. Postharvest Physiology of Perishable Plant Products, Van Nostrand Reinhold, New York, NY.

Ku, V.V.V., and R.B.H. Wills. 1999. Effect of 1-methylcyclopropene on the storage-life of broccoli. Postharvest Biol. Technol. 17:127-132.

Kupferman, E. 1997. Controlled atmosphere storage of apples. *In* E.J. Mitcham, ed., Apples and Pears, CA'97 Proceedings, vol. 3, pp. 1-30. Postharvest Hort. Ser. no. 16, University of California, Davis, CA.

Lakakul, R., R.M. Beaudry, and R.J. Hernandez. 1999. Modeling respiration of apple slices in modified-atmosphere packages. J. Food Sci. 64:105-110.

Mannapperuma, J., D. Zagory, R.P. Singh, and A.A. Kader. 1989. Design of polymeric packages for modified atmosphere storage of fresh produce. *In* J.K. Fellman, ed., Proceedings of the 5th International Controlled Atmosphere Research Conference, Other Commodities and Storage Recommendations, Wenatchee, WA, Vol. 2, pp. 225-233.

Mattheis, J.P., and J.P. Fellman. 2000. Impact of modified atmosphere packaging and controlled atmosphere on aroma, flavor and quality of horticultural produce. HortTechnology 10:507-510.

Meyers, R.A. 1985. Modified atmosphere packaging and process. U.S. Patent 4515266.

Mizutani, Y. 1989. Microporous polypropylene sheets. Ind. Eng. Chem. Res. 32:221-227.

Peiser, G., G. Lopez-Galvez, and M. Cantwell. 1997. Changes in off-odor volatiles of salad products during storage. *In* J. Gorny, ed., Fresh-Cut Fruits and Vegetables and MAP, CA'97 Proceedings, vol. 5, pp. 23-28. Postharvest Hort. Ser. no. 19, University of California, Davis, CA.

Reid, M.S. 1997. A summary of CA and MA requirements and recommendations for ornamentals and cut flowers. *In* M.E. Saltveit, ed., Vegetables and Ornamentals, CA'97 Proceedings, vol. 4, pp. 129-136. Postharvest Hort. Ser. no. 18, University of California, Davis, CA.

Richardson, D.G., and E. Kupferman. 1997. Controlled atmosphere storage of pears. *In* E.J. Mitcham, ed., Apples and Pears, CA'97 Proceedings, vol. 2, pp. 31-35. Postharvest Hort. Ser. no. 16, University of California, Davis, CA.

Saltveit, M.E. 1997. A summary of CA and MA recommendations for harvested vegetables. *In* M.E. Saltveit, ed., Vegetables and Ornamentals, CA'97 Proceedings, vol. 4, pp. 98-117. Postharvest Hort. Ser. no. 18, University of California, Davis, CA.

Sharp, A.K., A.R. Irving, and S.C. Morris. 1993. Does temperature variation limit the use of MA packaging during shipment in freight containers? *In* G. Blanpied, J. Bartsch, and J. Hicks, eds., Proceedings of the 6th International Controlled Atmosphere Research Conference, pp. 238-251. Cornell University, Ithaca, NY.

Shirazi, A., and A.C. Cameron. 1992. Controlling relative humidity in modified-atmosphere packages of tomato fruit. HortScience 27:336-339.

Smyth, A.B., J. Song, and A.C. Cameron. 1998. Modified-atmosphere packaged cut iceberg lettuce: effect of temperature and O_2 partial pressure on respiration and quality. J. Ag. Food Chem. 46:4556-4562.

Smyth, A.B., P.C. Talasila, and A.C. Cameron. 1999. An ethanol biosensor can detect low-oxygen injury in modified atmosphere packages of fresh-cut produce. Postharvest Biol. Technol. 15:127-134.

Song, J., W. Deng, L. Fan, et al. 1998. Aroma volatiles and quality changes in modified atmosphere packaging. *In* J.R. Gorny, ed., Fresh-Cut Fruits and Vegetables and MAP, CA'97 Proceedings, vol. 5, pp. 89-95. Postharvest Hort. Ser. no. 19, University of California, Davis, CA.

Watkins, C.B., E.W. Hewett, and C.J. Thompson. 1988. Effect of microperforated polyethylene bags on the storage quality of 'Cox Orange Pippin' apples. International Symposium on Postharvest Handling of Fruits and Vegetables, Acta Hort. (ISHS) 258:225-236.

Watkins, C.B., P.L. Brookfield, H.J. Elgar, and S.P. McLeod. 1998. Development of a modified atmosphere package for export of apple fruit. *In* S. Ben-Yehoshua, ed., Proceedings of the 1997 International Congress for Plastics in Agriculture, pp. 586-592, Laser Pages Publishing Ltd, Jerusalem, Israel.

Yang, C.C., and M.S. Chinnan. 1988. Modeling the effect of O_2 and CO_2 on respiration and quality of stored tomatoes. Trans. ASAE 31:920-925.

Wholesale Distribution Center Storage

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Most produce is shipped from the point of production to regional or local distributors, such as terminal markets, independent wholesalers, or chain store distribution centers. Produce orders are assembled at these sites and then shipped to retail stores, restaurants, or institutions such as schools or hospitals. Produce and floral items lose quality during these marketing steps, and the amount of quality loss accumulates at each step. The consumer will receive quality produce only if each operation in the handling chain minimizes abuse caused by mechanical damage, improper temperature and RH, moisture loss, ethylene damage, odor contamination, and excessive storage time.

Large wholesale distribution facilities, whether independently owned or integrated with a retail chain, strive to receive only the amount of produce that can be shipped the following day. A few fruits such as mature green avocados, bananas, mangos, and tomatoes are ripened before shipment to retail stores and may be held in special ripening rooms for several days.

Products should be received at their proper long-term storage temperature and then stored at that temperature. Fruits and vegetables can be divided into three categories or groups according to their optimum temperature requirements (table 1). The RH of the storage atmosphere should be 85 to 95%; however, for vegetables stored at low temperatures, it should be 90 to 98%. The lowest temperature range of 0 to 2 °C (32 to 36 °F) should be used for the majority of the green, nonfruit vegetables and temperate fruits and melons. If there is enough capacity in the facility, the fruits should be stored separately from the vegetables. This allows installing equipment to maintain higher RH (90 to 98%) for the vegetables as many of them are quite susceptible to water loss and wilting. Table 2 shows cut flowers and nursery items divided into the recommended three categories or groups. If handled with produce, the floral items in group 1 should be in the group 1A vegetable room to minimize exposure to ethylene produced by many fruits.

Table 1. Compatible fresh fruits and vegetables during 7-day storage*

	Groups 1A and 1B			Group 2	Group 3
	0-2 °C; group 1A: 90-98% RH; group 1B: 85-95% RH			7-10 °C; 85-95% RH	13-18 °C; 85-95% RH
		Group 1A			
Vegetables	Alfalfa sprouts	Chinese cabbage†	Mint†	Basil†	Bitter melon
	Amaranth†	Chinese turnip	Mushroom	Beans, snap, green, wax	Boniato†
	Anise†	Collard†	Mustard greens†	Cactus leaves (nopales)†	Cassava
	Artichoke	Corn, sweet, baby	Parsley†	Calabaza	Dry onion
	Arugula†	Cut vegetables	Parsnip	Chayote†	Ginger
	Asparagus†	Daikon†	Radicchio	Cowpea (Southern pea)	Jicama
	Beans, fava, lima	Endive†-chicory	Radish	Cucumber†	Potato
	Bean sprouts	Escarole†	Rutabaga	Eggplant†	Pumpkin
	Beet	Fennel†	Rhubarb	Kiwano (horned melon)	Squash, winter (hard rind)†
	Belgian endive†	Garlic	Salsify	Long bean	Sweet potato†
	Bok choy†	Green onion†	Scorzonera	Malanga†	Taro (dasheen)
	Broccoli†	Herbs† (not basil)	Shallot†	Okra†	Tomato, ripe, partially ripe,
					& mature green
	Broccoflower†	Horseradish	Snow pea†	Pepper, bell, chili	Yam†
	Brussels sprouts†	Jerusalem artichoke	Spinach†	Squash, summer (soft rind)†	
	Cabbage†	Kailon†	Sweet pea†	Tomatillo	
	Carrot†	Kale†	Swiss chard†	Winged bean	
	Cauliflower†	Kohlrabi	Turnip		
	Celeriac	Leek†	Turnip greens†		
	Celery†	Lettuce†	Water chestnut		
	Chard†		Watercress†		

Table 1. Compatible fresh fruits and vegetables during 7-day storage*—*Continued*

	Groups 1A and 1B			Group 2		Group 3	
	0-2 °C; group 1A: 90-98% RH; group 1B: 85-95% RH			7-10 °C; 85-95% RH		13-18 °C; 85-95% RH	
		Group 1B					
Fruits and melons	Apple‡	Elderberry	Prune†	Avocado, unripe‡	Lime†	Atemoya‡	Sapodilla‡
	Apricot‡	Fig	Quince†	Babaco	Limequat	Banana‡	Sapote‡
	Avocado, ripe‡	Gooseberry	Raspberry	Cactus pear, tuna	Mandarin	Breadfruit‡	Soursop‡
	Barbados cherry	Grape	Strawberry	Calamondin	Mango, ripe‡	Canistel‡	Watermelon
	Blackberry	Kiwifruit†‡		Carambola	Olive	Casaba melon	
	Blueberry	Loganberry		Cranberry	Orange	Cherimoya‡	
	Boysenberry	Longan		Custard apple‡	Passion fruit	Crenshaw melon‡	
	Caimito	Loquat		Durian, ripe‡	Pepino	Honeydew melon‡	
	Cantaloup‡	Lychee		Feijoa	Pineapple	Jaboticaba	
	Cashew apple	Nectarine		Granadilla‡	Pummelo	Jackfruit‡	
	Cherry	Peach		Grapefruit†	Sugar apple	Mamey‡	
	Coconut	Pear (Asian & European)		Guava‡	Tamarillo	Mangosteen‡	
	Currant	Persimmon†		Juan canary melon‡	Tamarind	Papaya‡	
	Fresh-cut fruits‡	Plum, ripe†		Kumquat	Tangelo	Persian melon‡	
	Date	Plumcot, ripe†		Lemon†	Tangerine	Plantain‡	
	Dewberry	Pomegranate			Ugli fruit	Rambutan	

Source: Thompson et al. 1996

*Ethylene should be kept below 1 μL L^{-1} (1 ppm) in the storage area.

†Sensitive to ethylene damage.

‡Produces significant ethylene.

Table 2. Compatible flowers, florist's foliage, and nursery items during 7-day storage†

	Group 1* 0-2 °C; 85-95% RH			Group 2 7-10 °C; 85-95% RH	Group 3 13-18°C; 85-95% RH
Flowers	Acacia	Gaillardia	Protea	Anemone	African violet
	Alstroemeria	Gardenia	Rannunculas	Bird of paradise	Anthurium
	Allium	Gerbera	Rose	Camellia	Ginger
	Aster	Gladiolus	Snapdragon	Eucharis	Heliconia
	Bouvardia	Gypsophlia	Snowdrop	Gloriosa	Orchid, cattleya, vandal
	Buddleia	Heather	Squill	Godetia	Poinsettia
	Calendula	Hyacinth	Statice	Sweet-william	Bulbs, corms, rhizomes, tubers, & roots
	Candytuft	Iris	Stephanotis		
	Carnation	Laceflower	Stevia		Nursery stock
	Chrysanthemum	Lilac	Stock		
	Clarkia	Lily	Strawflower		
	Columbine	Lily-of-the-valley	Sweet pea		
	Coreopsis	Lupine	Tulip		
	Cornflower	Marigolds	Violet		
	Cosmos	Mignonette	Zinnia		
	Crocus	Narcissus	Cuttings & scions		
	Dahlia	Orchid, cymbidium			
	Daisy, English, Marguerite, Shasta	Ornithogalum			
	Delphinium	Poppy			
	Feverfew	Peony			
	Forget-me-not	Phlox			
	Foxglove	Primrose			
	Freesia				
Florist's foliage (greens)	Adiantum (maidenhair)	Gallax	Pittosporum	Chamaedorea	Dieffenbachia
	Asparagus (plumose)	Ground pine	Rhododendron	Cordyline	Staghorn fern
	Buxus (boxwood)	Hedera	Salal (lemon leaf)	Palm	
	Camellia	Ilex (holly)	Scotch-broom	Podocarpus	
	Cedar	Juniper	Smilax		
	Croton	Leatherleaf	Vaccinium (huckleberry)		
	Dracaena	Leucothoe	Woodwardia fern		
	Fern, dagger, wood	Magnolia			
	Eucalyptus	Mistletoe			
		Mountain-laurel			
		Myrtus (myrtle)			
		Philodendron			

*Can be stored with group 1A vegetables in a mixed produce storage.

† Ethylene should be kept below 1 µL L^{-1} (1 ppm) in the storage area.

The two warmer temperature ranges in tables 1 and 2 are for chilling-sensitive produce (groups 2 and 3). The highest-temperature room can also be used to ripen fruit that only require a warm environment to ripen. If refrigerated space is limited, low-temperature fruits, vegetables, and flowers can be mixed in a room; air-conditioned space at 20 to 25 °C (68 to 77 °F) can be used for highest-temperature products (group 3).

Many green vegetables and most floral products are quite sensitive to ethylene damage. Ethylene must be kept away from these products. Minimize ethylene from nearby banana-ripening rooms by—

- using ethylene levels of 100 μL L^{-1} in the ripening rooms instead of the higher levels often used in commercial operations,
- venting ripening rooms to the outside after the exposure period is complete and before rooms are opened,
- ventilating the area around ripening rooms at least once a day or install an ethylene scrubber, and
- using battery-powered forklifts instead of internal combustion-driven units (for example, propane-powered units).

Floral products are particularly sensitive to ethylene. Some distribution facilities have found that the previously described precautions are inadequate in preventing damage to flowers. They have chosen to handle flowers with dairy or meat products, where ethylene is low, or they require that all floral products be chemically treated to resist ethylene damage.

Weak fiberboard containers are usually the cause of mechanical damage to produce between packing and retail display. If products arrive at the distribution facility in crushed boxes, store buyers must work with suppliers to use stronger boxes or ensure that packed boxes are correctly stacked and palletized.

The distribution center assembles pallets of mixed products to be shipped to retail outlets. Products can easily be damaged when boxes with different footprints are stacked and heavy bags of product are placed on weak boxes. Placing only strong containers on the bottom layers of a pallet load can minimize some of this damage. Plastic foam and returnable plastic containers are often stronger than typical fiberboard boxes and can reduce mechanical damage.

Most distribution facilities have special ripening rooms or areas reserved for fruit ripening. Ripening rooms are used extensively for bananas and may also be used to ripen avocados, kiwifruit, mangoes, tomatoes, nectarines, peaches, plums, and European pears. Pressurized or forced-air ripening rooms allow better control of ripening compared with older methods of space-stacking boxes in a warm room. The new designs force temperature-controlled air through the boxes to maintain fairly uniform product temperature. Ethylene gas (100 to 150 μL L^{-1}) is added to the atmosphere on a schedule appropriate for each product, and CO_2 levels are kept below 1% by ventilating the rooms with outside air. Ripening is done with air temperature in the range of 15 to 25 °C (59 to 77 °F), and water vapor is added to the air to keep RH above 85 to 95% in order to reduce moisture loss. The ripening of some products, like stone fruit and pears that were treated with ethylene at the packing operation, can be promoted by warming them to 13 to 18 °C (55 to 64 °F).

Reference

Thompson, J., A.A. Kader, and K. Sylva. 1996. Compatibility chart for fruits and vegetables in short-term transport and storage. Nat. Res. Pub. no. 21560, University of California, Division of Agriculture and Natural Resources, Oakland, CA.

Grocery Store Display Storage

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Introduction

Fresh produce received at the grocery store is kept in storage rooms and display areas (in cabinets and cases or on racks and tables) for a few hours to a few days before purchase by consumers or removal by produce personnel. During this time, the key factors in maintaining quality are careful handling to minimize mechanical injuries, storage and display within optimum ranges of temperature and RH, and proper sanitation of storage and display areas. Expedited handling and effective rotation of the produce (first in, first out) is also recommended.

Storage Room

The number and size of storage rooms depend on store size and frequency of produce delivery to the grocery store. If three rooms are available for produce, they are best designated for short-term storage of the three groups of fruits and vegetables mentioned in the chapter Wholesale Distribution Center Storage; that is, group 1 at 0 to 2 ºC (32 to 36 °F), group 2 at 7 to 10 °C (45 to 50 °F), and group 3 at 13 to 18 ºC (55 to 64 °F). If only two rooms are available, one should be used for group 1 at 0 to 2 ºC (32 to 36 °F) and the other for groups 2 and 3 (at a compromise temperature range of 10 to 14 ºC [50 to 57 °F]). If only one room is available, it should be kept at a compromise temperature of 5 ºC (41 °F) and used for groups 1 and 2, while group 3 should be kept in an air-conditioned area. Cut flowers and other ornamentals that are best kept at 0 to 2 °C (32 to 36 °F) can be combined with group 1 fruits and vegetables, because ethylene production and action at this temperature range are minimal. Ornamentals that are chilling-sensitive and ethylene-sensitive should be handled in a separate area from the ethylene-producing fruits of group 3 to avoid ethylene damage.

All produce items should be near their optimum storage temperature when received at the grocery store and should be unloaded and moved quickly to their appropriate storage area. Keeping cold commodities at warmer temperatures for more than a few minutes can result in water condensation on the commodity, which may encourage the growth of decay-producing pathogens. RH should be kept within the optimum range of 85 to 95% for most commodities to minimize water loss. Good air circulation within the storage room is essential to maintain proper product temperature and RH. Thus, space for air movement should be kept around stacks or pallets of boxes and between them and the room walls. Enough fresh, ethylene-free air should be introduced into storage rooms to keep ethylene <1 $\mu L\ L^{-1}$ (<1 ppm), and preferably <0.1 $\mu L\ L^{-1}$ (<0.1 ppm) if it can be done economically using fresh air exchanges and/or ethylene scrubbing systems.

Display Fixtures

Most produce items in groups 1 and 2 should be displayed in refrigerated display cases. Display at store ambient air temperature is acceptable for some commodities, including produce that does not lose water quickly and has a long shelf-life like apple, pear, kiwifruit, and orange. Produce that is on sale (special promotion) or that will be on display for a few hours (like grapes and strawberries) can also be stored at ambient temperatures.

Ideally, the display case temperature range should match the recommended range for each group of commodities: 0 to 2 ºC (32 to 36 °F) for group 1, including all fresh-cut products, and 7 to 10 °C (45 to 50 °F) for group 2. Since display cases usually do not have the refrigeration capacity to cool the products, it is important to ensure that the product is near its recommended temperature when it is placed in the display case. The produce should not obstruct the discharge air and return air outlets to maintain good cold air circulation within the case. Also, produce should not be stacked so densely that cold air circulation is blocked or so high that it is out of the refrigerated zone and becomes exposed to ambient air temperatures.

Refrigerated display cases have either a horizontal or a vertical air flow system and either single-tier or multi-tier display shelves. They should be equipped with easy-to-read, accurate thermometers, which should be calibrated and monitored regularly. Performance of refrigerated display cases is influenced primarily by their refrigeration capacity, defrost options, and air circulation system. Important secondary factors include temperature, RH, and movement of surrounding air and radiant heat from the lighting sources.

A 1989 survey of temperatures of fresh-cut salads kept in refrigerated display cases in a representative sample of grocery stores indicated an overall mean temperature of about 9 ºC (48 ºF), with more than 78% having temperatures above about 7 ºC (45 °F) and more than 17.5% having temperature above about 13 ºC (55 °F) (R.W. Daniels, Audits International, personal communication, 1989). A survey of temperatures of fresh-cut vegetable products kept in refrigerated display cases in some grocery stores indicates an overall mean of about 5 ºC (41 °F) with more than 40% of the products having temperature above about 7 ºC (45 °F) (Jeff Leshuk, Sensitech Inc., personal communication, 1989). This indicates significant improvements in maintaining the cold chain within the grocery stores, but more improvements are needed to bring the temperature range for fresh-cut products close to the recommended 0 to 2 °C (32 to 36 °F).

Water-loss reduction can be achieved by protecting produce from excessive air movement; packaging in perforated polymeric films (as moisture barriers); periodically adding sanitized, clean water by misting (only useful for commodities that tolerate wetting, such as those listed in table 1); and/or displaying on crushed ice (only useful for products that tolerate direct contact with ice). If ice is used, proper drainage of the melt water should be provided. It should be remembered that ice is not an effective way to keep the product cold unless it is well surrounded by the ice.

Table 1. Produce that benefit from misting while displayed in refrigerated cases

Artichoke	Corn, sweet	Peppers
Asparagus*	Eggplant	Radishes
Beans, snap	Endive	Rhubarb
Beets	Kale	Shallots, green
Broccoli	Leeks	Spinach
Brussels sprouts	Lettuce	Sprouts
Cabbage	Mustard greens	Squash, summer
Carrots	Onions, green	Swiss chard
Cauliflower	Parsley	Turnips
Celery	Parsnips	Watercress
Collards	Peas	

*Asparagus should be displayed vertically with cut ends on a wet absorbent pad.

Non-refrigerated display tables or racks are used for most group 3 fruits and vegetables, which should be displayed separately. Some of the fruits in groups 1 and 2, such as avocado, kiwifruit, and pear, may be displayed on non-refrigerated display tables or racks at ambient produce department temperatures to enhance their ripening. Daylight-simulating fluorescent bulbs can provide adequate lighting in the produce department without giving off heat.

During handling at the grocery store, all precautions should be taken to minimize potential chemical or microbial contamination to maintain safety of produce. All display tables, cases, cabinets, and other fixtures must be cleaned and sanitized regularly. Unmarketable produce should be collected separately from the other waste products and used for composting.

Further Reading

Anonymous. 1987. Professional Produce Manager's Manual. National-American Wholesale Grocers' Association (International Food Service Distributers), Falls Church, VA and Produce Marketing Association, Newark, DE.

Anonymous. 2011. Retail Fruit and Vegetable Marketing Guide, pp. 56. California Department of Public Health, Network for a Healthy California, Sacramento, CA. *At* http://ucce.ucdavis.edu/files/datastore/234-2083.pdf

Nunes, M.C.N., J.P. Emond, M. Rauth, S. Dea, and K.V. Chau. 2009. Environmental conditions encountered during typical consumer retail display affect fruit and vegetable quality and waste. Postharv. Biol. Technol. 51:232-241.

Produce Marketing Association. 2002. The Fresh Produce Manual. Produce Marketing Association, Newark, DE.

Thompson, J.F., and A.A. Kader. 2009. From the Farm to Your Table, A Consumer's Guide to Fresh Fruits and Vegetables. Publication no. 21643, Department of Agriculture and Natural Resources, University of California, Oakland, CA. *At* http://anrcatalog.ucdavis.edu/Items/21643.aspx

Chilling and Freezing Injury

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Chilling Injury

Many fruits, vegetables, and ornamentals of tropical or subtropical origin are sensitive to low temperatures (Paull 1990). These crops are injured after a period of exposure to chilling temperatures below 10 to 15 °C (50 to 59 °F) but above their freezing points (Lyons 1973, Wang 1990). Certain horticultural crops of temperate origin are also susceptible to chilling injury (Bramlage and Meir 1990). Those temperate crops, in general, have lower threshold temperatures of <5 °C (41 °F). At these chilling temperatures, the tissues weaken because they are unable to carry on normal metabolic processes. Various physiological and biochemical alterations and cellular dysfunctions occur in chilling-sensitive species in response to chilling stress (Wang 1982, Wang and Adams 1982, Raison and Orr 1990). When chilling stress is prolonged, these alterations and dysfunctions will lead to the development of a variety of chilling injury symptoms such as surface lesions, internal discoloration, water-soaking of the tissue, and failure to ripen normally (Saltveit and Morris 1990). Often, products that are chilled will still look sound when remaining in low temperatures. However, symptoms of chilling injury become evident shortly after they are moved to warmer temperatures. Fruits and vegetables that have been chilled may be particularly susceptible to decay. Weak pathogens such as *Alternaria* spp., which do not grow readily on healthy tissues, can attack tissues that have been weakened by low-temperature exposure (McColloch and Worthington 1952, McColloch 1962).

Both temperature and duration of exposure are involved in the development of chilling injury. Damage may occur in a short time if temperatures are considerably below the threshold level, but a product may be able to withstand temperatures a few degrees into the critical zone for a longer time before injury becomes irreversible. Maturity at harvest and degree of ripeness are important factors in determining chilling sensitivity in some fruits like avocados (Kosiyachinda and Young 1976), honeydew melons (Lipton 1978), and tomatoes (McColloch et al. 1966). The effects of chilling are cumulative in some commodities. Low temperatures in transit, or even in the field shortly before harvest, add to the total effects of chilling that occur in cold storage.

Treatments shown to alleviate chilling injury include intermittent warming; high- or low-temperature preconditioning; CA storage; pretreatments with ethylene, abscisic acid, methyl jasmonate, and other natural compounds; calcium or other chemical applications; hypobaric storage; waxing; film packaging; and genetic manipulation (Ryall and Lipton 1979, Wang 1993, 1994, Meir et al. 1996).

Chilling injury is discussed more specifically under each commodity. Many of the commodities susceptible to chilling injury are listed in table 1 with threshold temperatures and some of the symptoms.

Table 1. Fresh produce susceptible to chilling injury when stored at low but nonfreezing temperatures

Commodity	Lowest Safe Temperature º C	º F	Symptoms of injury when stored between 0 ºC and safe temperature*
Apples—certain cultivars	2-3†	36-38	Internal browning, brown core, soggy breakdown, soft scald
Asparagus	0-2	32-36	Dull, gray-green, limp tips
Atemoya	4	39	Skin darkening, failure to ripen, pulp discoloration
Avocados	4.5-13†	40-55	Grayish-brown discoloration of flesh
Bael	3	38	Brown spots on skin
Bananas	11.5-13†	53-56	Dull color when ripened
Bean (lima)	1-4.5	34-40	Rusty brown specks, spots or areas
Bean (snap)	7†	45	Pitting and russeting
Breadfruit	7-12	45-53	Abnormal ripening, dull brown discoloration
Choyote	5-10	41-50	Dull brown discoloration, pitting, flesh darkening
Cranberries	2	36	Rubbery texture, red flesh
Cucumbers	7	45	Pitting, water-soaked spots, decay
Eggplants	7	45	Surface scald, alternaria rot, blackening of seeds
Ginger	7	45	Softening, tissue breakdown, decay
Guavas	4.5†	40	Pulp injury, decay
Grapefruit	10†	50	Scald, pitting, watery breakdown
Jicama	13-18	55-65	Surface decay, discoloration
Lemons	11-13†	52-55	Pitting, membranous staining, red blotch
Limes	7-9	45-48	Pitting, turning tan with time
Lychee	3	38	Skin browning
Mangos	10-13†	50-55	Grayish scald-like discoloration of skin, uneven ripening
Mangosteen	4-8	39-47	Hardening and browning of the cortex
Melons			
Cantaloupe	2-5†	36-41	Pitting, surface decay
Honeydew	7-10	45-50	Reddish-tan discoloration, pitting, surface decay, failure to ripen
Casaba	7-10	45-50	Pitting, surface decay, failure to ripen
Crenshaw and Persian	7-10	45-50	Pitting, surface decay, failure to ripen
Okra	7	45	Discoloration, water-soaked areas, pitting, decay
Olive, fresh	7	45	Internal browning
Oranges	3†	38	Pitting, brown stain
Papayas	7	45	Pitting, failure to ripen, off flavors, decay

Table 1. Fresh produce susceptible to chilling injury when stored at low but nonfreezing temperatures—*Continued*

Commodity	Lowest Safe Temperature º C	º F	Symptoms of injury when stored between 0 ºC and safe temperature*
Passion fruit	10	50	Dark red discoloration on skin, loss of flavor, decay
Peppers, sweet	7	45	Sheet pitting, alternaria rot on pods and calyxes, darkening of seeds
Pineapples	7-10†	45-50	Dull green when ripe, internal browning
Pomegranates	4.5	40	Pitting, external and internal browning
Potatoes	3†	38	Mahogany browning, sweetening
Pumpkins and hardshell squash	10	50	Decay, especially alternaria rot
Rambutan	10	50	Darkening of exocarp
Sweet potatoes	13	55	Decay, pitting, internal discoloration, hardcore when cooked
Tamarillos	3-4	37-40	Surface pitting, discoloration
Taro	10	50	Internal browning, decay
Tomatoes			
Ripe	7-10†	45-50	Water soaking and softening, decay
Mature-green	13	55	Poor color when ripe, alternaria rot
Water convolvulus	10	50	Darkening of leaves and stems
Watermelons	4.5	40	Pitting, objectionable flavor

*Symptoms often become apparent only after removal to warm temperatures, as in marketing.
†See individual commodity sections in this Handbook.

Freezing Injury

The recommended storage temperatures for commodities that are not susceptible to chilling injury are as low as possible but slightly above the freezing point. Freezing injury occurs when ice crystals form in the tissues. Cultivars, locations, and growing conditions may affect the freezing point. To be on the safe side, the highest temperature at which freezing of a specific commodity may occur should be used as a guide for recommending the optimum storage temperature. More detailed discussion of freezing points and factors affecting them can be found in McColloch (1953), Whiteman (1957), and Parsons and Day (1970,1971). The most common symptom of freezing injury is a water-soaked appearance. Tissues injured by freezing generally lose rigidity and become mushy upon thawing.

The susceptibility of different fresh fruits and vegetables to freezing injury varies widely. Some commodities may be frozen and thawed a number of times with little or no injury, whereas others are permanently injured by even a slight freezing. All fruits and vegetables can be categorized into three groups based on their sensitivity to freezing: *most susceptible*—those that are likely to be injured by even one light freezing, *moderately susceptible*—those that will recover from one or two light freezing periods, and *least susceptible*—those that can be lightly frozen several times without serious damage. Table 2 shows the relative susceptibility of a number of fruits and vegetables to freezing injury.

Table 2. Susceptibility of fresh fruits and vegetables to freezing injury

Most susceptible	Moderately susceptible	Least susceptible
Apricots	Apples	Beets
Asparagus	Broccoli	Brussels sprouts
Avocados	Carrots	Cabbage, mature and savory
Bananas	Cauliflower	Dates
Beans, snap	Celery	Kale
Berries (except cranberries)	Cranberries	Kohlrabi
Cucumbers	Grapefruit	Parsnips
Eggplants	Grapes	Rutabagas
Lemons	Onion (dry)	Salsify
Lettuce	Oranges	Turnips
Limes	Parsley	
Okra	Pears	
Peaches	Peas	
Peppers, sweet	Radishes	
Plums	Spinach	
Potatoes	Squash, winter	
Squash, summer		
Sweet potatoes		
Tomatoes		

The freezing point of the commodity is no indication of the damage to be expected by freezing. For example, both tomatoes and parsnips have freezing points of -1.1 to -0.6 °C (30 to 31 °F), but parsnips can be frozen and thawed several times without apparent injury, whereas tomatoes are ruined after only one freezing. The severity of freezing injury is influenced by a combination of time and temperature. For example, apples that would be injured little by exposure to temperatures slightly below the freezing point for a few days would be severely injured by just a few hours of exposure to -7 to -10 °C (19 to 14 °F). The susceptibility to freezing injury is not necessarily similar for the same type of fruit or vegetable. For example, leafy lettuce is very susceptible to freezing injury, whereas some other leafy vegetables, such as kale and cabbage, can withstand several light freezing periods without serious injury.

When left undisturbed, most fruits and vegetables can usually be cooled one to several degrees below their freezing point before they actually freeze. This cooling without freezing is known as undercooling or supercooling. They may remain undercooled for several hours, but they will usually start to freeze immediately if jarred or moved. If permitted to warm above the freezing point, many commodities that have been undercooled may escape having ice crystals form in them. For example, potatoes, which are very sensitive to freezing damage, showed no freezing symptoms from having been undercooled for a short time to -4 °C (25 °F), about 3 °C (5 °F) below their freezing point, when they were carefully warmed after undercooling (Hruschka et al. 1961).

Plant tissues are very sensitive to bruising while frozen, and this sensitivity is another reason for leaving commodities undisturbed until they have warmed. Selecting a suitable thawing temperature involves a compromise. Fast thawing damages tissues, but very slow thawing such as at 0 to 1 °C (32 to 34 °F) allows ice to remain in the tissues too long and causes injury. Research on the rate of thawing has suggested that thawing at 4 °C (39 °F) causes the least damage for most commodities (Lutz 1936). Even though a number of fruits and vegetables are somewhat tolerant to freezing, commodities recovered from freezing often have shorter storage life and are more susceptible to invasion by microorganisms. For example, apples that recover from freezing are softer than normal fruit, and carrots that have been frozen are especially subject to decay. Therefore, it is best to avoid subjecting fresh produce to freezing temperatures in the first place.

References

Bramlage, W.J., and S. Meir. 1990. Chilling injury of crops of temperate origin. *In* C.Y. Wang, ed., Chilling Injury of Horticultural Crops, pp. 37-49. CRC Press, Boca Raton, FL.

Hruschka, H.W., R.V. Akeley, and E.H. Ralph. 1961. Seed potato productivity after cooling, supercooling or freezing. Marketing Research Report 507, U.S. Department of Agriculture, Washington, DC.

Kosiyachinda, S., and R.E. Young. 1976. Chilling sensitivity of avocado fruit at different stages of the respiratory climacteric. J. Amer. Soc. Hort. Sci. 101:665-667.

Lipton, W.J. 1978. Chilling injury of ‘Honey Dew’ muskmelons: symptoms and relation to degree of ripeness at harvest. HortScience 13:45-46.

Lutz, J.M. 1936. The influence of rate of thawing on freezing injury of apples, potatoes and onions. Proc. Amer. Soc. Hort. Sci. 33:227-233.

Lyons, J.M. 1973. Chilling injury in plants. Ann. Rev. Plant Physiol. 24:445-466.

McColloch, L.P. 1953. Injuries from chilling and freezing. *In* Plant Diseases, the Yearbook of Agriculture 1953, pp. 826-830. U.S. Department of Agriculture, Washington, DC.

McColloch, L.P. 1962. Alternaria rot following chilling injury of acorn squashes. Marketing Research Report 518, U.S. Department of Agriculture, Washington, DC.

McColloch, L.P., and J.T. Worthington. 1952. Low temperature as a factor in the susceptibility of mature-green tomatoes to *Alternaria* rot. Phytopathology 42:425-427.

McColloch, L.P., J.N. Yeatman, and P. Loyd. 1966. Color changes and chilling injury of pink tomatoes held at various temperatures. Marketing Research Report 735, U.S. Department of Agriculture, Washington, DC.

Meir, S., S. Philosoph-Hadas, S. Lurie, et al. 1996. Reduction of chilling injury in stored avocado, grapefruit, and bell pepper by methyl jasmonate. Can. J. Bot. 74:870-874.

Parsons, C.S., and R.H. Day. 1970. Freezing injury of root crops: Beets, carrots, parsnips, radishes, and turnips. Marketing Research Report 866, U.S. Department of Agriculture, Washington, DC.

Parsons, C.S., and R.H. Day. 1971. Freezing injury to bell peppers. Marketing Research Report 895, U.S. Department of Agriculture, Washington, DC.

Paull, R.E. 1990. Chilling injury of crops of tropical and subtropical origin. *In* C.Y. Wang, ed., Chilling Injury of Horticultural Crops, pp. 17-36. CRC Press, Boca Raton, FL.

Raison, J.K., and G.R. Orr. 1990. Proposals for a better understanding of the molecular basis of chilling injury. *In* C.Y. Wang, ed., Chilling Injury of Horticultural Crops, pp. 145-164. CRC Press, Boca Raton, FL.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation, and Storage of Fruits and Vegetables, vol. 1, Vegetables and Melons, 2nd ed. AVI Publishing Company, Westport, CT.

Saltveit, M.E., and L.L. Morris. 1990. Overview on chilling injury of horticultural crops. *In* C.Y. Wang, ed., Chilling Injury of Horticultural Crops, pp. 3-15. CRC Press, Boca Raton, FL.

Wang, C.Y. 1982. Physiological and biochemical responses of plants to chilling stress. HortScience 17:173-186.

Wang, C.Y. 1990. Chilling Injury of Horticultural Crops. CRC Press, Boca Raton, FL.

Wang, C.Y. 1993. Approaches to reduce chilling injury of fruits and vegetables. Hort. Rev. 15:63-95.

Wang, C.Y. 1994. Reduction of chilling injury by methyl jasmonate. Acta. Hort. 368:901-907.

Wang, C.Y., and D.O. Adams. 1982. Chilling-induced ethylene production in cucumbers (*Cucumis sativus* L). Plant Physiol. 69:424-427.

Whiteman, T.M. 1957. Freezing points of fruits, vegetables and florist stocks. Marketing Research Report 196, U.S. Department of Agriculture, Washington, DC.

Respiratory Metabolism

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Introduction

All of the commodities covered in this handbook are alive and carry on processes characteristic of all living things. One of the most important of these is respiratory metabolism. The process of respiration involves combining O_2 in the air with organic molecules in the tissue (usually a sugar) to form various intermediate compounds and eventually CO_2 and water. Energy produced by the series of reactions making up respiration can be captured as high-energy bonds in compounds used by the cell in subsequent reactions, or it can be lost as heat. The energy and organic molecules produced during respiration are used by other metabolic processes to maintain the health of the commodity. Heat produced during respiration is called "vital heat," and it contributes to the refrigeration load that must be considered in designing storage rooms.

There is little the postharvest physiologist can do to alter the internal factors affecting respiration of harvested commodities, because they are largely a function of the commodity itself once harvested. However, a major part of postharvest technology is devoted to reducing respiration and other metabolic reactions associated with quality retention by manipulating the external environment.

In general, the storage life of commodities varies inversely with the rate of respiration. This is because respiration supplies compounds that determine the rate of metabolic processes directly related to quality parameters such as firmness, sugar content, aroma, and flavor. Commodities and cultivars with higher rates of respiration tend to have shorter storage life than those with lower rates of respiration. Storage life of broccoli, lettuce, peas, spinach, and sweet corn, all of which have high respiration rates, is short in comparison to that of apples, cranberries, limes, onions, and potatoes, all of which have low respiration rates (table 1).

Table 1. Respiration rates of various perishable commodities

Class	Range at 5 °C	Commodities
	mg CO_2 kg^{-1} h^{-1}	
Very Low	<5	Nuts, dates
Low	5 to 10	Apple, citrus, grape, kiwifruit, onion, potato
Moderate	10 to 20	Apricot, banana, cherry, peach, nectarine, pear, plum, fig, cabbage, carrot, lettuce, pepper, tomato
High	20 to 40	Strawberry, blackberry, raspberry, cauliflower, lima bean, avocado
Very High	40 to 60	Artichoke, snap bean, Brussels sprouts, cut flowers
Extremely High	>60	Asparagus, broccoli, mushroom, pea, spinach, sweet corn

Factors Affecting Respiration

Respiration is affected by a wide range of environmental factors that include light, chemical stress (for example, fumigants), radiation stress, water stress, growth regulators, and pathogen attack. The most important postharvest factors are temperature, atmospheric composition, and physical stress.

Temperature. The most important factor affecting postharvest life is temperature, because temperature has a profound effect on the rates of biological reactions; for example, metabolism and respiration. Over the physiological range of most crops, 0 to 30 °C (32 to 86 °F), increased temperatures cause an exponential rise in respiration. The Van't Hoff Rule states that the velocity of a biological reaction increases 2 to 3-fold for every 10 °C (18 °F) rise in temperature.

The temperature quotient for a 10 °C (18 °F) interval is called the Q_{10}. The Q_{10} can be calculated by dividing the reaction rate at a higher temperature by the rate at a 10 °C (18 °F) lower temperature: $Q_{10} = R_2/R_1$. The temperature quotient is useful because it allows us to calculate the respiration rates at one temperature from a known rate at another temperature. However, the respiration rate does not follow ideal behavior, and the Q_{10} can vary considerably with temperature. At higher temperatures, the Q_{10} is usually smaller than that at lower temperatures.

The following are typical values for Q_{10} at various temperature ranges:

Temperature	Q_{10}
0 to 10 °C	2.5 to 4.0
10 to 20 °C	2.0 to 2.5
20 to 30 °C	1.5 to 2.0
30 to 40 °C	1.0 to 1.5

These typical Q_{10} values allow us to construct a table showing the effect of different temperatures on the rates of respiration or deterioration and relative shelf-life of a typical perishable commodity (table 2). This table shows that, if a commodity has a mean shelf-life of 13 days at 20 °C (68 °F), it can be stored for as long as 100 days at 0 °C (32 °F) but will last no more than 4 days at 40 °C (104 °F).

Table 2. Effect of temperature on rate of deterioration

Temperature	Assumed Q_{10}	Relative velocity of deterioration	Relative shelf-life
°C			
0	—	1.0	100
10	3.0	3.0	33
20	2.5	7.5	13
30	2.0	15.0	7
40	1.5	22.5	4

Chilling stress. Although respiration is normally reduced at low but nonfreezing temperatures, certain commodities, chiefly those originating in the tropics and subtropics, exhibit abnormal respiration when their temperature falls below 10 to 12 °C (50 to 54 ºF). Typically, the Q_{10} is much higher at those low temperatures for chilling-sensitive crops than it would be for chilling-tolerant ones. Respiration may increase dramatically at the chilling temperatures or when the commodity is returned to nonchilling temperatures. This enhanced respiration presumably reflects the cells' efforts to detoxify metabolic intermediates that accumulated during chilling, as well as to repair damage to membranes and other subcellular structures. Enhanced respiration is only one of many symptoms that signal the onset of chilling injury.

Heat stress. As the temperature rises beyond the physiological range, the rate of increase in respiration falls. It becomes negative as the tissue nears its thermal death point, when metabolism is disorderly and enzyme proteins are denatured. Many tissues can tolerate high temperatures for short periods of time (for example, minutes), and this property is used to advantage in killing surface fungi on some fruits. Continued exposure to high temperature results in phytotoxic symptoms and then complete tissue collapse. However, conditioning and heat shocks—that is, short exposure to potentially injurious temperatures—can modify the tissue's responses to subsequent harmful stresses.

Atmospheric composition. Adequate O_2 levels are required to maintain aerobic respiration. The exact level of O_2 that reduces respiration while still permitting aerobic respiration varies among commodities. In most crops, O_2 levels at around 2% to 3% produce a beneficial reduction in the rate of respiration and other metabolic reactions. Levels as low as 1% improve the storage life of some crops—for example, apples—but only when the storage temperature is optimal. At higher storage temperatures, the demand for adenosine triphosphate (ATP) may outstrip the supply and promote anaerobic respiration (see chapters "Controlled Atmosphere Storage" and "Modified Atmosphere Packaging"). The need for adequate O_2 should be considered in selecting the various postharvest handling procedures, such as waxing and other surface coatings, film wrapping, and packaging. Unintentional modification of the atmosphere, by packaging for example, can result in production of undesirable fermentative products and development of foul odors.

Increasing the CO_2 level around some commodities reduces respiration, delays senescence, and retards fungal growth. In low O_2 environments, however, increased CO_2 levels can promote fermentative metabolism. Some commodities tolerate brief storage in a pure N_2 atmosphere (for example, a few days at low temperatures) or in very high concentrations of CO_2. The biochemical basis for this ability to withstand these atmospheres is unknown.

Physical stress. Even mild physical stress can perturb respiration, while physical abuse can cause a substantial rise in respiration that is often associated with increased ethylene evolution. The signal produced by physical stress migrates from the site of injury and induces a wide range of physiological changes in adjacent, non-wounded tissue. Some of the more important changes include enhanced respiration, ethylene production, phenolic metabolism, and wound healing. Wound-induced respiration is often transitory, lasting a few hours or days. However, in some tissues, wounding stimulates developmental changes, such as promotion of ripening, that result in a prolonged increase in respiration. Ethylene stimulates respiration and stress-induced ethylene may have many physiological effects on commodities besides stimulating respiration.

Stage of development. Respiration rates vary among and within commodities. Storage organs such as nuts and tubers have low respiration rates. Tissues with vegetative or floral meristems such as asparagus and broccoli have very high respiration rates. As plant organs mature, their rate of respiration typically declines. This means that commodities harvested during active growth, such as many vegetables and immature fruits, have high respiration rates. Mature fruits, dormant buds, and storage organs have relatively low rates.

After harvest, the respiration rate typically declines—slowly in nonclimacteric fruits and storage organs and rapidly in vegetative tissues and immature fruits. The rapid decline presumably reflects depletion of respirable substrates, which are typically low in such tissues. An important exception to the general decline in respiration following harvest is the rapid and sometimes dramatic rise in respiration during the ripening of climacteric fruit (figure 1). This rise, which has been the subject of intense study for many years, normally consists of four distinct phases: (1) preclimacteric minimum, (2) climacteric rise, (3) climacteric peak, and (4) postclimacteric decline.

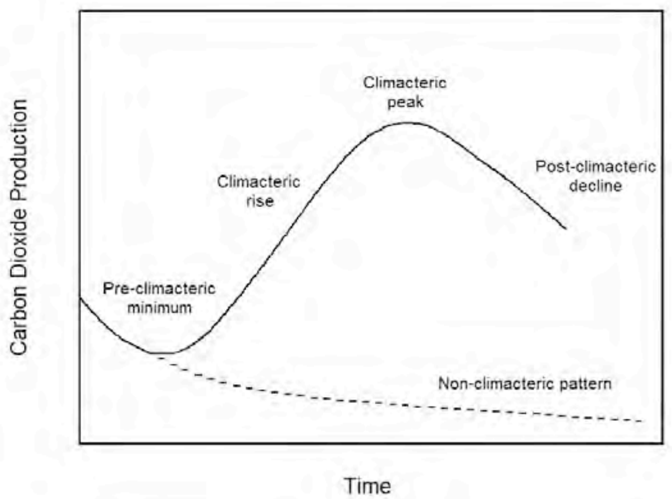

Figure 1. The climacteric pattern of respiration in ripening fruit.

The division of fruits into climacteric and nonclimacteric types has been very useful for postharvest physiologists. However, some fruits, kiwifruit and cucumber for example, appear to blur the distinction between the groups. Respiratory rises also occur during stress and other developmental stages, but a true climacteric only occurs coincident with fruit ripening. The following is a general classification of fruits according to their respiratory behavior during ripening:

Climacteric Fruits		Nonclimacteric Fruits
Apple	Papaya	Blueberry
Apricot	Passion fruit	Cacao
Avocado	Peach	Caju
Banana	Pear	Cherry
Biriba	Persimmon	Cucumber
Breadfruit	Plum	Grape
Cherimoya	Sapote	Grapefruit
Feijoa	Soursop	Lemon
Fig	Tomato	Lime
Guava	Watermelon	Olive
Jackfruit		Orange
Kiwifruit		Pepper
Mango		Pineapple
Muskmelon		Strawberry
Nectarine		Tamarillo

Significance of Respiration

Shelf-life and respiration rate. In general, there is an inverse relationship between respiration rates and postharvest life of fresh commodities. The higher the respiration rate, the more perishable the commodity usually is; that is, the shorter postharvest life it has. Respiration plays a major role in the postharvest life of fresh commodities because it reflects the metabolic activity of the tissue that also includes the loss of substrate, the synthesis of new compounds, and the release of heat energy. See the section "Summary of Respiration and Ethylene Production Rates" in the Introduction of this Handbook.

Loss of substrate. Use of various substrates in respiration can result in loss of food reserves in the tissue and loss of taste quality (especially sweetness) and food value to the consumer. For certain commodities that are stored for extended periods of time, such as onions used for dehydrated product, the loss of dry weight due to respiration can be significant. When a hexose sugar (for example, glucose) is the substrate, 180 g of sugar is lost for each 264 g of CO_2 produced by the commodity. The rate of dry weight loss can be estimated as follows:

Dry weight loss (g kg^{-1} h^{-1}) = Respiration (mg CO_2 kg^{-1} h^{-1}) × 0.068

or

% dry weight loss (g 100 g^{-1} h^{-1}) = Respiration (mg CO_2 kg^{-1} h^{-1}) × 68 × 10^{-6}

For example, onions held at 30 °C (86 °F) will respire at about 35 mg CO_2 kg^{-1} h^{-1}. The percentage dry weight loss per hour would be 35 x 0.68/10,000 = 0.0024%, while the percentage dry weight loss per month would be 0.0024 x 24 x 30 = 1.73%.

Synthesis of new compounds. Postharvest storage can be used either to prevent any reduction in quality or to promote changes that increase quality. The quality of most vegetables (for example, cucumbers and lettuce) and nonclimacteric fruit (for example, strawberries) is maximal at harvest, and storage conditions are optimized to prevent quality loss. In contrast, many flowers (for example, carnations and roses), nonclimacteric fruit (for example, lemons and oranges), and climacteric fruit (for example, bananas and tomatoes) are harvested before they reach their best quality, and storage conditions are optimized to permit development of optimum quality. In the first case, the synthesis of new compounds is unnecessary because they lead to reduced quality (for example, enzymes that destroy chlorophyll in lettuce or promote lignification in asparagus). In the second case, synthesis of pigments and volatiles (for example, lycopene in tomatoes and amyl esters in banana), loss of chlorophyll (for example, chlorophyll-degrading enzymes in banana and lemons), and the conversion of starch to sugar (for example, sweetening of apples and bananas) is necessary for development of maximum quality. These synthetic reactions require energy and organic molecules derived from respiration.

Release of heat energy. The heat produced by respiration (vital heat), about 673 kcal for each mole of sugar (180 g) used, can be a major factor in establishing the refrigeration requirements during transport and storage. Vital heat must be considered in selecting proper methods for cooling, package design, and stacking of packages, as well as selection of refrigerated storage facilities (that is, refrigeration capacity, air circulation, and ventilation). The approximate rates of heat production by various crops at different storage temperatures can be calculated from the respiration rates for many fruits and vegetables given in section "Summary of Respiration and Ethylene Production Rates" in the Introduction of this Handbook.

Calculation of heat production from the respiration equation shows that production of 1 mg of CO_2 yields 2.55 cal. In the language of the refrigeration engineer, a respiration rate of 1 mg CO_2 kg^{-1} h^{-1} indicates heat production of 61.2 kcal $tonne^{-1}$ day^{1} (220 BTU ton^{-1} day^{-1}). The British thermal unit (BTU) is the heat required to raise 1 lb of water by 1 °F.

Some commodities have high respiration rates and require considerably more refrigeration than more slowly respiring produce to keep them at a specified temperature. For example, asparagus, broccoli, mushrooms, and peas respire about 10 times faster than apples, cabbage, lemons, and tomatoes.

Meaning of the respiratory quotient (RQ). The composition of a commodity frequently determines which substrates are used in respiration and consequently the value of the respiratory quotient (RQ). RQ is defined as the ratio of CO_2 produced to O_2 consumed; CO_2 and O_2 can be measured in moles or volumes. Depending on the substrate being oxidized, RQ values for fresh commodities range from 0.7 to 1.3 for aerobic respiration. When carbohydrates are being aerobically respired, RQ is near 1, while it is <1 for lipids and >1 for organic acids. Very high RQ values usually indicate anaerobic respiration in those tissues that produce ethanol. In such tissues, a rapid change in RQ can be used as an indication of the shift from aerobic to anaerobic respiration.

Measuring the Rate of Respiration

The rate of any reaction can be determined by measuring the rate at which the substrates disappear or the products appear. Apart from the water produced by respiration, which is relatively trivial compared with the very high water content of most harvested commodities, all the substrates and products of respiration have been used to determine the rate of respiration. They are loss of substrate (for example, glucose) loss of O_2, increase in CO_2, and production of heat. The most commonly used method is to measure production of CO_2 with either a static or a dynamic system.

In a static system, the commodity is enclosed in an airtight container and gas samples are taken after sufficient CO_2 has accumulated to be accurately detected by any one of a number of commercially available instruments (for example, gas chromatograph and infrared CO_2 analyzer). If the container is properly sealed, CO_2 should increase linearly with time. Multiplying the change in concentration times the container volume and dividing by weight of the commodity and duration of time between samples gives the production rate.

In the dynamic system a flow of air (or other gas mixture) is passed through the container at a known rate. The system will come into equilibrium (>99.3%) in about the same time it takes for 5 times the volume to flow through the container. The difference in CO_2 concentration between the inlet and outlet is measured after the system has reached equilibrium by taking gas samples at both points and analyzing them. Multiplying the difference in concentration by the flow rate and dividing by the weight of the commodity calculates the production rate.

Biochemistry of Respiration

Respiration is the oxidative breakdown of complex substrate molecules normally present in plant cells, such as starches, sugars, and organic acids, to simpler molecules such as CO_2 and H_2O. Concomitant with this catabolic reaction is the production of energy and intermediate molecules that are required to sustain the myriad of metabolic reactions essential for the maintenance of cellular organization and membrane integrity of living cells. Since respiration rate is so tightly coupled to the rate of metabolism, measurements of respiration provide an easy, nondestructive means of monitoring the metabolic and physiological state of tissues. For example, events of senescence and ripening are often signaled by abrupt changes in respiration.

Maintaining a supply of high-energy compounds like adenosine triphosphate (ATP), nicotinamide adenine dinucleotide (NADH), and pyrophosphate (PPi) is a primary function of respiration. The overall process of aerobic respiration involves regeneration of ATP from ADP (adenosine diphosphate) and P_i (inorganic phosphate) with release of CO_2 and H_2O. If glucose is used as substrate, the overall equation for respiration can be written as follows:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + 686\ \text{kcal mole}^{-1}$$

The components of this reaction have various sources and destinations. The one mole of glucose (180 g) can come from stored simple sugars like glucose and sucrose or complex polysaccharides like starch. Fats and proteins can also provide substrates for respiration, but their derivatives (fatty acids, glycerol, and amino acids) enter at later stages in the overall process and as smaller, partially metabolized molecules. The 192 g of O_2 (6 moles × 32 g mol^{-1}) used to oxidize the 1 mole of glucose diffuses into the tissue from the surrounding atmosphere, while the 6 moles of CO_2 (264 g) diffuses out of the tissue. The 6 moles of H_2O (108 g) that are produced are simply incorporated into the aqueous solution of the cell.

There are three fates for the energy (686 kcal mol^{-1}) released by aerobic respiration. Around 13 kcal is lost due to the increase in entropy (disorder) when the complex glucose molecule is broken down into simpler molecules. Of the remaining 673 kcal that are capable of doing work, around 281 kcal (about 41% of the total energy) is used to produce 38 ATP molecules (38 ATP × 7.4 kcal ATP^{-1}). The remaining 392 kcal (57%) is lost as heat. In actuality, most energy is lost as heat since energy is lost to heat every time energy is transferred during a metabolic reaction.

Aerobic respiration involves a series of three complex reactions, each of which is catalyzed by a number of specific enzymes that perform one of the following actions: add an energy-containing phosphate group to the substrate molecule, rearrange the molecule, and break down the molecule to a simpler one. The three interconnected metabolic pathways are glycolysis, tricarboxylic acid (TCA) cycle, and electron transport system.

Glycolysis, the breakdown, or lysing, of glucose, occurs in the cytoplasm of the cell. It involves the production of two molecules of pyruvate from each molecule of glucose. Each of the 10 distinct, sequential reactions in glycolysis is catalyzed by one enzyme. Two key enzymes in glycolysis are phosphofructokinase (PFK) and pyruvate kinase

(PK). Cells can control their rate of energy production by altering the rate of glycolysis, primarily through controlling PFK and PK activity. One of the products of respiration, ATP, is used as a negative feedback inhibitor to control the activity of PFK. Glycolysis produces two molecules of ATP and two molecules of NADH from the breakdown of each molecule of glucose.

Tricarboxylic acid (TCA) cycle, which occurs in the mitochondrial matrix, involves the breakdown of pyruvate into CO_2 in nine sequential, enzymatic reactions. Pyruvate is decarboxylated (removal of CO_2) to form acetate, which condenses with a co-enzyme to form acetyl CoA. This compound then enters the cycle by condensation with oxaloacetate to form citric acid. Citric acid has three carboxyl groups from which the cycle derives its name. Through a series of seven successive rearrangements, oxidations, and decarboxylations, citric acid is converted back into oxaloacetate that is then ready to accept another acetyl CoA molecule. In addition to producing the many small molecules that are used in the synthetic reactions of the cell, the TCA cycle also produces one molecule of flavin adenine dinucleotide ($FADH_2$) and four molecules of NADH for each molecule of pyruvate metabolized.

Electron transport system, which occurs on membranes in the mitochondria, involves the production of ATP from the high-energy intermediates $FADH_2$ and NADH. The energy contained in a molecule of NADH or $FADH_2$ is more than is needed for most cellular processes. In a series of reactions, one NADH molecule produces three ATP molecules, while one FADH molecule produces two ATP molecules. The production of ATP depends not only on the energy contained in NADH and $FADH_2$ but also on the chemical environment (pH and ion concentrations) within the cell and mitochondria.

In the absence of O_2, NADH and $FADH_2$ accumulate in the reduced form. As the oxidized forms (NAD^+ and FAD) are consumed, the TCA cycle comes to a halt and glycolysis becomes the sole source of ATP production. Regeneration of NAD^+ is absolutely essential for the survival of the anaerobic cell and takes place during the reductive decarboxylation of pyruvate to ethanol in fermentative metabolism.

Fermentation, or anaerobic respiration, involves the conversion of hexose sugars into alcohol and CO_2 in the absence of O_2. Pyruvate produced through glycolysis via a series of reactions that do not require O_2 can be converted to lactic acid, malic acid, acetyl CoA, or acetaldehyde. The pathway chosen depends on cellular pH, prior stresses, and the current metabolic needs of the cell. Acidification of the cytoplasm enhances the activity of pyruvic decarboxylase that then shunts pyruvate to form CO_2 and acetaldehyde. The acetaldehyde is converted by the enzyme alcohol dehydrogenase to ethanol with the regeneration of NAD^+. Two molecules of ATP and 21 kcal of heat energy are produced in anaerobic respiration (alcoholic fermentation) from each molecule of glucose. To maintain the supply of ATP at the aerobic rate, 19 times as many glucose molecules would be needed, and glycolysis would increase 19-fold. However, since only two molecules of CO_2 are produced during glycolysis, instead of six during aerobic respiration, the rate of CO_2 production would not increase by 19-fold but only by 6.3-fold (that is, $19 \div 3$). Concomitantly, there would be substantial accumulation of ethanol and smaller amounts of acetaldehyde. However, glycolysis usually increases only 3- to 6-fold.

The O_2 concentration at which a shift from predominantly aerobic to predominantly anaerobic respiration occurs varies among tissues and is known as the extinction point, the anaerobic compensation point, and the fermentative threshold. Since O_2 concentration at any point in a fruit or vegetable varies with rates of gas diffusion and respiration, some parts of the commodity may become anaerobic while others remain aerobic.

Further Reading

Abeles, F.B., P.W. Morgan, and M.E. Saltveit. 1992. Ethylene in Plant Biology, 2nd ed. Academic Press, New York, NY.

Biale, J.B., and R.E. Young. 1981. Respiration and ripening in fruits—retrospect and prospect. *In* J. Friend and M.J.C. Rhodes, eds., Recent Advances in the Biochemistry of Fruits and Vegetables, pp 1-39. Academic Press, New York, NY.

Kays, S.J. 1991. Postharvest Physiology of Perishable Plant Products. Van Nostrand, New York, NY.

Lopez-Galvez, G., M.E. Saltveit, and M. Cantwell. 1996. Wound-induced phenylalanine ammonia lyase activity: factors affecting its induction and correlation with the quality of minimally processed lettuce. Postharv. Biol. Technol. 9:223-233.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation and Storage of Fruits and Vegetables, vol. 1, Vegetables and Melon, 2nd ed., pp. 1-13. AVI Publishing Company, Westport, CT.

Ryall A.L., and W.T. Pentzer. 1974. Handling, Transportation and Storage of Fruits and Vegetables, vol. 2, Fruits, pp. 4-12. AVI Publishing Company, Westport, CT.

Saltveit, M.E. 1996. Physical and physiological changes in minimally processed fruits and vegetables. *In* F.A. Tomás-Barberán, ed., Phytochemistry of Fruit and Vegetables, pp. 205-220. Oxford University Press, New York, NY.

Tomás-Barberán, F.A., J. Loaiza-Velarde, A. Bonfanti, and M.E. Saltveit. 1997. Early wound- and ethylene-induced changes in phenylpropanoid metabolism in harvested lettuce. J. Amer. Soc. Hort. Sci. 122(3):399-404.

Wills, R.H.H., T.H. Lee, D. Graham, et al. 1981. Postharvest - An Introduction to the Physiology and Handling of Fruit and Vegetables. AVI Publishing Company, Westport, CT.

Ethylene Effects

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Introduction

Ethylene (C_2H_4) is a simple, naturally occurring organic molecule that is a colorless gas at biological temperatures. The following is a list of biological attributes of ethylene:

- It is a colorless gas at biological temperatures.
- It is a naturally occurring organic compound.
- It readily diffuses from tissue.
- It is produced from methionine via aminocyclopropane carboxylate (ACC) by a highly regulated metabolic pathway.
- Key enzymes are ACC synthase and ACC oxidase.
- C_2H_4 synthesis is inhibited by C_2H_4 in vegetative and immature reproductive tissue.
- C_2H_4 synthesis is promoted (autocatalytic) by C_2H_4 in mature reproductive climacteric tissue.
- It is effective at ppm and ppb concentrations (1 ppm = 6.5 x 10^{-9} M at 25 °C).
- It requires O_2 to be synthesized, and O_2 and low levels of CO_2 to be active.

Many biotic and abiotic sources contribute to the presence of C_2H_4 in the postharvest environment. Ripening and diseased plant tissues are a significant source of C_2H_4, as are industrial sources, the most prominent ones being internal combustion engines and fires.

Ethylene is biologically active at very low concentrations measured in the ppm and ppb range. Most plants synthesize small amounts of C_2H_4 that appear to coordinate growth and development. Because it is a gas, C_2H_4 readily diffuses from sites of production, and continuous synthesis is needed to maintain biologically active levels in the tissues. Barriers to diffusive loss include not only the commodity's epidermis but also postharvest coatings and packaging. Under biotic or abiotic stress or during climacteric ripening, C_2H_4 production can increase dramatically, and emanations from stimulated tissue can accumulate in packages or storerooms and produce unwanted effects in adjacent tissue. Other molecules with specific configurations can mimic C_2H_4 but are less effective. For example, C_2H_4 analogs propylene (C_3H_6) and acetylene (C_2H_2) require 100- and 2,700-fold, respectively, the concentration of C_2H_4 to elicit the same effect.

Plants produce C_2H_4 through an actively regulated biosynthetic pathway in which the amino acid methionine is converted to ACC (1-aminocyclopropane-1-carboxylic acid) and then to C_2H_4 through a series of biochemical reactions. O_2 is required for the synthesis of C_2H_4 and both O_2 and CO_2 are required for its biological activity. Each reaction in the synthesis and action of C_2H_4 involves a biological catalyst, an enzyme that focuses the reaction into producing the next specific chemical for that pathway. Enzyme activity is regulated either through its synthesis and/or destruction, or by interactions with substrates and products. These interactions can create a positive or a negative feedback of C_2H_4 on its synthesis (figure 1).

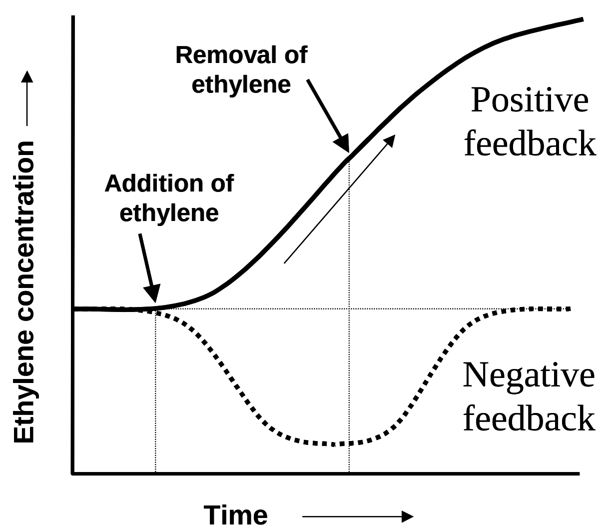

Figure 1. Effect of adding and removing ethylene from the atmosphere surrounding tissues that respond with a positive (ethylene promotes its own synthesis) or negative (ethylene inhibits its own synthesis) feedback. Modified from Saltveit (1999).

In vegetative tissue and in nonclimacteric and immature climacteric fruit tissue, C_2H_4 suppresses its own synthesis, and in ripening climacteric fruit C_2H_4 enhances its own synthesis. This positive feedback of C_2H_4 on C_2H_4 synthesis is called autocatalytic C_2H_4 production. Plants respond to C_2H_4 in a number of ways.

Ethylene stimulates the following:

- Synthesis of C_2H_4 in ripening climacteric fruit
- Ripening of climacteric fruit and some nonclimacteric fruit
- Anthocyanin synthesis in ripening fruit
- Chlorophyll destruction and yellowing (for example, degreening of citrus)
- Seed germination
- Adventitious root formation
- Respiration and phenylpropanoid metabolism
- Flower initiation in bromeliads (for example, pineapple)
- Abscission and senescence

Ethylene inhibits the following:

- Ethylene synthesis in vegetative tissue and nonclimacteric fruit
- Flowering and flower development in most plants
- Auxin transport
- Shoot and root elongation; that is, growth

Depending on a number of variables, C_2H_4 has both beneficial and deleterious effects on harvested fruits, vegetables, and ornamentals.

Beneficial effects:

- Promotes color development in fruit
- Stimulates ripening of climacteric fruit
- Promotes degreening of citrus
- Stimulates dehiscence in nuts
- Alters sex expression (Cucurbitaceae)
- Promotes flowering (for example, in pineapple)
- Reduces lodging of cereals

Detrimental effects:

- Accelerates senescence
- Enhances excessive softening of fruits
- Stimulates chlorophyll loss (for example, yellowing)
- Stimulates sprouting of potato
- Promotes discoloration (for example, browning)
- Promotes abscission of leaves and flowers
- Stimulates phenylpropanoid metabolism

Often an C_2H_4-induced change in one commodity is viewed as beneficial, while the same change in another commodity is viewed as detrimental. For example, C_2H_4 is used to promote ripening of bananas, melons, and tomatoes; degreening of oranges; and synthesis of pigments in apples. Yet the same changes are unwanted when C_2H_4 promotes over-ripening of fruit, yellowing of broccoli, development of brown russet spot lesions in lettuce, and senescence of flowers. Because of these diverse and often opposite effects of C_2H_4, controlling its action in plants is of great economic importance to producers, wholesalers, retailers, and consumers of fresh fruits, vegetables, and ornamentals.

In most vegetative tissues, C_2H_4 is only produced in biologically active amounts during early stages of development or in response to biotic or abiotic stress. Mutant plants that do not respond to C_2H_4 often grow normally, with only a few insignificant alterations in development. Most of the effects of C_2H_4 on vegetative tissue are therefore the result of the tissue's response to a stress or to the intentional or unintentional exposure of tissue to active levels of C_2H_4.

In contrast to its effects on vegetative tissue, biologically produced C_2H_4 plays a crucial role in the development of reproductive tissues and in the ripening of certain climacteric fruit. The rates of C_2H_4 production and its internal concentration often vary by orders of magnitude during early stages of development and during the initiation and development of reproductive structures. Increased rates of C_2H_4 production are especially pronounced during the ripening of climacteric fruit such as apples, avocados, bananas, melons, pears, and tomatoes. In these fruit, the autocatalytic production of C_2H_4 heralds the onset of ripening and is required for many of the reactions associated with ripening to continue. See section "Summary of Respiration and Ethylene Production Rates" in the Introduction of this handbook.

Once internal C_2H_4 exceeds a level characteristic for the species, tissue, and developmental stage, the further production of C_2H_4 is stimulated by presence of previously produced C_2H_4. In this way, autocatalytic positive feedback can increase rates of C_2H_4 production and internal concentration of C_2H_4 by 1,000-fold during ripening. External application of C_2H_4 can promote the ripening of climacteric fruit—for example, avocado, banana, honeydew, and tomato—and beneficial quality changes in nonclimacteric fruit; for example, degreening of lemon and orange. Once autocatalytic C_2H_4 production has started in climacteric fruit, lowering its external concentration has an insignificant effect on its internal levels, rates of production, or action.

Ethylene is an important plant growth regulator that has pronounced effects on many aspects of plant growth and development. Regulating its effectiveness is commercially important for many crops. Controlling its effectiveness can mean either increasing its beneficial effects or decreasing its detrimental effects. There are a number of ways to accomplish either objective.

<u>Reducing Effectiveness of Ethylene</u>
Use C_2H_4-tolerant cultivars
Keep atmosphere free of C_2H_4
Maintain at coldest possible temperature
Store under CA or MA or in MAP
Minimize time between exposure and use

<u>Increasing Effectiveness of Ethylene</u>
Use C_2H_4-sensitive cultivars
Keep an active level of C_2H_4 in the air
Maintain at optimum temperature
Store under adequate levels of O_2 and CO_2
Allow sufficient time for plant response

Ethylene Interactions in Plants

There are some significant interactions between the plant and its environment that are important in understanding how to control biological activity of C_2H_4 in plants (figure 2).

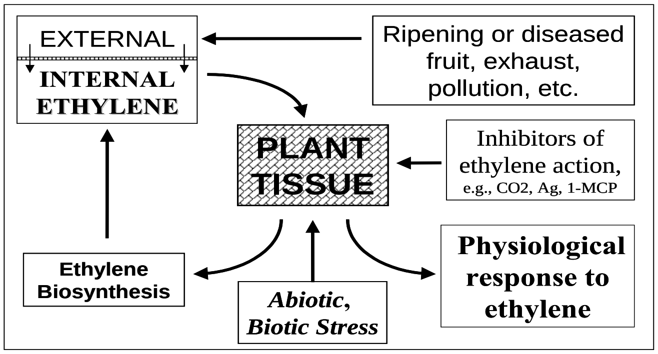

Figure 2. Interactions among a plant and ethylene in its environment (Saltveit 1999).

Ethylene in the atmosphere can have a direct effect on plant tissue by raising the internal concentration to an active level. Sources of atmospheric C_2H_4 include exhaust from trucks and forklifts, pollution from industrial activity and from the burning of fuels, and biosynthesis by diseased plants or ripening fruit. In some cases, C_2H_4, whether applied as a gas or as an C_2H_4-releasing compound such as ethephon, is intentionally added to the plant's environment to stimulate desirable changes. The changes can include promotion of flowering in pineapple; ripening of avocado, banana, melon, and tomato fruit; degreening of citrus; altering sex expression in cucurbits; defoliation; and promotion of latex secretion by rubber trees.

The activity of C_2H_4 inside plants is regulated not only by the absolute level of C_2H_4 but also by the responsiveness of tissues and the presence of CO_2, the natural antagonist of C_2H_4 action. The response of plants to C_2H_4, therefore, depends on a number of factors, only one of which is the rate of C_2H_4 production by the plant. Tissue sensitivity depends on species, cultivar, cultural practices, and stage of development.

Prior and current stresses have a significant effect on modulating the effect of C_2H_4. For example, wounding stimulates C_2H_4 production, as well as a host of plant defense responses such as increased phenylpropanoid metabolism. Some of these responses involve C_2H_4, while others do not. Increased phenolic metabolism greatly increases the susceptibility of some crops like lettuce to develop browning—for example, russet spotting—when exposed to C_2H_4 and/or mechanical injury.

The effect of tissue susceptibility is most clearly seen in fruit tissue. Immature climacteric fruit respond to C_2H_4 with increased respiration and reduced C_2H_4 production. Once the tissue has reached a certain stage of maturity, however, C_2H_4 not only promotes increased respiration but also increased C_2H_4 synthesis.

Controlling the effectiveness of C_2H_4 does not always involve a reduction in its activity. There are many beneficial effects of C_2H_4 that can be enhanced (see above). The techniques used to increase the effectiveness of C_2H_4 are almost the mirror image of techniques used to reduce its effectiveness.

Ethylene action can be enhanced by using cultivars that are sensitive and respond uniformly to C_2H_4 rather than cultivars that are C_2H_4 insensitive. An effective concentration of C_2H_4 should be maintained around the tissue for a sufficient time to elicit the full response. However, since the response to C_2H_4 is log-linear (a log increase in C_2H_4 concentration results in a linear increase in the response), there is an extremely large range over which the concentrations are effective. The application of C_2H_4 must be at the proper stage of development and at the proper temperature for the desired effects to be induced. Ethephon and similar C_2H_4-releasing chemicals permit the commercial application of C_2H_4 in the field. After harvest, C_2H_4 gas, either from compressed gas cylinders or catalytically generated from alcohol, can be used in enclosed storage rooms.

Controlling Ethylene Action

There are roughly three ways to control the action of C_2H_4 in plants. The first is to prevent the plant from being exposed to biologically active levels of C_2H_4. The second is to prevent the plant tissue from perceiving the C_2H_4 that is in its surrounding atmosphere or that is being produced by the tissue. The third is to prevent the plant from responding to the perceived C_2H_4 by controlling exposure to C_2H_4.

Preventing Exposure to Ethylene

The following should be done to prevent exposure to C_2H_4:

- Keep the air around the commodity C_2H_4 free.
- Use fresh, C_2H_4-free air from outside.
- Scrub C_2H_4 from the storage atmosphere.
- Use sachets of C_2H_4 absorbers inside packages to reduce levels.
- Segregate C_2H_4-producing commodities from C_2H_4-sensitive ones.
- Keep exposure to a minimum (in terms of both duration and level).
- Inhibit C_2H_4 synthesis (AVG, ACC synthase, low O_2, ACC oxidase).

Risk of exposure to C_2H_4 is usually not much of a problem in the field because the levels of C_2H_4 found even in polluted air rarely reach biologically active levels. However, in greenhouses, cold-storage rooms, and transportation vehicles, C_2H_4 can frequently accumulate to reach biologically active levels. Ethylene found in these enclosed spaces comes from varied sources, and the two most prominent sources are diseased, stressed, or ripening plant tissue and the incomplete combustion of organic fuels.

With proper ventilation of enclosed spaces and with persistent attention to the condition of adjacent plants and the operation of heaters and gas-powered forklifts, C_2H_4 can be kept below biologically active levels. Sometimes the C_2H_4 that we are concerned with comes from the plant itself. Application of inhibitors of C_2H_4 biosynthesis, such as AVG and AOA, to the tissue before or after harvest can significantly reduce this source of C_2H_4 exposure. For example, tissue can be prevented from making either stress or autocatalytic C_2H_4 by blocking the biosynthetic pathway for C_2H_4 synthesis. If exposure cannot be prevented or has already occurred, then both the duration of exposure and the level of C_2H_4 in the atmosphere should be kept as low as possible.

Preventing Perception of Ethylene

If significant amounts of C_2H_4 are in the immediate environment, certain methods can be used to block the perception of C_2H_4 by the plant. Here are some possible methods:

- Store at the coldest possible temperature.
- Use inhibitor of C_2H_4 perception: CO_2, silver (for example, silver thiosulfate), and 1-methyl cyclopropene (1-MCP).
- Use C_2H_4-insensitive cultivars.
- Interrupt the C_2H_4-induced signal.

Since perception is a metabolic process, holding the tissue at the lowest possible temperature will effectively reduce perception. Specific chemical inhibitors can also be used that directly interfere with the perception event.

A gaseous inhibitor like CO_2 or 1-MCP can be introduced into the atmosphere. The tissue can be dipped or fed a nonvolatile inhibitor such as silver thiosulfate, but this treatment is limited to nonfood crops. Ethylene-resistant cultivars can be selected or the tissue genetically engineered to lack the necessary biochemical receptors for ethylene or the signal pathway necessary to transduce the signal into a physiological event.

Even after the molecular perception event has occurred, blocking the transduced signal will effectively prevent perception. However, effective methods to do this will require a far greater understanding of the signal pathway than is currently available.

Preventing Response by the Plant

The third way to control C_2H_4 is to prevent the plant from responding to the perceived C_2H_4. This can be done by interfering with the metabolic machinery that is induced by exposure to C_2H_4, by methods such as the following:

- Store at coldest possible temperature.
- Store under CA or MA or in MAP.
- Inhibit or reduce specific enzyme activities using chemical inhibitors (for example, AIP) or genetic engineering (for example, antisense or other gene knockout techniques).
- Divert protein synthesis—by heat-shock, for example.
- Minimize time before use (for example, consumption).

Since all the effects of C_2H_4 on plants that we are interested in involve metabolic changes, reducing the rate of metabolism by lowering the temperature, withholding a vital reactant (for example, O_2), or by inhibiting a specific enzyme (for example, with a chemical or through genetic engineering) will prevent a response to C_2H_4. For example, ripening promoted by C_2H_4 often entails tissue softening that significantly reduces shelf-life. Using antisense technology to reduce the activity of enzymes involved in tissue softening has produced fruit that remain firmer longer. Ethylene also promotes phenylpropanoid metabolism in many tissues that use stress-produced C_2H_4 as a signal to induce defense mechanisms. Interfering with synthesis or activity of phenylalanine ammonia lyase (PAL, the first enzyme in phenolic metabolism) with chemical inhibitors or heat treatment eliminates tissue response to C_2H_4, preventing development of postharvest disorders.

Application of Ethylene

The quality of some fruits is increased when they are harvested at a mature but unripe stage that can withstand the rigors and duration of transport and then treated with C_2H_4 to promote ripening before sale. These fruit include avocados, bananas, honeydew melons, lemons, oranges, and tomatoes.

An effective atmosphere of 100 to 150 µL L^{-1} C_2H_4 in air can be produced by a number of methods. The "shot" method introduces a relative large amount of gaseous C_2H_4 into a ripening room by metering C_2H_4 from compressed gas cylinders. Ethylene in air mixtures between 3.1% and 32% are explosive. While these concentrations are more than 200-fold higher than recommended, they have been reached when metering equipment has malfunctioned. Use of compressed gas containing around 3.1% C_2H_4 in N_2 ("banana gas"), eliminates this problem.

Catalytic converters are instruments that use a heated metal catalyst to convert alcohol into C_2H_4. They deliver a continuous flow of low C_2H_4 into the storage room. Ethylene can also be applied in aqueous form from decomposition of compounds such as Ethrel. While stable at acidic pH, Ethrel quickly breaks down to C_2H_4 as temperature and pH increase. Field application is approved for many food crops, but postharvest application is not approved.

Treatment with C_2H_4 stimulates many metabolic pathways, including respiration. Oxygen use is increased, as is the production of CO_2 and heat. Rooms designed to hold produce being exposed to C_2H_4 must be designed with extra air-moving capacity to ensure that an optimal ripening environment is maintained around the crop. Exposure to C_2H_4 must be uniform throughout the room and within packages. Heat of respiration and excessive CO_2 must be removed to maintain a proper environment. Loss of water by the crop will be increased by the rise in respiratory heat production. Maintaining a high RH can lessen water loss, but too much water vapor can decrease the strength of cardboard boxes and promote pathogen growth. Judicious maintenance of proper ripening environments will ensure production of high-quality fruit. Care must be exercised in venting and opening ripening rooms to prevent release of sufficient amounts of C_2H_4 to adversely affect other commodities stored in the same warehouse.

Conclusion

Ethylene can be both beneficial and detrimental to horticultural crops in storage. Practical uses for C_2H_4 and treatments to minimize its adverse effects have slowly accumulated over almost a century of study. The three general methods used to modulate C_2H_4 activity involve controlling exposure, altering perception, and varying the response of the tissue. An understanding of ethylene's synthetic pathway and mode of action has greatly improved the ability of postharvest physiologists to devise treatments and storage conditions to control C_2H_4 during the commercial storage and handling of horticultural crops. Simple methods like ventilation and temperature management can be combined with more sophisticated treatments like MAP and inhibitors of specific induced enzymes to provide conditions that optimize both storage life and product quality.

References

Saltveit, M.E. 1999. Effect of ethylene on quality of fresh fruits and vegetables. Postharv. Biol. Technol. 15:279-292.

Further Reading

Abeles, F.B., P.W. Morgan, and M.E. Saltveit. 1992. Ethylene in Plant Biology, 2nd ed. Academic Press, New York, NY.

Kader, A.A. 1985. Ethylene-induced senescence and physiological disorders in harvested horticultural crops. HortScience 20:54-57.

Lelievre, J.M., A. Latche, B. Jones, et al. 1997. Ethylene and fruit ripening. Physiol. Plant. 101:727-739.

Saltveit, M.E., S.F. Yang, and W.T. Kim. 1998. Discovery of ethylene. *In* S.D. Kung and S.F. Yang, eds., Discoveries in Plant Biology, vol. 1, pp. 47-70. World Sci. Pub. Co., Singapore.

Watada, A.E. 1986. Effects of ethylene on the quality of fruits and vegetables. Food Technol. 40:82-85.

Weichmann, J. 1987. Postharvest Physiology of Vegetables. Marcel Dekker, New York, NY.

1-Methylcyclopropene (1-MCP)

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Introduction

The plant hormone ethylene affects a wide range of physiological processes in horticultural crops, including abscission, senescence and ripening, chlorophyll loss, softening, physiological disorders, sprouting, isocoumarin synthesis, lignification, discoloration (browning), decay, and stimulation of defense systems (Saltveit 1999). Depending on the desired use of the produce, these effects can be positive or negative. However, most postharvest handling is focused on controlling ethylene production or action. Among the available methods, chemical control of ethylene biosynthesis by aminoethoxyvinylglycine (AVG) and inhibition of its action by 1-methylcyclopropene (1-MCP) have become useful tools for the horticulture industry as they seek to maintain quality of produce after harvest (Venburg et al. 2008, Watkins 2008c).

1-MCP belongs to a class of compounds known as cyclopropenes. The discovery that cyclopropenes inhibit ethylene perception by competitively binding to ethylene receptors represented a major breakthrough in controlling ethylene responses of horticultural products (Blankenship and Dole 2003). The process of discovery of the effects of cyclopropenes and their proposed method of action has been described (Sisler and Serek 2003, Sisler 2006).

1-MCP has several characteristics that make it conveniently useful by the fresh produce industry. It is a gaseous molecule that is easily applied, has an excellent safety profile, leaves no residues in or on treated produce, and is active at very low concentrations (parts per billion).

Of the cyclopropenes, 1-MCP proved to be extremely active, but it is unstable in the liquid phase. A process has been developed in which 1-MCP is complexed with α-cyclodextrin, maintaining the stability of 1-MCP. After application, 1-MCP is released from the complex to expose horticultural products to the molecule.

When applied during the preharvest period, 1-MCP has the useful effects of delaying fruit drop, slowing fruit maturation and ripening, and maintaining postharvest quality (McArtney et al. 2008, Watkins 2010, Watkins et al. 2010). Produce must be exposed to 1-MCP at an effective rate and for a sufficiently long time to elicit physiological responses. In essence, this means applying a higher preharvest concentration of 1-MCP than that used for postharvest application, while ensuring stability of the formulation without inducing phytotoxicity.

Some reports on postharvest dipping of fruit into aqueous 1-MCP have been published (Choi et al. 2008), but this method is not currently used commercially.

Registration

The U.S. Environmental Protection Agency (EPA) approved use of 1-MCP on floriculture and ornamental products in 1999 and on edible food products in 2002. By 2011, more than 40 countries had approved use of 1-MCP. It is registered for use on a wide variety of fruits and vegetables including apple, apricot, Asian pear, avocado, banana, broccoli, calabrese, cauliflower, Brussels sprouts, cabbage, carrot, cherimoya, cucumber, date, guava, kiwifruit, lime, mango, melon, nectarine, papaya, paprika, peach, pear, pepper, persimmon, pineapple, plantain, plum, plumcot, squash, tomato, and many ornamentals. The specific products for which 1-MCP is registered in each country vary greatly according to the importance of the crop in that country. For example, 1-MCP can be applied to tulip bulbs in the Netherlands.

Recently, 1-MCP formulations have been approved by the EPA and other regulatory authorities for preharvest application.

Semicommercial trials have been carried out at several locations in the United States, Argentina, Brazil, Canada, Chile, New Zealand, and South Africa.

Effects of 1-MCP on Fruits, Vegetables, and Ornamental Products

The availability of 1-MCP has provided outstanding opportunities for researchers to investigate both ethylene-dependent and ethylene-independent events during ripening and senescence, in addition to developing practical uses for 1-MCP. Studies have focused on the effects of 1-MCP on quality of horticultural crops, specific postharvest issues such as handling and packaging, physiological and biochemical responses, and storage disorders. A number of detailed reviews on the effects of 1-MCP have been published (Blankenship and Dole 2003, Serek et al. 2006, Watkins 2006,2007, Huber 2008, Watkins 2008a,2008b,2010). These reviews report on the use of an extensive range in 1-MCP concentration, depending on the responsiveness of the product to the molecule.

Ripening and Senescence. 1-MCP affects many ripening and senescence processes, including pigments, softening and cell wall metabolism, flavor and aroma, and nutritional properties (Watkins 2006,2008b, Serek et al. 2006). These processes are affected to varying degrees in both nonclimacteric and climacteric products. The range of responses reflects the enormous diversity of these crops in terms of both inherent diversity and morphological derivation (Huber 2008).

Several generalizations can be made about responses of crops to 1-MCP:

- Genotype, cultivar, and maturity effects can be highly variable, but responses to 1-MCP are typically “concentration × exposure time” dependent.
- Most if not all climacteric fruit are affected by 1-MCP treatment, but the capacity to interrupt the progression of ripening, once initiated, varies by fruit and by attributes studied.
- Nonclimacteric fruit can also respond to 1-MCP; such effects are providing interesting insights about ethylene-dependent and ethylene-independent events during ripening.
- Treated fruit are firmer, slower to soften, slower to change peel color and they develop aroma and flavor slower, but if 1-MCP concentrations and exposure periods are appropriate for the product, the final quality attained in the ripened fruit is similar to that of untreated product.
- Rate of loss of nutritionally important compounds such as vitamin C are usually reduced in 1-MCP-treated fruits and vegetables, and effects on phenolic compounds are minor.

Physiological Disorders. An important area of postharvest responses to 1-MCP is its effects on physiological disorders (Watkins 2007,2008a,2008b). These disorders can be divided into categories:

- Ethylene-induced disorders. Examples include russet spotting of lettuce and isocoumarin accumulation in carrots (Fan and Mattheis 2000a), lignification of asparagus (Liu and Jiang 2006), and water-soaking of watermelons (Mao et al. 2004). These disorders are preventable by inhibition of ethylene perception.
- Senescence-related disorders. Examples include senescent breakdown of apples (Moran and McManus 2005), senescent scald and breakdown of pears (Ekman et al. 2004), and yellowing of broccoli (Fan and Mattheis 2000b). These disorders are also prevented by inhibition of ethylene perception.
- Controlled atmosphere-related storage disorders. 1-MCP can increase susceptibility of apple fruit to carbon dioxide injuries. Incidence of both internal and external forms of injury is increased by 1-MCP (DeEll et al. 2003, Fawbush et al. 2008, Argenta et al. 2010).

- Chilling-related disorders that are increased by inhibition of ethylene perception. Examples include woolliness and internal breakdown of peaches and nectarines (Dong et al. 2001), chilling injury of citrus and bananas (Porat et al. 1999, Jiang et al. 2004), and flesh browning of the 'Empire' apple (Watkins 2008b).
- Chilling-related disorders that are decreased by inhibition of ethylene perception. Examples include superficial scald; brown core (coreflush) and soft scald of apples and pears (Fan et al. 1999); internal flesh browning of avocados and pineapples (Selvarajah et al. 2001, Pesis et al. 2002); and chilling injury of bamboo shoots (Luo et al. 2008), melons (Gal et al. 2006), and persimmon (Luo 2007).

Pathological Disorders: Disease incidence can be increased, decreased, or unaffected by 1-MCP, depending on the product, although results are not always consistent because of the complex interaction between host, pathogen, and environment (Watkins 2008b). In some instances, disease incidence can be lower because the beneficial effects of 1-MCP on skin integrity and flesh firmness result in greater resistance to infection. However, ethylene is necessary for defense systems in other plant systems (Marcos et al. 2005).

Application

For postharvest use of 1-MCP on both ornamental plants and edible food products, material must be treated in an enclosed area, such as a storage room, greenhouse, trailer, or shipping container. Leakage of 1-MCP from the treatment area can reduce its concentration and therefore effectiveness. *1-MCP can only be applied by authorized service providers, not by commercial storage operators.* Testing of rooms for leakage, certification of product quality, and application of the proper 1-MCP concentration for the product maximize the benefits of treatment.

The apple has been an excellent crop for use of 1-MCP, which is used extensively around the world to maintain quality through the whole marketing chain from storage to consumer (Watkins 2008b). Applications rates for apples vary from 625 to 1,000 nL L^{-1}, depending on the country of registration. The major benefit of 1-MCP to the grower is more time to get high quality produce through marketing channels to the consumer. The successful use of 1-MCP on apples is largely associated with varieties for which maintenance of at-harvest quality and only moderate softening to a crisp texture is desirable.

In contrast, challenges exist for effective use of 1-MCP on fruits that ripen to a melting texture or have major color change. For example, failure to ripen normally has been shown in avocado, banana, pear, and tomato after fruit were treated at an early ripening stage or if the applied 1-MCP concentration was too high (Golding et al. 1998, Mir et al. 2004, Hurr et al. 2005, Bai et al. 2006). Fruit must ripen uniformly to quality characteristics (texture, flavor, aroma, color) that are expected by the consumer. Despite the challenges, successful 1-MCP treatment of avocados, bananas, melons, persimmons, and tomatoes has resulted from careful attenuation of 1-MCP concentrations or selecting fruit at the appropriate ripening stage at harvest. Research on reinitiating ripening after 1-MCP treatment in extremely sensitive fruit like pear is ongoing (Bai et al. 2006, Chiriboga et al. 2011, Villalobos-Acuna et al. 2011). A considerable amount of research on crops other than apple is proprietary and therefore not yet in the public domain.

References

Argenta, L.C., J.P. Mattheis, and X.T. Fan. 2010. Interactive effects of CA storage, 1-methylcyclopropene and methyl jasmonate on quality of apple fruit. Acta Hort. 857:259-266.

Bai, J., J.P. Mattheis, and N. Reed. 2006. Re-initiating softening ability of 1-methylcyclopropene-treated ‘Bartlett’ and ‘d’Anjou’ pears after regular air or controlled atmosphere storage. J. Hort. Sci. Biotechnol. 81:959-964.

Blankenship, S.M., and J.M. Dole. 2003. 1-Methylcyclopropene: a review. Postharv. Biol. Technol. 28:1-25.

Chiriboga, M.A., W.C. Schotsmans, C. Larrigaudiere, et al. 2011. How to prevent ripening blockage in 1-MCP-treated ‘Conference’ pears. J. Sci. Food Agric. 91:1781-1788.

Choi, S.T., P. Tsouvaltzis, C.I. Lim, and D.J. Huber. 2008. Suppression of ripening and induction of asynchronous ripening in tomato and avocado fruits subjected to complete or partial exposure to aqueous solutions of 1-methylcyclopropene. Postharv. Biol. Technol. 48:206-214.

DeEll, J.R., D.P. Murr, L. Wiley, and M.D. Porteous. 2003. 1-Methylcyclopropene (1-MCP) increases CO_2 injury in apples. Acta Hort. 600:277-280.

Dong, L., H.W. Zhou, L. Sonego, et al. 2001. Ethylene involvement in the cold storage disorder of ‘Flavortop’ nectarine. Postharv. Biol. Technol. 23:105-115.

Ekman, J.H., M. Clayton, W.V. Biasi, and E.J. Mitcham. 2004. Interactions between 1-MCP concentration, treatment interval and storage time for ‘Bartlett’ pears. Postharv. Biol. Technol. 31:127-136.

Fan, X.T., and J.P. Mattheis. 2000a. Reduction of ethylene-induced physiological disorders of carrots and iceberg lettuce by 1-methylcyclopropene. HortScience 35:1312-1314.

Fan, X.T., and J.P. Mattheis. 2000b. Yellowing of broccoli in storage is reduced by 1-methylcyclopropene. HortScience 35:885-887.

Fan, X.T., J.P. Mattheis, and S. Blankenship. 1999. Development of apple superficial scald, soft scald, core flush, and greasiness is reduced by MCP. J. Agric. Food Chem. 47:3063-3068.

Fawbush, F., J.F. Nock, and C.B. Watkins. 2008. External carbon dioxide injury and 1-methylcyclopropene (1-MCP) in the ‘Empire’ apple. Postharv. Biol. Technol. 48:92-98.

Gal, S., S. Alkalai-Tuvia, Y. Elkind, and E. Fallik. 2006. Influence of different concentrations of 1-methylcyclopropene and times of exposure on the quality of ‘Galia’-type melon harvested at different stages of maturity. J. Hort. Sci. Biotechnol. 81:975-982.

Golding, J.B., D. Shearer, S.G. Wyllie, and W.B. McGlasson. 1998. Application of 1-MCP and propylene to identify ethylene-dependent ripening processes in mature banana fruit. Postharv. Biol. Technol. 14:87-98.

Huber, D.J. 2008. Suppression of ethylene responses through application of 1-methylcyclopropene: a powerful tool for elucidating ripening and senescence mechanisms in climacteric and nonclimacteric fruits and vegetables. HortScience 43:106-111.

Hurr, B.M., D.J. Huber, and J.H. Lee. 2005. Differential responses in color changes and softening of ‘Florida 47’ tomato fruit treated at green and advanced ripening stages with the ethylene antagonist 1-methylcyclopropene. HortTechnology 15:617-622.

Jiang, Y.M., D.C. Joyce, W.B. Jiang, and W.J. Lu. 2004. Effects of chilling temperatures on ethylene binding by banana fruit. Plant Growth Regul. 43:109-115.

Liu, Z.Y., and W.B. Jiang. 2006. Lignin deposition and effect of postharvest treatment on lignification of green asparagus (*Asparagus officinalis* L.). Plant Growth Regul. 48:187-193.

Luo, Z.S. 2007. Effect of 1-methylcyclopropene on ripening of postharvest persimmon (*Diospyros kaki* L.) fruit. LWT—Food Sci. Technol. 40:285-291.

Luo, Z.S., X.L. Xu, and B.F. Yan. 2008. Use of 1-methylcyclopropene for alleviating chilling injury and lignification of bamboo shoot *(Phyllostachys praecox* f. *prevernalis)* during cold storage. J. Sci. Food Agric. 88:151-157.

Mao, L.C., Y. Karakurt, and D.J. Huber. 2004. Incidence of water-soaking and phospholipid catabolism in ripe watermelon *(Citrullus lanatus)* fruit: induction by ethylene and prophylactic effects of 1-methylcyclopropene. Postharv. Biol. Technol. 33:1-9.

Marcos, J.F., L. Gonzalez-Candelas, and L. Zacarias. 2005. Involvement of ethylene biosynthesis and perception in the susceptibility of citrus fruits to *Penicillium digitatum* infection and the accumulation of defence-related mRNAs. J. Exp. Bot. 56:2183-2193.

McArtney, S.J., J.D. Obermiller, J.R. Schupp, et al. 2008. Preharvest 1-methylcyclopropene delays fruit maturity and reduces softening and superficial scald of apples during long-term storage. HortScience 43:366-371.

Mir, N., M. Canoles, R. Beaudry, et al. 2004. Inhibiting tomato ripening with 1-methylcyclopropene. J. Amer. Soc. Hort. Sci. 129:112-120.

Moran, R.E., and P. McManus. 2005. Firmness retention, and prevention of coreline browning and senescence in ‘Macoun’ apples with 1-methylcyclopropene. HortScience 40:161-163.

Pesis, E., M. Ackerman, R. Ben-Arie, et al. 2002. Ethylene involvement in chilling injury symptoms of avocado during cold storage. Postharv. Biol. Technol. 24:171-181.

Porat, R., B. Weiss, L. Cohen, et al. 1999. Effects of ethylene and 1-methylcyclopropene on the postharvest qualities of ‘Shamouti’ oranges. Postharv. Biol. Technol. 15:155-163.

Saltveit, M.E. 1999. Effect of ethylene on quality of fresh fruits and vegetables. Postharv. Biol. Technol. 15:279-292.

Selvarajah, S., A.D. Bauchot, and P. John. 2001. Internal browning in cold-stored pineapples is suppressed by a postharvest application of 1-methylcyclopropene. Postharv. Biol. Technol. 23:167-170.

Serek, M., E.J. Woltering, E.C. Sisler, et al. 2006. Controlling ethylene responses in flowers at the receptor level. Biotechnol. Adv. 24:368-381.

Sisler, E.C. 2006. The discovery and development of compounds counteracting ethylene at the receptor level. Biotechnol. Adv. 24:357-367.

Sisler, E.C., and M. Serek. 2003. Compounds interacting with the ethylene receptor in plants. Plant Biol. 5:473-480.

Venburg, G.D., R. Hopkins, J. Retamales, et al. 2008. Recent developments in AVG research. Acta Hort. 796:43-49.

Villalobos-Acuna, M.G.V., W.V. Biasi, E..J. Mitcham, and D. Holcroft. 2011. Fruit temperature and ethylene modulate 1-MCP response in ‘Bartlett’ pears. Postharv. Biol. Technol. 60:17-23.

Watkins, C.B. 2006. The use of 1-methylcyclopropene (1-MCP) on fruits and vegetables. Biotechnol. Adv. 24:389-409.

Watkins, C.B. 2007. The effect of 1-MCP on the development of physiological storage disorders in horticultural crops. Stewart Postharvest Rev. vol. 3, article 11.

Watkins, C.B. 2008a. Overview of 1-methylcyclopropene trials and uses for edible horticultural crops. HortScience 43:86-94.

Watkins, C.B. 2008b. Postharvest effects on the quality of horticultural products: using 1-MCP to understand the effects of ethylene on ripening and senescence processes. Acta Hort. 768:19-32.

Watkins, C.B. 2008c. Postharvest ripening regulation and innovation in storage technology. Acta Hort. 796:51-58.

Watkins, C.B. 2010. Managing physiological processes in fruits and vegetables with inhibitors of ethylene biosynthesis and perception. Acta Hort. 880:301-310.

Watkins, C.B., H. James, J.F. Nock, et al. 2010. Preharvest application of 1-methylcyclopropene (1-MCP) to control fruit drop of apples, and its effects on postharvest quality. Acta Hort. 877:365-374.

Texture

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Introduction

Texture is a quality attribute critical in determining the acceptability of fruits and vegetables. It is convenient to define quality as the composite of intrinsic characteristics that differentiate units of the commodity—individual pieces of the product—and to think of acceptability as consumers' perceptions of and reactions to those characteristics. Though the term is widely used, texture is not a single, well-defined attribute. It is a collective term that encompasses the structural and mechanical properties of a food and the sensory perception of that food in the hand or mouth. Though some definitions of texture are restricted to only sensory attributes or to sensory attributes and mechanical properties directly related to them, the term texture is sometimes extended to include some mechanical properties of commercial interest that may not be of direct interest to the consumer, such as resistance to mechanical damage. In this review, we will use the term texture in the broadest sense.

Many terms are used to describe sensory texture of fruits or vegetables, including hard, firm, soft, crisp, limp, mealy, tough, leathery, melting, gritty, wooly, stringy, dry, and juicy. There are no accepted instrumental methods for measuring these attributes. In fact, there is some disagreement among sensory, horticultural, and engineering uses of certain terms, particularly firmness, which is discussed below.

Textural attributes of fruits and vegetables are related to the structural, physiological, and biochemical characteristics of the living cells; their changes over time; and their alteration by processes such as cooking or freezing. The continuous physiological changes in living cells plus the inherent variability among individual units of the commodity make the assessment of fruit or vegetable texture difficult. Because of their continuous change, textural measurements are often relevant only at the time of evaluation; that is, they usually cannot be used to predict condition much later in the storage period or marketing chain.

Physiological Basis of Texture

To understand the texture of a product, it is important to identify the main elements of tissue strength and determine which elements are responsible for the textural attributes of interest. For example, it may be necessary to avoid tough strands of vascular material when measuring texture of soft tissues because the small amount of fiber produces an artificially high reading that does not agree with the sensory assessment of softness. On the other hand, it is important to measure the strength of fibers when determining toughness, such as in asparagus spears and broccoli stalks. Thus, method development and the solution to many texture problems require a good understanding of the anatomy of tissues within the fruit or vegetable, the structure of its cells, the biological changes that occur following harvest, and sensory texture perception.

Parenchyma Cells

Fruits are derived from flower parts, while vegetables are derived from roots, stems, leaves, or flowers, and several that we call vegetables are actually fruit (table 1). The common factor is that all fruits and vegetables are relatively soft, even carrots and apples eaten raw or cooked, largely due to the presence of parenchyma cells. These parenchyma cells are not lignified, and their primary walls are separated by a morphologically distinct region known as the middle lamella,

Table 1. Examples of fruits and vegetables derived from various plant parts

Plant part	Fruit	Vegetable	Seasoning or garnish
Root		Beet, carrot, cassava (yucca, *Manihot*), parsnip, radish, sweet potato (*Ipomoea*), turnip, yam (*Dioscorea*)	Licorice
Tuber		Potato, jerusalem artichoke, taro	
Rhizome			Ginger, turmeric
Bulb		Onion, shallot	Garlic
Corm		Water chestnut	
Sprouted seeds		Bean sprouts, etc.	
Stem		Asparagus	Cinnamon (bark)
Leaf buds		Cabbage, brussels sprouts, belgian endive (etiolated)	
Petiole		Celery, rhubarb	
Leaf		Collards, kale, leek, lettuce, mustard greens, onion (green), spinach, watercress	Basil, bay, chives, cilantro, dill leaf, marjoram, mint, oregano, parsley, rosemary, sage, tarragon, thyme
Flower buds		Artichoke (globe), broccoli, cauliflower, lily bud	Capers, cloves
Flowers		Squash blossoms	Edible flowers (garnishes)
Floral receptacle		Strawberry, fig	
Fruit, immature		Chayote (christophene, mirliton), cucumber, eggplant, beans (green), snap peas, pepper (*Capsicum*), summer squash, zucchini	Gherkin (pickled)

Table 1. Examples of fruits and vegetables derived from various plant parts—*Continued*

Plant part	Fruit	Vegetable	Seasoning or garnish
Fruit, mature	Apple, atemoya, avocado, blueberry, carambola, cherimoya, cherry, citrus, cranberry, date, grape, jackfruit, mango, olive, papaya, peach, pear, pineapple, pomegranate, strawberry	Breadfruit, tomatillo, tomato, winter squashes (pumpkin, hubbard, acorn, etc.)	Allspice, caper berries, juniper, mace, pepper (red, *Capsicum*), tamarind, vanilla bean
Seeds	Nuts, inclusions in numerous fruits	Beans (mature), coconut, peanuts, sweet corn, nuts, inclusions in numerous fruit—type vegetables (for examples, squashes, tomatoes, and beans)	Anise, caraway, cardamon, cumin, dill seed, fennel, mustard, nutmeg, pepper (black, *Piper*), pomegranate, poppy seed, sesame seed
Fungi		Mushrooms, truffles	

which separates adjacent cells and is rich in pectic substances. The unique mixture of matrix (pectic and hemicellulosic) and fibrous (cellulosic) polysaccharides in the cell wall mostly determines the mechanical properties of these cells. The polysaccharides confer on the wall two important but seemingly incompatible properties. The first is the wall's plasticity, which enables it to expand as the cell enlarges during plant development. The second is the wall's rigidity, which confers strength and determines cell shape. However, on its own the cell wall is unable to provide much mechanical support. Rather, it is the interaction between rigidity of the wall and internal hydrostatic pressure (turgor) of cell contents that provides support.

The arrangement and packing of parenchyma cells within the tissue is another factor that influences mechanical strength of produce. In carrots, the cells are small (approximately 50 µm in diameter), isodiametric in shape, and closely packed with a high degree of contact between neighboring cells and a small volume of intercellular gas-filled spaces. The cells can be arranged either as columns or as a staggered array where each cell overlays the junction of the two lower cells (Sørensen et al. 1999). These differences in cell packing may, in part, explain genotypic differences in susceptibility to harvest splitting in carrot. In apple cortical tissue, the cells are large (up to 300 µm in diameter), elongated along the direction of the fruit radius, and organized into distinct columns (Khan and Vincent 1993). As a result of this orientation of apple cells, the tissue stiffness (elastic modulus) is higher and the strain at failure is lower when tissue plugs are compressed in a radial rather than a vertical or tangential orientation (Khan and Vincent 1993, Abbott and Lu 1996). Up to 25% of the volume of apple tissue may be gas-filled intercellular spaces, which indicates relatively inefficient cell packing and a low degree of cell-to-cell contact, both of which correlate well (negatively) with tissue stiffness (Vincent 1989).

Cell Wall

From a chemical perspective, the primary cell wall of parenchyma cells is composed of a mixture of cellulose, hemicellulose, and pectin. The specific intermolecular interactions among these polysaccharides are poorly understood but usually assumed to follow the models described by Carpita and Gibeaut (1993). The cell wall itself is an important constituent of produce, providing dietary fiber, thought to protect against colorectal cancer (Harris et al. 1993).

Changes that occur in the cell wall during ripening of fruit, storage of produce, and cooking are critical to the texture of the final product. During maturation of some vegetative parts, especially stems and petioles, cell walls become lignified (Okimoto 1948, Price and Floros 1993). Lignification results in toughening of the product, such as woodiness in asparagus, broccoli, pineapple, and rutabaga. During fruit ripening, cell wall changes include solublization and degradation of pectin and a net loss of the noncellulosic neutral sugars galactose and arabinose, and there may be a decrease in the molecular weight distribution of hemicelluloses (Harker et al. 1997). Numerous enzymes have been suggested as being critical to these changes in the cell wall including polygalacturonases and several glycosidases, including β-galactosidase, xyloglucanase, endotransglycosylase, and cellulases (Dey and del Campillo 1984, Huber 1992, Seymour and Gross 1996, Harker et al. 1997). The possible role of expansins—proteins that are proposed to disrupt hydrogen bonds within the cell wall—has been considered (Civello et al. 1999). The use of molecular approaches, including antisense technologies, has been a powerful tool in the search for an understanding of fruit softening (Giovannoni et al. 1989). However, no single enzyme has been identified as the major determinant of fruit softening, suggesting that wall breakdown results from the coordinated action of several enzymes or that the key enzyme has not been identified.

Cooking often results in degradation of pectic polymers via β-elimination, which is usually related to the degree of methyl esterification of pectin (Waldron et al. 1997). Along with turgor loss, this process is responsible for thermal softening. However, some vegetables either don't soften or soften very slowly during cooking—for example, Chinese water chestnut, sugar beet, and beetroot. In Chinese water chestnut, the thermal stability of texture is associated with the presence of ferulic acid in the cell wall (Waldron et al. 1997).

Postharvest treatments involving dipping or infiltrating with calcium maintain firmness during storage of a wide range of fruit (Conway et al. 1994). Examination of fracture surfaces following tensile testing of apple cortex indicated that tissue failure from calcium-treated fruit was due to cell rupture, whereas failure in control apples was due to cell debonding (Glenn and Poovaiah 1990). While evidence suggests that calcium influences texture through its interaction with the cell wall (pectin), it may also affect texture through interactions with membranes.

The cell wall may also influence perception of juiciness through its ability to hold and release fluid. In some fruits, the cell wall swells considerably during ripening (Redgwell et al. 1997). It has been suggested that hydrated cell walls and perhaps the presence of free juice over the surface of undamaged cells could be responsible for the sensation of juiciness in fruit with soft melting textures (Harker et al. 1997). In stonefruit, loss of juiciness is thought to occur when pectates bind water into a gel-like structure within the wall (Ben-Arie and Lavee 1971). Separation of cells at the middle lamella rather than rupture of cells during chewing is at least partially responsible for the dry, mealy mouth-feel of overripe apples and wooliness of peaches (Harker and Hallett 1992).

Cell Turgor

Plant cells tend to maintain a small positive pressure, known as turgor pressure, which develops when the concentration of solutes inside the cell (more specifically inside the plasma membrane) is higher than that outside the cell. The extracellular solution fills the pores of the cell wall, sometimes infiltrates into gas-filled spaces, and usually is continuous with vascular (water-conducting) pathways of the plant. Differences in solute concentration at the inner and outer surface of the plasma membrane cause water to flow into the cell by osmosis. This net movement of water is halted by the physical constraint of the rigid cell wall and, as a result of this, turgor develops inside the cell. At equilibrium,

$$\Psi = \Psi p + \Psi \pi$$

Where:

Ψ is the turgor (generally a positive value),

Ψp is the water potential (water activity, generally a negative value) of the tissue, and

$\Psi \pi$ is osmotic pressure (generally a positive value) of the cell (Tomos 1988).

Turgor has the effect of stressing the cell wall. The consequences of this stressing depend on whether compressive loads or tensile loads are applied. When tissues are subjected to compressive loads, higher-turgor tends to make the cell more brittle; that is, makes it fail at a lower force (Lin and Pitt 1986). When tissues are subjected to tensile measurements, turgor tends to harden the cell wall and a greater force is needed before cells fail (De Belie et al. 2000a). However, turgor is unlikely to influence tissue strength if the mechanism of failure is cell-to-cell debonding, rather than fracturing across individual cells, unless an increasing turgor, and thus swelling, reduces cell-to-cell contact area (Glenn and Poovaiah 1990, Harker and Hallett 1992).

The importance of turgor has been demonstrated in a number of ways. The rapid phase of cooking-induced softening of carrot occurs as a result of membrane disruption and the elimination of the turgor component of texture (Greve et al. 1994). Similarly, when produce experiences a freeze-thaw cycle, the membranes are damaged and the tissues become more flaccid in the case of leafy vegetables (and softer in the case of fruits) and often leak much juice upon thawing. Firmness and turgor correlate well in apple (Tong et al. 1999), and turgor declines during tomato ripening (Shackel et al. 1991). Also, turgor is thought to play a central role in softening and development of mealiness during storage of apples (Hatfield and Knee 1988).

Cell-to-Cell Debonding Versus Cell Rupture

The strength of the cell wall relative to the adhesion between neighboring cells will determine whether cell rupture or cell-to-cell debonding is the mechanism of tissue failure. Cell rupture is generally associated with crisp and often juicy produce, as well as with unripe fruit and raw vegetables. Cell-to-cell debonding is frequently associated with dry, unpleasant texture such as in mealy apples or chilling-injured stonefruit and tomato and with juice loss in citrus (Harker et al. 1997).

However, a dry texture is not always unacceptable to consumers—in banana, for example. In some fruits, cell-to-cell debonding does not result in a dry texture; rather, a layer of juice covers the intact cells exposed following cell separation (Harker et al. 1997). Furthermore, cell-to-cell debonding is a common outcome of cooking of vegetables such as potato (Waldron et al. 1997) and carrot (Ng and Waldron 1997). In fresh produce, cell adhesion is presumed to be a function of three factors: strength of the middle lamella, the area of cell-to-cell contact, and the extent of plasmodesmatal connections (Harker et al. 1997). Tissue collapse can also occur without cell wall breakdown or cell separation. In some tissues, fluids are forced out of cells by compressive forces known as “cell relaxation” (Peleg et al. 1976) or “exosmosis” (Jackman and Stanley 1995).

Other Elements of Tissue Strength

The strength and integrity of many edible plant organs are influenced by a number of additional factors (Harker et al. 1997). Many fruits and vegetables contain a number of tissue zones: periderm, pericycle, and phloem parenchyma in carrot; skin, outer pericarp, inner pericarp, and core in kiwifruit; and outer pericarp, locular gel, seeds, and columella in tomato. These tissues differ in strength and biological properties and often need to be considered individually when measuring texture. For example, failure of the core of kiwifruit to soften to the same extent as the pericarp causes a texture that is unacceptable to consumers. In some multiple fruit that do not adhere to the receptacle, such as raspberry, the main element of strength is the adhesion between neighboring drupelets due to hair-like protuberances. However, it is the skin of many types of produce that plays a key role in holding the flesh together, particularly in soft fruit. The cuticle of epidermal cells and thickened cell walls of hypodermal cells contribute to strength of simple skins. In harder, inedible skins, specialized cells may be present: collenchyma, sclerenchyma, tannin-impregnated cells, and cork.

The presence of tough strands of vascular tissue may strengthen the flesh but often results in an unpleasant fibrous texture. For example, toughness of asparagus spears is principally due to fiber content and fiber lignification (Lipton 1990). Rarely is the stringiness desirable, as in spaghetti squash. In most commercial fruits, with the exception of pineapple (Okimoto 1948), fibrousness of the flesh is not a major problem. However, some fruits, including peaches and muskmelons, can have a problem with stringiness (Diehl and Hamann 1979). Generally, the perception of stringiness is greater with very ripe fruit due to the contrast between the soft melting texture of the parenchyma cells and the fibrousness of the vascular tissues. Similarly, the gritty texture of pear and guava (Harker et al. 1997) becomes particularly noticeable when the surrounding cells are soft. However, while stringiness is caused by vascular tissues, grittiness is caused by sclerenchymatous stone cells (Harker et al. 1997).

Sensory Evaluation of Texture

People sense texture in numerous ways: the look of the product, the feel in the hand, the way it feels as they cut it, the sounds as they bite and chew it, and, most important of all, the feel of the product in the mouth. Szczesniak (1963) proposed a texture profile, a systematic approach to sensory texture analysis based on mechanical, geometrical, and other characteristics. Mechanical characteristics included basic parameters (hardness, cohesiveness, viscosity, elasticity, and adhesiveness) and secondary parameters (brittleness or fracturability, chewiness, and gumminess). Geometrical properties related to size, shape, and orientation of particles. The other characteristics comprised moisture and fat content. Sherman (1969) and others have proposed revisions of the texture profile classification scheme, but the original is generally used with only minor changes by sensory texture specialists. Most sensory analysis textbooks contain a small chapter on evaluation of texture; for example, Meilgaard et al. (1999). Harker et al. (1997) reviewed fruit texture and included extensive discussion of oral sensation of textural attributes.

Shewfelt (1999) suggested that the combination of characteristics of the product be termed “quality” and that the consumer’s perception and response to those characteristics be referred to as “acceptability.” Texture may be a limiting factor in acceptability if textural attributes are outside the individual’s range of acceptability for that commodity. People have different expectations and impose different limits for various commodities. The relationship of instrumental measurements to specific sensory attributes and their relationship to consumer acceptability must be considered (Shewfelt 1999). Instruments may be designed to imitate human testing methods, or fundamental mechanical measurements may be statistically related to human perceptions and judgments to predict quality categories. Only people can judge quality, but instruments that measure quality-related attributes are vital for research and inspection (Abbott et al. 1997).

Instrumental Measurement of Texture

The ability to measure texture is critical for evaluation and control of quality. The complex nature of texture is associated with the diversity of tissues involved, the attributes required to describe textural properties, and changes in these attributes as the product ripens and senesces. Instrumental measurements are preferred over sensory evaluations for research and commercial applications because they are less subject to human influences, are more precise, and can provide a common language among researchers, companies, regulatory agencies, and customers. It is often suggested that the relevance of instrumental measurements depends on how well they predict sensory attributes (Voisey 1971), but there are also valid uses for mechanical property measurements that relate only to functional behavior of the fruit or vegetable, such as bruise resistance or the ability to be sliced for fresh-cut preparations.

There have been numerous reviews of methods for instrumental measurement of fruit and vegetable texture (Bourne 1980, Chen and Sun 1991, Abbott et al. 1997, Harker et al. 1997). Interaction among characteristics and the continuing physiological changes over time complicate the measurement of fruit or vegetable texture. For example, as the parenchymal tissue of honeydew melon softens, the perception of fibers (vascular bundles) increases (Diehl and Hamann 1979). On the other hand, the fibrousness in asparagus is related to active lignification of fiber and vascular bundles (Chang 1987). Similar effects can affect instrumental measurements. For example, fibers are held relatively rigidly in a hard melon and thus contribute to the overall force required to cut through the flesh, but the fibers in a soft melon can be displaced by the instrument's probe and alter distribution of forces within tissue. The displaced fibers can also effectively change the shape of the probe as it progresses through the flesh accumulating a "cap" of fibers.

Most instrumental measurements of texture have been developed empirically. While they may provide satisfactory assessments of the quality of produce, they often do not fulfill engineering requirements for fundamental measurements (Bourne 1982). Fundamental material properties measurements were developed to study the strength of materials for construction or manufacture. After the failure point of such a material is exceeded, there is little interest in the subsequent behavior of the material. On the other hand, scientists who study food are interested in initial failure but they are also interested in the continuous breakdown of the food in the mouth in preparation for swallowing. As Bourne (1982) pointed out, "Food texture measurement might be considered more as a study of the weakness of materials rather than strength of materials." In fact, both strength and breakdown characteristics are important components of texture.

Elastic and Viscoelastic Behavior

Fruits and vegetables exhibit viscoelastic behavior under mechanical loading, which means that force, distance, and time—in the form of rate, extent, and duration of load—determine the value of measurements. For example, impact of the fruit against a hard surface is very rapid loading, whereas the weight of other fruit on an individual fruit at the bottom of a bin and the force of a carton wall against tightly packed fruit are long-term loads. The fruit will respond quite differently to the two forms of loading. Because of the viscoelastic character of fruit and vegetable tissues, every effort should be made to use a consistent action and speed when making manual texture measurements such as the Magness-Taylor puncture test (Blanpied et al. 1978, Harker et al. 1996). The rate of loading should be controlled and specified in mechanized measurements. The optimal rate of loading differs for different commodities. People use different loading rates (chewing speeds) when eating foods of different textures (Harker et al. 1997), but the optimum loading rate for instrumental measurements may not resemble the rate of human mastication (Thybo et al. 2000).

There are many types of mechanical loading: puncture, compression, shearing, twisting, extrusion, crushing, tension, bending, vibration, and impact. And there are four basic values that can be obtained from mechanical properties tests: force (load), deformation (distance, displacement, penetration), slope (ratio of force to deformation), and area under the force/deformation curve (energy). The engineering terms based on these measurements are stress, strain, modulus, and energy, respectively.

Stress is force per unit area, of either contact or cross-section depending on the test. *Strain* is deformation as a percentage of initial height or length of the portion of sample subject to loading. *Modulus of elasticity* (tangent, secant, chord, or initial tangent) is a measure of stiffness based on the stress/strain ratio.

Force and *deformation* values are more commonly used in food applications than stress and strain values and are sufficient, provided that the contact area and the distance the probe travels are constant and sample dimensions are similar from sample to sample. (Sample here means the portion of tissue tested, not necessarily the size of the fruit or vegetable.) In many horticultural texture tests, deformation is kept constant and the force value is reported. For example, in penetrometer tests of fruit firmness such as the Magness-Taylor test discussed below, the force required to insert a probe into the flesh to an inscribed mark is read from a gauge. No compensation is made for different probe diameters (contact areas), so the value read is force, not pressure or stress. In a few horticultural tests, a known force is applied to the product and the deformation after a specified time is reported; an example is the tomato creep test (Hamson 1952, Ahrens and Huber 1990).

Puncture, compression, bending, and shear tests made on instruments such as those listed in table 2 are made at relatively low speeds, usually 60 to 300 mm min^{-1} (0.1 to 20 in min^{-1}). In contrast, typical impact velocities in fruit and vegetable handling systems are likely to be around 400 mm s^{-1} (945 in min^{-1}), equivalent to a drop of only 8.1 mm, and sometimes much greater.

Table 2. Magness-Taylor fruit firmness tester and related penetrometers

Instrument	Type*	Force†	Readout	Manufacturer
Magness-Taylor	MT	Manual	Gauge	D. Ballauff Manufacturing Co., Laurel, MD
Effe-gi‡	MT	Manual	Gauge	Effe-gi, Ravenna, Italy
McCormick‡	MT	Manual	Gauge	McCormick Fruit Tech Co., Yakima, WA (manufactured by Effe-gi)
Wagner	MT	Manual	Gauge	Wagner Instruments, Greenwich, CT (manufactured by Effe-gi)
EPT	MT	Mechanical	Electronic	Lake City Technical Products, Kelowna, BC, Canada
U.C. (University of California)	MT	Mechanical	Gauge	None. Uses AMETEK force gauge and manual drill press
Universal testing machines or materials testers	Universal	Mechanical	Electronic	AMETEK Test and Calibration Instruments (Paoli, PA) Chatillon (Largo, FL) Food Technology Corp. (of General Kinetics, Inc.) Instron Corp. (Canton, MA) Lloyd Instruments Material Testing Products (Hampshire, UK) Stable Micro Systems, Ltd. (Surrey, UK) Tinius Olsen Testing Machine Co. (Willow Grove, PA)

*MT = Magness-Taylor tester.

†MT firmness, regardless of instrument, is measred as force and should be reported in pounds-force (lbf, English units) or Newtons (N, metric units), not in kilograms force (kgf), though the gauges of some instruments indicate kg. To convert: lbf x 4.448 = N; kgf x 9.807 = N; N x 0.225 = lbf; N x 0.102 = kgf.

‡Other labels, such as “McCormick,” may occur on Effe-gi instruments.

A typical force/deformation (F/D) curve for a cylindrical piece of apple tissue compressed at constant speed is shown in figure 1. F/D curves for puncture tests look similar to compression curves. The portion of the initial slope up to point (a) in figure 1 represents nondestructive elastic deformation; point (a) is the inflection point at which the curve begins to have a concave-downward shape and is called the "elastic limit." The region before point (a) is where slope or elastic modulus should be measured. Beyond the elastic limit, permanent tissue damage begins. There may be a bioyield point (b), at which cells start to rupture or move with respect to their neighbors, causing a noticeable decrease in slope. Point (c) marks rupture, where major tissue failure causes the force to decrease substantially. In some F/D curves, including figure 1, bioyield may not be distinguishable from rupture. Beyond rupture, the force may again increase, level off, or decrease as deformation increases (Bourne 1965).

At the maximum deformation point specified by the user, the probe is withdrawn and the force diminishes until contact is lost. In the apple tissue shown in figure 1, maximum force occurred at maximum deformation, point (c), but other apples in the same lot had maxima at rupture point (a) or at some point between rupture and maximum deformation, such as marked by point (b). Of course, F/D curves that differ from the one shown in figure 1 are also reported for apple and for other commodities. F/D curves for very soft, noncrisp, or spongy tissues do not have sharp peaks but show gradual increase in force to a rupture point, followed by gradual decrease. Some may not even show rupture; for example, a cylinder of eggplant compressed like apple tissue in figure 1 may show smoothly increasing force to the point of maximum deformation. Samples with a mixture of parenchyma and fibers or stone cells may have quite jagged F/D curves, with several local maxima and ruptures as the probe encounters resistant clusters of stone or fiber cells.

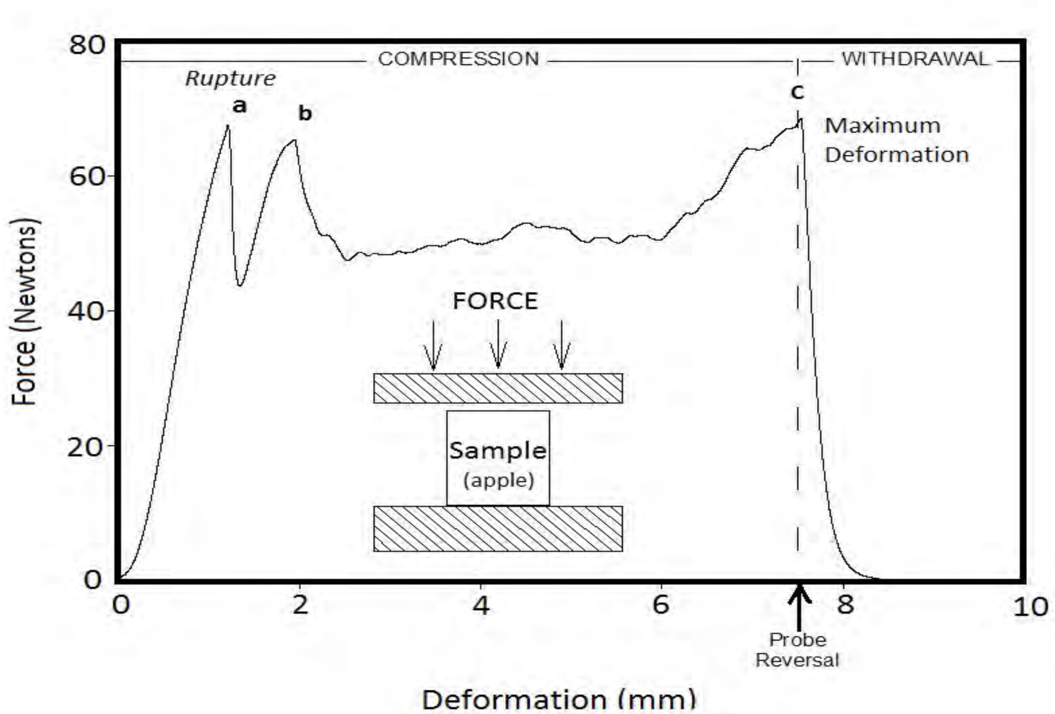

Figure 1. Actual force/deformation curve of a cylindrical piece of apple tissue under compression of 1 mm s^{-1} demonstrating elastic limit (a), bioyield (b), and rupture or massive tissue failure (c). Maximum force is at point (c) but could also occur at point (a) or point (b) in other apples. Force/deformation (F/D) for Magness-Taylor puncture would look similar (with somewhat different maximum forces) but would terminate at 5/16 in or 8 mm, depending on whether original or metric specification was selected to control the universal testing instrument.

Firmness of horticultural products can be measured at different force or deformation levels in all three regions of figure 1, depending on the purpose of the measurement and the definitions of the quality attributes. F/D characteristics beyond the elastic limit may be more important than those before it, because they simulate the destruction that occurs in bruising or eating (Szczesniak 1963, Bourne 1968). The two most common texture tests of fruits and vegetables, the Magness-Taylor puncture and the Kramer Shear report only the maximum force attained, regardless of the deformation at which it occurs. On the other hand, elastic modulus or Young's modulus is often used by engineers as an index of product firmness. The modulus of elasticity is the ratio of stress to strain as calculated from the slope of the F/D curve before the elastic limit. Any nondestructive method should limit the force or deformation level to the elastic region so that negligible tissue damage is sustained during measurement. It is important to recognize and understand the fundamental properties measured by both destructive tests and nondestructive methods, the differences between them, and the factors that can affect the tests.

Numerous mechanical instruments have been developed over the past century for measuring textural attributes of horticultural products. Despite the large variations in design, these mechanical instruments either measure or control functions of force, deformation, and time. The types of loading by these instruments include puncture, compression, shearing, twisting, extrusion, crushing, tension, and bending.

Puncture Tests

Puncture testers based on the original Magness-Taylor pressure tester (MT), also called the USDA or Ballauff tester (Magness and Taylor 1925, Haller 1941) and more correctly called the Magness-Taylor fruit firmness tester, are used to measure firmness of numerous fruits and vegetables to estimate harvest maturity or for postharvest evaluation of firmness. There are several adaptations of the Magness-Taylor tester that differ in instrument size and shape, manual or mechanical use, and dial (analog) or digital readout (table 2). The term "Magness-Taylor firmness" is used generically for the measurements made with the several variants of the MT. All use rounded-tip probes of specific geometry and measure the maximum force required to insert the probe 7.94 mm (5/16 in) into the flesh (Haller 1941). The rounded portion of a Magness-Taylor probe is only a portion of a full hemisphere . A probe measuring 11.11 mm (28/64 in) in diameter with a radius of curvature of 8.73 mm (11/32 in) is used for apples. A probe measuring 7.94 mm (5/16 in) in diameter with a radius of curvature of 5.16 mm (13/64 in) is used for cucumber, kiwifruit, mango, papaya, peaches, pears, and plums. A thin slice of skin (about 2 mm thick and slightly larger diameter than the probe) should be removed from the area to be tested, except for cucumbers, which are tested with the skin intact.

A group of U.S. researchers published recommendations for making manual penetrometer tests (Blanpied et al. 1978), stating that steady force should be applied so that the probe is inserted to the inscribed depth mark in 2 s. The probes can also be mounted in materials testers (universal F/D testing machines) made by numerous manufacturers (Bourne 1974, Breene et al. 1974, Abbott et al. 1976, Harker et al. 1996, Lehman-Salada 1996). A group sponsored by the Commission of the European Communities recommended that a materials tester be used to drive the probe to a depth of 8 mm at speeds between 50 and 250 mm min^{-1} (Smith 1985). Because of the curvature of the MT probes and the fact that firmness as measured in puncture tests is a combination of shear and compression in variable proportions, it is not possible to convert measurements made with one size MT probe to the other MT size, or to accurately convert to or from values for probes of other geometries (Bourne 1982). A random sample of 20 to 30 fruit of similar size and temperature should be tested with punches on two opposite sides, depending on uniformity of the lot. Peaches are often more variable around the circumference than other fruit so a larger number is recommended (Blanpied et al. 1978). Similar measurements are made on cherry, grape, and strawberry using a 3-mm probe and on olive using a 1.5-mm probe on the U.C. tester (E.J. Mitcham 2000, personal communication). Numerous puncture tests with flat-faced cylindrical or hemispherical probes and a few with conical probes have been conducted. None have achieved the acceptance of the Magness-Taylor fruit firmness test.

Shear Tests

Shearing in engineering terms does not mean cutting with a knife or scissors but, instead, sliding adjacent parallel planes of cells past one another. Engineering shear tests are seldom used on fruits and vegetables, but shear modulus can be obtained from compression (Mohsenin 1986), torsion (Diehl et al. 1979), impact (Bajema and Hyde 1998), extrusion, and dynamic (Ramana and Taylor 1992) tests. Although it does not measure true shear, the Kramer Shear device (FTC Texture Test System, Food Technology Corporation, Reston, VA) is used extensively in the food processing industry and by some fresh-cut processors for quality control. The key component of the original Kramer Shear device is a multiblade cell with 10 blades 2.9 mm (about 7/64 in) thick that mesh with slots in the bottom of a cell measuring 67×67×63 mm (approximately 2 5/8×2 5/8×2 1/2 in, internal dimensions) that can be used on any materials tester with sufficient load capacity. The cell is generally filled with randomly oriented pieces of the product, either to full capacity or to 100 g. The force measured by the test involves compression, shear, extrusion, and friction between the tissue and blades.

While the maximum force to pass the blades through the sample may relate to the complex of material properties sensed in the mouth during chewing, the test does not satisfy requirements for engineering tests because of the undefined and uncontrolled stresses and strains applied to the food. The amount of sample and the pattern of loading the cell, size and orientation of pieces, etc. affect the maximum force value as well as the shape of the F/D curve (Szczesniak et al. 1970, Voisey and Kloek 1981). The orientation of pieces of fruit or vegetable, especially with regard to vascular bundles and fibers, and the spaces between pieces would be expected to affect significantly the F/D profile as the blades penetrate through the contents of the shear cell; therefore some standardization of loading practice is advisable. Adaptations with smaller cells and fewer blades are available; for example, Stable Micro Systems. As with the MT probe, comparisons should not be made between results from cells of different geometries.

Compression

Though compression tests are not commonly used by the fruit and vegetable industry, they are widely used in research on horticultural products. They can be made on tissue specimens or intact products using a variety of contact geometries (Mohsenin 1986, ASAE 2000). Though fruits and vegetables are viscoelastic, they are often treated as elastic, so the force required to attain a specified deformation or to rupture (bruise or burst) the product is generally measured. Modulus of elasticity, stiffness, force, contact stress, and deformation to bioyield and to rupture can be calculated from elastic measurements, dimensions of the specimen, and Poisson's ratio (the ratio of transverse strain to axial strain at less than the elastic limit). For convex specimens such as whole or halved fruits, see ASAE Std. 368.4 (2000). Often, for food science applications only maximum force or distance is reported.

Compression tests using pieces of tissue, usually cylindrical, excised from the fruit or vegetable are quite common in research (Bourne 1968, Khan and Vincent 1993, Abbott and Lu 1996, Wann 1996). Intact product compression tests involve contact with small flat or curved indenters or with parallel plates significantly larger than the area of contact (ASAE 2000). Modulus of elasticity values from whole fruit compression represents fruit morphology, size, shape, cellular structure, strength, and turgor. Though elastic properties can be determined nondestructively (discussed below), horticultural and food science measurements are frequently made beyond the elastic limit. Sundstrom and Carter (1983) used rupture force of intact watermelons pressed between parallel flat plates to evaluate causes of cracking. Jackman et al. (1990) found that whole tomato compression was relatively insensitive to small differences in firmness due to chilling injury. Kader et al. (1978) compressed tomatoes between a pair of spherical indenters as a measure of firmness.

If the viscous element is a significant contributor to the texture, as it is for intact tomatoes and citrus, measurement of continuing deformation under a constant force (creep) (Hamson 1952, El Assi et al. 1997) or decrease in force under a fixed deformation (relaxation) (Sakurai and Nevins 1992, Errington et al. 1997, Kajuna et al. 1998, Wu and Abbott 2002) provides textural information in addition to elastic properties. To minimize the effect of loading position on firmness measurement in tomato, Kattan (1957) designed a creep tester that applied force around the fruit's circumference with a belt. The failure of creep or force-relaxation testers to be adopted commercially is due to the time required for adequate relaxation, which can be up to 60 s.

Tension Test

Tensile tests measure the force required to stretch or pull a sample apart. Failure can be through cell rupture, cell separation, or a combination of both. Tensile measurement has not been as popular as puncture or compression testing because it is not intuitively as closely related to crushing or chewing as is puncture or compression and because it requires gripping or otherwise holding the ends of the sample so that they can be pulled apart without crushing the tissues where they are held. Schoorl and Holt (1983) used clamps to hold apple tissue. Stow (1989) and Harker and Hallett (1992) used shaped samples held by special claw-like hooks. Harker and Hallett (1994) used quick-set adhesive to glue the ends to instrument fixtures. Researchers often examine the broken ends of tensile test samples to determine the mode of fracture. Microscopic analyses of the broken ends (Lapsley et al. 1992, Harker and Sutherland 1993, Harker and Hallett 1994, Harker et al. 1997) reveal that tissue from unripe fruit generally fractures due to individual cells breaking, whereas cells from ripe fruits that tend to be crisp (apple and watermelon) usually break or rupture and cells from ripened soft fruits (banana, nectarine, and kiwifruit) tend to separate at the middle lamellae.

Torsion Test

True torsion tests are rarely used on horticultural specimens because of the difficulties in shaping and holding the tissue (Diehl and Hamann 1979, Diehl et al. 1979).

Twist Test

Studman and Yuwana (1992) proposed a simple twist tester consisting of a sharp spindle with a rectangular blade that is forced into the flesh; the torque (twisting force) required to cause crushing or yielding of the tissue is measured. Though called a "twist test," this is not to be confused with a torsion test: The properties tested are likely a combination of shear and compression. Harker et al. (1996) found the twist test to be more precise than several testers using the MT puncture probe; however, Hopkirk et al. (1996) suggest that puncture and twist tests may measure different mechanical properties, resulting in quite different firmness judgments. The twist test has the advantage of being able to measure strength of tissue zones at specific depths from the surface without requiring the excision of tissue samples.

Nondestructive Measurements for Online Sorting

Most F/D measurements are destructive, such as the familiar Magness-Taylor fruit firmness test and the Kramer shear test; or they are too slow for online use, such as the Cornell firmness tester. However, remember that eating is destructive! Rupture forces usually provide the best correlation with sensory texture evaluations of foods. Unfortunately, destructive tests cannot be used to sort fruits and vegetables for subsequent sale, so a great deal of research has gone into developing nondestructive methods to estimate the mechanical properties and the textural quality of fruits and vegetables (Chen and Sun 1991, Abbott et al. 1997, Hung et al. 2001). None of these nondestructive methods has attained wide commercial acceptance to date.

During development, new instrumental texture measurements are most often initially calibrated against existing instruments. If they are to be used to predict sensory attributes or acceptability, the new measurement should also be compared directly with descriptive sensory analyses to develop calibration equations for quantitative attributes (how much of a trait is present) or with consumer evaluations to predict acceptability. Alternatively, instrumental measurements may be compared with commercially useful traits like bruising, days from bloom, or storage life to develop predictive equations. After the relationship between an instrumental measurement and a quality attribute or acceptability has been well established, the instrumental measurement is usually used to replace human evaluations. It is advisable to verify the relationships occasionally, because changes in factors such as genetics, growing or storage conditions, consumer preference, or wear on the instrument may change the relationships.

Laser Air-Puff Test. A nondestructive, noncontact firmness detector was recently patented (Prussia et al. 1994) that uses a laser to measure deflection caused by a short puff of high-pressure air, similar to some devices used by ophthalmologists to detect glaucoma. This is essentially a nondestructive compression test. Under fixed air pressure, firmer products deflect less than softer ones. Laser-puff readings correlate well with destructive Magness-Taylor firmness values for apple, cantaloupe, kiwifruit, nectarine, orange, pear, peach, plum, and strawberry (Fan et al. 1994, Hung et al. 1998, McGlone et al. 1999, McGlone and Jordan 2000).

Impact or Bounce Test. When one object collides with another object, its response is related to its mechanical properties, its mass, and the contact geometry. Numerous studies have been conducted on the impact responses of horticultural products and a number of impact parameters have been proposed to measure firmness, including peak force, coefficient of restitution, contact time, and the impact frequency spectrum. The coefficient of restitution is the ratio of the velocities of the product just before and after impact and reflects the energy absorbed in the product during impact.

There is no agreement on the best parameter to measure; selection seems to depend on commodity, impact method, and the firmness reference used by the investigators. Most impact tests involve dropping the product onto a sensor (Rohrbach 1981, Delwiche et al. 1987, Zapp et al. 1990, McGlone and Schaare 1993, Patel et al. 1993) or striking the product with the sensor (Delwiche et al. 1989, Brusewitz et al. 1991, Chen et al. 1996, Bajema and Hyde 1998). Delwiche et al. (1989, 1991) developed a single-lane firmness sorting system for pear and peach. Impact measurements often do not correlate highly with the Magness-Taylor puncture measurement (Hopkirk et al. 1996). A potential problem with impact tests is that bruising may occur unless a soft sensor is developed (Thai 1994).

Sonic or Acoustic Tests. Sonic (acoustic) vibrations are those within the human audibility range of 20 to about 20,000 Hz (vibrations per second). Sonic measurements provide a means of measuring fruit and vegetable firmness. The traditional watermelon ripeness test is based on the acoustic principle: One thumps the melon and listens to the pitch of the response.

A number of sonic instruments and laboratory prototype sorting machines have been developed and tested (Abbott et al. 1968, 1992, Armstrong et al. 1990, Peleg et al. 1990, Zhang et al. 1994, Stone et al. 1998, Schotte et al. 1999, De Belie et al. 2000b, Muramatsu et al. 2000). When an object is caused to vibrate, amplitude varies with frequency of the vibration and will be at a maximum at some particular frequency determined by a combination of the shape, size, and density of the object; such a condition is referred to as resonance. Resonance measurement can be achieved by applying an impulse or thump that contains a range of frequencies. Modulus of elasticity values obtained from resonant frequency data have correlated well with those measured by conventional compression tests, but they often correlated poorly with MT puncture forces. Abbott et al. (1968) proposed a stiffness coefficient, f^2m, which was based on the modulus of elasticity using the resonant frequency (f) and mass (m) of the specimen; this was later modified by Cooke and Rand (1973) to $f^2m^{2/3}$.

Farabee and Stone (1991) developed a portable sonic instrument for field determination of watermelon ripeness and hollow heart detection. Kawano et al. (1994) reported a commercial sorting machine for detecting internal voids in Japanese watermelon. Shmulevich et al. (1995) developed a sonic instrument using a lightweight flexible piezoelectric film sensor to follow changes in fruit during storage. Muramatsu et al. (2000) examined the relationship of both phase shifts and resonant frequencies to firmness. Nybom (1962) and Peleg et al. (1990, 1999) examined the sonic energy transmitted by the specimen rather than the resonant frequencies. Despite considerable research, sonic vibration has not yet become a viable option for the horticultural industry. However, several advanced commercial prototypes are currently being evaluated.

Ultrasonic Tests. Ultrasonic frequencies (>20,000 Hz) are widely used in the medical field and for analyzing meat. Ultrasonic tests have been used with limited success for measuring physical and chemical properties of fruits and vegetables because of the high attenuation (energy absorption) of plant tissues. The commonly measured ultrasonic parameters are velocity, attenuation, and frequency spectrum composition. Bruises in apples (Upchurch et al. 1987) and hollow heart of potatoes (Cheng and Haugh 1994) could be detected in the laboratory using ultrasonics. Mizrach and Flitsanov (1999) and Mizrach et al. (1994, 1999) have followed the softening process in avocados, melons, and mangoes, respectively.

Light Scatter Imaging. As light passes through tissue, cellular contents such as starch granules, cell walls, and intercellular spaces cause scatter. The extent of scatter of collumated light such as a laser beam may change during ripening due to compositional changes and changes in cell-to-cell contact. Measurement of the scatter using computer vision may thus provide an indirect indication of textural changes. Significant correlations between mechanical properties and image size have been shown in apples (Duprat et al. 1995, McGlone et al. 1997, Cho and Han 1999, De Belie et al. 2000a) and tomatoes (Tu et al. 2000).

Juiciness

The importance of juiciness has been demonstrated by numerous consumer awareness studies; however, there has been little progress in developing instrumental measurements of juiciness. Intuitively, one would expect total moisture content to determine juiciness, but the correlations between them are often low for fruits and vegetables (Szczesniak and Ilker 1988). Apparently, inability of cells to release juice has a greater effect. For example, water content of juicy and chilling-injured peaches is similar, yet injured fruit have a dry mouth-feel. Also, mealy apples feel dry to the palate because cells separate at the middle lamella, rather than being ruptured and releasing juice during chewing. Generally, juiciness is characterized as weight or percentage of juice released from a fixed weight of tissue. Juice can be extracted from tissue by the following methods: using a press (like a cider press), homogenizing and centrifuging to separate juice from solids, using juice extractors, and measuring juice released during compression testing of excised tissue (Harker et al. 1997).

Summary

Texture measurement has become widely accepted by horticultural industries as a critical indicator of nonvisual aspects of quality. The ability to measure texture has allowed industries to set standards for quality at pack-out and to monitor deterioration in quality during storage and distribution. Furthermore, the study of the chemical, physiological, and molecular changes that control or influence texture has been facilitated by the development of methods for quantifying texture change.

Much of the commercial and research interest in texture has focused primarily on the mechanical properties of the tissues. The diversity of tissues involved, the variety of attributes required to fully describe textural properties, and the changes in these attributes as the product ripens and senesces contribute to the complexity of texture measurement. This complexity of texture can still only be fully measured by sensory evaluation, which involves using a panel of assessors that have been trained to score defined attributes against a set of standards. However, instrumental measurements are preferred over sensory evaluations for both commercial and research applications because instruments are more convenient to use, widely available, tend to provide consistent values when used by different (often untrained) people, and are less expensive than sensory panels. These instrumental measurements are widely understood and can provide a common language among researchers, industry, and customers.

There are numerous empirical and fundamental measurements that relate to textural attributes. Mechanical methods measure functions of force, deformation, and time. Some indirect methods measure chemical constituents or physical characteristics. Destructive mechanical methods generally relate more closely to sensory evaluations than do nondestructive measurements, but by their destructive nature they cannot be used for sorting produce. Therefore, the commodity and purpose of measurement, and sometimes regulations, guide the choice of textural measurement.

References

Abbott, J.A., H.A. Affeldt, and L.A. Liljedahl. 1992. Firmness measurement of stored 'Delicious' apples by sensory methods, Magness-Taylor, and sonic transmission. J. Am. Soc. Hort. Sci. 117:590-595.

Abbott, J.A., G.S. Bachman, N.F. Childers, et al. 1968. Sonic techniques for measuring texture of fruits and vegetables. Food Technol. 22:101-112.

Abbott, J.A., and R. Lu. 1996. Anisotropic mechanical properties of apples. Trans. Am. Soc. Agr. Eng. 39:1451-1459.

Abbott, J.A., R. Lu, B.L. Upchurch, and R.L. Stroshine. 1997. Technologies for nondestructive quality evaluation of fruits and vegetables. Hort. Rev. 20:1-120.

Abbott, J.A., A.E. Watada, and D.R. Massie. 1976. Effe-gi, Magness-Taylor, and Instron fruit pressure testing devices for apples, peaches, and nectarines. J. Am. Soc. Hort. Sci. 101:698-700.

Ahrens, M.J., and D.J. Huber. 1990. Physiology and firmness determination of ripening tomato fruit. Physiol. Plant. 78:8-14.

Armstrong, P., H.R. Zapp, and G.K. Brown. 1990. Impulsive excitation of acoustic vibrations in apples for firmness determination. Trans. Am. Soc. Agr. Eng. 33:1353-1359.

ASAE [American Society of Agricultural Engineers]. 2000. Compression test of food materials of convex shape. ASAE Standard 368.4, American Society of Agricultural Engineers, St. Joseph, MI.

Bajema, R.W., and G.M. Hyde. 1998. Instrumented pendulum for impact characterization of whole fruit and vegetable specimens. Trans. Am. Soc. Agr. Eng.. 41:1399-1405.

Ben-Arie, R., and S. Lavee. 1971. Pectic changes occurring in Elberta peaches suffering from woolly breakdown. Phytochemistry 10:531-538.

Blanpied, G.D., W.J. Bramlage, D.H. Dewey, et al. 1978. A standardized method for collecting apple pressure test data. N.Y. Food and Life Sciences Bull. 74.

Bourne, M.C. 1965. Studies on punch testing of apples. Food Technol. 19:413-415.

Bourne, M.C. 1968. Texture profile of ripening pears. J. Food Sci. 33:223-226.

Bourne, M.C. 1974. Comparison of results from the use of the Magness-Taylor pressure tip in hand- and machine-operation. J. Texture Studies 5:105-108.

Bourne, M. C. 1980. Texture evaluation of horticultural crops. HortScience 15:51-57.

Bourne, M.C. 1982. Food Texture and Viscosity: Concept and Measurement. Academic Press, New York, NY.

Breene, W.M., I.J. Jeon, and S.N. Bernard. 1974. Observations on texture measurement of raw cucumbers with the fruit pressure tester. J. Texture Studies 5:317-327.

Brusewitz, G.H., T.G. McCollum, and X. Zhang. 1991. Impact bruise resistance of peaches. Trans. Am. Soc. Agr. Eng. 34:962-965.

Carpita, N.C., and D.M. Gibeaut. 1993. Structural models of primary cell walls in flowering plants: consistency of molecular structure with the physical properties of the walls during growth. Plant J. 3:1-30.

Chang, D.N. 1987. Asparagus. *In* J. Weichmann, ed., Postharvest Physiology of Vegetables, pp. 523-525. M. Dekker, New York, NY.

Chen, P., M. Ruiz-Altisent, and P. Barreiro. 1996. Effect of impacting mass on firmness sensing of fruits. Trans. Am. Soc. Agr. Eng. 39:1019-1023.

Chen, P., and Z. Sun. 1991. A review of nondestructive methods for quality evaluation and sorting of agricultural products. J. Agr. Eng. Res. 49:85-98.

Cheng, Y., and C.G. Haugh. 1994. Detecting hollow heart in potatoes using ultrasound. Trans. Am. Soc. Agr. Eng. 37:217-222.

Cho, Y.J., and Y.J. Han. 1999. Nondestructive characterization of apple firmness by quantitation of laser scatter. J. Texture Stud. 30:625-638.

Civello, P.M., A.L.T. Powell, A. Sabehat, and A.B. Bennett. 1999. An expansin gene expressed in ripening strawberry fruit. Plant Physiol. 121:1273-1279.

Conway, W.S., C.E. Sams, C.Y. Wang, and J.A. Abbott. 1994. Additive effects of postharvest calcium and heat treatment on reducing decay and maintaining quality in apples. J. Am. Soc. Hort. Sci. 119:49-53.

Cooke, J.R., and R.H. Rand. 1973. A mathematical study of resonance in intact fruits and vegetables using a 3-media elastic sphere model. J. Agr. Eng. Res. 18:141-157.

De Belie, N., I.C. Hallett, F.R. Harker, and J. De Baerdemaeker. 2000a. Influence of ripening and turgor on the tensile properties of pears: a microscopic study of cellular and tissue changes. J. Amer. Soc. Hort. Sci. 125:350-356.

De Belie, N., S. Schotte, P. Coucke, and J. De Baerdemaeker. 2000b. Development of an automated monitoring device to quantify changes in firmness of apples during storage. Postharv. Biol. Technol. 18:1-8.

Delwiche, M.J., T. McDonald, and S.V. Bowers. 1987. Determination of peach firmness by analysis of impact force. Trans. Am. Soc. Agr. Eng. 30:249-254.

Delwiche, M.J., N. Singh, H. Arevalo, and J. Mehlschau. 1991. A second generation fruit firmness sorter. Am. Soc. Agr. Eng. Paper 91-6042.

Delwiche, M.J., S. Tang, and J. J. Mehlschau. 1989. An impact force response fruit firmness sorter. Trans. Am. Soc. Agr. Eng. 32:321-326.

Dey, P.M., and E. del Campillo. 1984. Biochemistry of the multiple forms of glycosidases in plants. Adv. Enzymol. 56:141-249.

Diehl, K.C., and D.D. Hamann. 1979. Relationships between sensory profile parameters and fundamental mechanical parameters for raw potatoes, melons and apples. J. Text. Stud. 10:401-420.

Diehl, K.C., D.D. Hamann, and J.K. Whitfield. 1979. Structural failure in selected raw fruits and vegetables. J. Texture Studies 10:371-400.

Duprat, F., H. Chen, M. Grotte, et al. 1995. Laser light based machine vision system for nondestructive ripeness sensing of Golden apples, pp. 85-91. *In* J. de Baerdemaeker, and J. Vandewalle, eds., Proceedings of the 1st Workshop on Control Applications in Postharvest Processing Technology, June 1995, Ostend, Belgium.

El Assi, N.E., D.J. Huber, and J.K. Brecht. 1997. Irradiation-induced changes in tomato fruit and pericarp firmness, electrolyte efflux, and cell wall enzyme activity as influenced by ripening stage. J. Am. Soc. Hort. Sci. 122:100-106.

Errington, N., J.R. Mitchell, and G.A. Tucker. 1997. Changes in the force relaxation and compression responses of tomatoes during ripening: the effect of continual testing and polygalacturonase activity. Postharv. Biol. Technol. 11:141-147.

Fan, S., S.E. Prussia, and Y.C. Hung. 1994. Evaluating the UGA laser-puff food firmness detector. Amer. Soc. Agr. Eng. Paper 94-6540.

Farabee, L.M., and M.L. Stone. 1991. Determination of watermelon maturity with sonic impulse testing. Amer. Soc. Agr. Eng. Paper 91-3013.

Giovannoni, J.J., D. DellaPenna, A.B. Bennett, and R.L. Fischer. 1989. Expression of a chimeric polygalacturonase gene in transgenic *rin* (ripening inhibitor) tomato fruit results in polyuronide degradation but not fruit softening. Plant Cell 1:53-63.

Glenn, G.M., and B.W. Poovaiah. 1990. Calcium-mediated postharvest changes in texture and cell wall structure and composition in ‘Golden Delicious’ apples. J. Am. Soc. Hort. Sci. 115:962-968.

Greve, L.C., K.A. Shackel, H. Ahmadi, et al. 1994. Impact of heating on carrot firmness: contribution of cellular turgor. Jour. Agr. and Food Chemistry 42:2896-2899.

Haller, M.H. 1941. Fruit pressure testers and their practical applications. Circular 627, U.S. Department of Agriculture, Washington, DC.

Hamson, A.R. 1952. Measuring firmness of tomatoes in a breeding program. Proc. Am. Soc. Hort. Sci. 60:425-433.

Harker, F.R., and I.C. Hallett. 1992. Physiological changes associated with development of mealiness of apple fruit during cool storage. HortScience 27:1291-1294.

Harker, F.R.. and I.C. Hallett. 1994. Physiological and mechanical properties of kiwifruit tissue associated with texture change during cold storage. J. Am. Soc. Hort. Sci. 119:987-993.

Harker, F.R., J.H. Maindonald, and P.J. Jackson. 1996. Penetrometer measurement of apple and kiwifruit firmness: operator and instrument differences. J. Am. Soc. Hort. Sci.121:927-936.

Harker, F.R., R.J. Redgwell, I.C. Hallett, and S.H. Murray. 1997. Texture of fresh fruit. Hort. Rev. 20:121-224.

Harker, F.R., and P.W. Sutherland. 1993. Physiological changes associated with fruit ripening and the development of mealy texture during storage of nectarines. Postharv. Biol. Technol. 2:269-277.

Harris, P.J., A.M. Robertson, M.E. Watson, et al. 1993. The effects of soluble-fiber polysaccharides on the adsorption of a hydrophobic carcinogen to an insoluble dietary fiber. Nutr. Cancer 19:43-54.

Hatfield, S.G.S, and M. Knee. 1988. Effects of water loss on apples in storage. Intl. J. Food Sci. Technol. 23:575-585.

Hopkirk, G., J.H. Maindonald, and A. White. 1996. Comparison of four new devices for measuring kiwifruit firmness. N.Z. J. Crop Hort. Sci. 24:273-286.

Huber, D.J. 1992. The inactivation of pectin depolymerase associated with isolated tomato fruit cell wall: implications for the analysis of pectin solubility and molecular weight. Physiol. Plant. 86:25-32.

Hung, Y.C., K.H. McWatters, and S.E. Prussia. 1998. Sorting performance of a nondestructive laser air-puff firmness detector. Appl. Eng. Agr. 14:513-516.

Jackman, R.L., A.G. Marangoni, and D.W. Stanley. 1990. Measurement of tomato fruit firmness. HortScience 25:781-783.

Jackman, R.L., and D.W. Stanley. 1995. Creep behaviour of tomato pericarp tissue as influenced by ambient temperature ripening and chilled storage. J. Texture Studies.

Kader, A.A., L.L. Morris, and P. Chen. 1978. Evaluation of two objective methods and a subjective rating scale for measuring tomato fruit firmness. J. Am. Soc. Hort. Sci. 103:70-73.

Kajuna, S.T.A.R., W.K. Bilanski, and G.S. Mittal. 1998. Effect of ripening on the parameters of three stress relaxation models for banana and plantain. Appl. Eng. Agr. 14:55-61.

Kattan, A.A. 1957. Changes in color and firmness during ripening of detached tomatoes, and the use of a new instrument for measuring firmness. Proc. Am. Soc. Hort. Sci. 70:379-383.

Kawano, S., H. Abe, and M. Iwamoto. 1994. Novel applications of nondestructive techniques for quality evaluation of fruits and vegetables. *In* G. Brown and Y. Sarig, eds., Nondestructive Technologies for Quality Evaluation of Fruits and Vegetables, Proceedings of the International Workshop, US-Israel BARD Fund, Spokane, WA, June 1993, pp. 1-8. American Society of Agricultural Engineers, St. Joseph, MI.

Khan, A.A., and J.F.V. Vincent. 1993. Compressive stiffness and fracture properties of apple and potato parenchyma. J. Texture Studies. 24:423-435.

Lapsley, K.G., F.E. Escher, and E. Hoehn. 1992. The cellular structure of selected apple varieties. Food Struct. 11:339-349.

Lehman-Salada, L. 1996. Instrument and operator effects on apple firmness readings. HortScience 31:994-997.

Lin, T.T., and R.E. Pitt. 1986. Rheology of apple and potato tissue as affected by cell turgor pressure. J. Texture Stud. 17:291-313.

Lipton, W.J. 1990. Postharvest biology of fresh asparagus. Hort. Rev. 12:69-155.

Magness, J.R., and G.F. Taylor. 1925. An improved type of pressure tester for the determination of fruit maturity. Circular 350, U.S. Department of Agriculture, Washington, DC

McGlone, V.A., H. Abe, and S. Kawano. 1997. Kiwifruit firmness by near infrared light scattering. J. Near Infrared Spect. 5:83-89.

McGlone, V.A., and R.B. Jordan. 2000. Kiwifruit and apricot firmness measurement by the noncontact laser air-puff method. Postharv. Biol. Technol. 19:47-54.

McGlone, V.A., S.M.W. Ko, and R.B. Jordan. 1999. Noncontact fruit firmness measurement by the laser air-puff method. Trans. Amer. Soc. Agr. Eng. 42:1391-1397.

McGlone, V.A., and P.N. Schaare. 1993. The application of impact response analysis in the New Zealand fruit industry. Paper 93-6537, American Society of Agricultural Engineers, St. Joseph, MI.

Meilgaard, M., G.V. Civille, and B.T. Carr. 1999. Sensory evaluation techniques. CRC Press, Boca Raton, FL.

Mizrach, A., and U. Flitsanov. 1999. Nondestructive ultrasonic determination of avocado softening process. J. Food Eng. 40:139-144.

Mizrach, A., U. Flitsanov, Z. Schmilovitch, and Y. Fuchs. 1999. Determination of mango physiological indices by mechanical wave analysis. Postharvest Biol. Technol. 16:179-186.

Mizrach, A., D. C. Teitel, N. Galili, and G. Rosenhouse. 1994. Evaluation of some ripening parameters of autumn- and winter-grown 'Galia' melons. Scientia Hort. 56:291-297.

Mohsenin, N.N. 1986. Physical Properties of Plant and Animal Materials, 2nd ed. Gordon and Breach Science Publishers, New York, NY.

Muramatsu, N., N. Sakurai, N. Wada, et al. 2000. Remote sensing of fruit textural changes with a laser doppler vibrometer. J. Amer. Soc. Hort. Sci. 125:120-127.

Ng, A., and K.W. Waldron. 1997. Effect of steaming on cell chemistry of potatoes (*Solanum tuberosum* cv. Bintje) in relation to firmness. J. Agr. Food Chem. 45:3411-3418.

Okimoto, M.C. 1948. Anatomy and histology of the pineapple inflorescence and fruit. Bot. Gaz. 110:217-231.

Patel, N., V.A. McGlone, P.N. Schaare, and H. Hall. 1993. "BerryBounce": a technique for the rapid and nondestructive measurement of firmness in small fruit. Acta Hort. 352:189-198.

Peleg, K. 1999. Development of a commercial fruit firmness sorter. J. Agric. Eng. Res. 72:231-238.

Peleg, K., U. Ben-Hanan, and S. Hinga. 1990. Classification of avocado by firmness and maturity. J. Texture Studies 21:123-129.

Peleg, M., L. Gomez-Brito, and Y. Malevski. 1976. Compressive failure patterns of some juicy fruits. J. Food Sci. 41:1320-1324.

Peyron, M., L. Mioche, and J. Culioli. 1994. Bite force and sample deformation during hardness assessment of viscoelastic models of foods. J. Texture Studies 24:59-76.

Price, J.L., and J.D. Floros. 1993. Quality decline in minimally processed fruits and vegetables. Dev. Food Sci. 32:405-427.

Prussia, S.E., J.J. Astleford, Y.C. Hung, and R. Hewlett. 1994. Nondestructive firmness measuring device. U.S. Patent No. 5,372,030.

Ramana, S.V., and A.J. Taylor. 1992. Dynamic measurement of tissue rigidity during freezing and cooking of vegetables. J. Sci. Food Agr. 58:261-266.

Redgwell, R.J., E. MacRae, I. Hallett, et al. 1997. In vivo and in vitro swelling of cell walls during fruit ripening. Planta 203:162-173.

Rohrbach, R.P. 1981. Sorting blueberries to improve fresh market shelf life. Paper 81-1501, American Society of Agricultural Engineers, St. Joseph, MI.

Sakurai, N., and D.J. Nevins. 1992. Evaluation of stress-relaxation in fruit tissue. HortTechnology 2:398-402.

Schoorl, D., and J.E. Holt. 1983. A practical method for tensile testing of apple tissue. J. Texture Studies 14:155-164.

Schotte, S., N. De Belie, and J. De Baerdemaeker. 1999. Acoustic impulse-response technique for evaluation and modelling of firmness of tomato fruit. Postharv. Biol. Technol. 17:105-115.

Seymour, G.B., and K.C. Gross. 1996. Cell wall disassembly and fruit softening. Postharv. News Info. 7:45N-52N.

Shackel, K.A., C. Greve, J.M. Labavitch, and H. Ahmadi. 1991. Cell turgor changes associated with ripening in tomato pericarp tissue. Plant Physiol. 97:814-816.

Sherman, P. 1969. A texture profile of foodstuffs based upon well-defined rheological properties. J. Food Sci. 34:458-462.

Shewfelt, R.L. 1999. What is quality? Postharv. Biol. Technol. 15:197-200.

Shmulevich, I., N. Galili, and N. Benichou. 1995. Development of a nondestructive method for measuring the shelf-life of mango fruit, pp. 275-287, *In* Proceedings of the Food Processing Automation IV Conference, Chicago, IL, American Society of Agricultural Engineers, St. Joseph, MI.

Smith, S.M. 1985. Measurement of the quality of apples: recommendations of an EEC working group. Commission of the European Communities, Brussels, Belgium.

Sørensen, L. 1999. Harvest Splitting in Carrot (*Daucus carota* L.) Storage Roots. Ph.D. Thesis, The Royal Veterinary and Agricultural University, Copenhagen, Denmark.

Stone, M.L., P.R. Armstrong, D.D. Chen, and G.H. Brusewitz. 1998. Peach firmness prediction by multiple location impulse testing. Trans. Am. Soc. Agr. Eng. 41:115-119.

Stow, J. 1989. The involvement of calcium ions in maintenance of apple fruit tissue structure. J. Exp. Bot. 40:1053-1057.

Studman, C.J., and L. Yuwana. 1992. Twist test for measuring fruit firmness. J. Tex. Stud. 23:215-227.

Sundstrom, F.J., and S.J. Carter. 1983. Influence of K and Ca on quality and yield of watermelon. J. Am. Soc. Hort. Sci. 108:879-881.

Szczesniak, A.S. 1963. Classification of textural characteristics. J. Food Sci. 28:385-389.

Szczesniak, A.S., P.R. Humbaugh, and H.W. Block. 1970. Behavior of different foods in the standard compression cell of the shear press and the effect of sample weight on peak area and maximum force. J. Tex. Stud. 1:356-378.

Szczesniak, A.S., and R. Ilker. 1988. The meaning of textural characteristics - juiciness in plant foodstuffs. J. Texture Studies 19:61-78.

Thai, C.N. 1994. Soft transducer for firmness measurement. Paper 94-6538/94-6549, American Society of Agricultural Engineers, St. Joseph, MI.

Thybo, A.K., M. Nielsen, and M. Martens. 2000. Influence of uniaxial compression rate on rheological parameters and sensory texture prediction of cooked potatoes. J. Texture Studies 31:25-40.

Tomos, A.D. 1988. Cellular water relations in plants. Water Sci. Rev. 3:186-277.

Tong, C., D. Krueger, Z. Vickers, et al. 1999. Comparison of softening-related changes during storage of ‘Honeycrisp’ apple, it parents, and ‘Delicious.’ J. Am. Soc. Hort. Sci. 124:407-415.

Tu, K., P. Jancsok, B. Nicolai, and J. De Baerdemaeker. 2000. Use of laser-scattering imaging to study tomato-fruit quality in relation to acoustic and compression measurements. Int. J. Food Sci. Technol. 35:503-510.

Upchurch, B.L., G.E. Miles, R.L. Stroshine, et al. 1987. Ultrasonic measurement for detecting apple bruises. Trans. Am. Soc. Agr. Eng. 30:803-809.

Vincent, J.F.V. 1989. Relationship between density and stiffness of apple flesh. J. Sci. Food Agr. 47:443-462.

Voisey, P.W. 1971. Modernization of texture instrumentation. J. Texture Studies 2:129-195.

Voisey, P.W., and M. Kloek. 1981. Effect of cell size on the performance of the shear-compression texture test cell. J. Texture Studies. 12:133-139.

Waldron, K.W., A.C. Smith, A.J. Parr, et al. 1997. New approaches to understanding and controlling cell separation in relation to fruit and vegetable texture. Trends in Food Sc. Technol. 8:213-221.

Wann, E.V. 1996. Physical characteristics of mature green and ripe tomato fruit of normal and firm genotypes. J. Am. Soc. Hort. Sci. 121:380-383.

Wu, T., and J.A. Abbott. 2002. Firmness and force relaxation characteristics of tomatoes stored intact or as slices. Postharv. Biol. Technol. 24:59-68.

Zapp, H.R., S.H. Ehlert, G.K. Brown, et al. 1990. Advanced instrumented sphere (IS) for impact measurements. Trans. Am. Soc. Agr. Eng. 33:955-960.

Zhang, X., M.L. Stone, D. Chen, et al. 1994. Peach firmness determination by puncture resistance, drop impact, and sonic impulse. Trans. Am. Soc. Agr. Eng. 37:495-500.

Postharvest Pathology

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Introduction

Losses caused by postharvest diseases are greater than generally realized because the value of fresh fruits and vegetables increases several-fold while passing from the field to the consumer (Eckert and Sommer 1967). Postharvest losses are estimated to range from 10 to 30% per year despite the use of modern storage facilities and techniques (Harvey 1978).

Postharvest diseases affect a wide variety of crops, particularly in developing countries that lack sophisticated postharvest storage facilities (Jeffries and Jeger 1990). Infection by fungi and bacteria may occur during the growing season; at harvest time; during handling, storage, transport and marketing; or even after purchase by the consumer (Dennis 1983). Reduction of losses in perishable food crops resulting from postharvest diseases has become a major objective of international organizations (Kelman 1989). The reality is that there is a portending food crisis that will require the concerted efforts of all who are involved in food production to redouble their efforts. In fact, to adequately feed the world's expected 10 billion people within the next 40 to 50 years, food production efficiency and distribution will need to be improved immensely (Campbell 1998).

Specific causes of postharvest losses of fruits and vegetables may be classed as parasitic, nonparasitic, or physical (Cappellini and Ceponis 1984).This chapter deals with the parasitic causes that are of microbiological origin that begin as latent infections before harvest or occur at harvest or afterward during storage. Fungi are more commonly found attacking fruit, and bacteria are more common as postharvest pathogens of vegetables. This chapter will provide a general overview of the subject touching on noteworthy research where it can be used to illustrate postharvest pathology. The reader is encouraged to consult the references for specific information on the topics that are covered.

Factors that Influence Postharvest Pathology

Postharvest losses vary each year. Prevailing weather while the crop is growing and at harvest contribute greatly to the possibility of decay. Certain cultivars are more prone than others to decay caused by specific pathogens. Resistance of major apple cultivars to the fungi that cause blue mold, gray mold, bull's-eye rot, and Mucor rot depended on cultivar (Spotts et al. 1999). Condition of the crop, as determined by fertilizer and soil factors, is very important in susceptibility of the crop to disease. Maturity of the crop at harvest, handling, and type of storage have great influence on how long the crop can be stored without decay. The following sections address how these preharvest factors lead to disease in specific crops.

Weather. Weather affects many factors related to plant diseases, from the amount of inoculum that overwinters successfully to the amount of pesticide residue that remains on the crop at harvest (Conway 1984). Abundant inoculum and favorable conditions for infection during the season often result in heavy infection by the time the produce is harvested. For example, conidia of the fungus that causes bull's-eye rot are rain-dispersed from cankers and infected bark to fruit, especially if rainfall is prolonged near harvest time, resulting in rotten fruit in cold storage several months later (Spotts 1990).

Pinpoint or storage scab of apple caused by the same fungus that causes apple scab and gray mold caused by the fungus *Botrytis cinerea* are also very much influenced by the weather. Storage scab only occurs in years with unusually wet summers and early falls, when the fruit remain wet for a day or more. These late-season infections may not become visible until the apples are in storage (Pierson et al. 1971). Flowers and fruit are most vulnerable to *Botrytis cinerea* infection when conditions are wet. For example, in grapes infection occurs at 15 to 20 ºC (59 to 68 ºF) in the presence of free water after approximately 15 h (Bulit and Dubos 1988). In wet seasons, strawberries and raspberries may be harvested in apparently sound condition only to decay during transit and marketing (Snowdon 1990).

Postharvest decay involves further development of preharvest infections together with new infections arising from germination of spores on the fruit surface. From these examples it is apparent that decay often has a weather component, making thorough weather records an important source of information for predicting possible decay in storage.

Physiological Condition. Condition of produce at harvest determines how long the crop can be safely stored. For example, apples are picked mature but preclimacteric to ensure that they can be stored safely for several months. The onset of ripening and senescence in various fruit and vegetables renders them more susceptible to infection by pathogens (Kader 1985). On the other hand, fruit and vegetables can be made less prone to decay by management of crop nutrition. For example, calcium has been more closely related to disease resistance than any other cation associated with the cell wall (Sams 1994).

In a study on the effect of increased flesh calcium content of apples in storage, fruit were treated with solutions of $CaCl_2$ by dipping, vacuum, or pressure infiltration. Both vacuum and pressure infiltration increased calcium content of the fruit sufficiently to significantly reduce decay (Conway 1982). Increased calcium contents in potatoes and peaches have also been documented with reduced postharvest decay (Conway 1989). In general, produce containing adequate levels of calcium do not develop physiological disorders and can be stored longer before they breakdown or decay. Conversely, high nitrogen content in fruit predisposes them to decay (Conway 1984). In pears, it has been found that management of trees for low nitrogen and high calcium in the fruit reduced severity of postharvest fungal decay (Sugar et al. 1992). Apple cultivars can be selected for resistance to certain postharvest diseases (Spotts et al. 1999). For example, 'Royal Gala' is extremely resistant to wound pathogens, 'Granny Smith' to skin punctures, and 'Braeburn' to infiltration of fungal spores into the core.

Fungicide Sprays. Certain preharvest sprays are known to reduce decay in storage. Several studies done on the effectiveness of preharvest ziram fungicide application on pome fruit showed an average reduction in decay of about 25 to 50% with a single spray (Sugar and Spotts 1995). Iprodione was used for several years as a preharvest spray 1 day before harvest to prevent infection of stone fruit by *Monilinia* spp. In combination with wax and/or oil, its decay control spectrum is increased and it will also control postharvest fungi such as *Rhizopus* and *Alternaria* (Ogawa et al. 1992). Cyprodinil prevented gray mold infection in apple 3 months after it was applied (Sholberg and Bedford 1999). The new class of strobilurin fungicides promises to provide postharvest control of several diseases in fruits and vegetables, is especially effective against fruit scab on apples, and should reduce the presence of pinpoint scab in storage.

Packing Sanitation. It is important to maintain sanitary conditions in all areas where produce is packed. Organic matter (culls, extraneous plant parts, and soil) can act as substrates for decay-causing pathogens. For example, in apple and pear packinghouses, the flumes and dump tank accumulate spores (Blanpied and Purnasiri 1968) and may act as sources of contamination if steps are not taken to destroy or remove them.

Chlorine readily kills microorganisms suspended in dump tanks and flumes if the amount of available chlorine is adequate. A level of 50 to 100 ppm of active chlorine provides excellent fungicidal activity (Spotts and Peters 1980). Chlorine measured as hypochlorous acid can be obtained by adding chlorine gas, sodium hypochlorite, or dry calcium hypochlorite. Though chlorine effectively kills spores in water, it does not protect wounded tissue against subsequent infection from spores lodged in wounds. Organic matter in the water inactivates chlorine, and levels of chlorine must be constantly monitored. The use of a sand filter in association with chlorination improves its efficiency probably because it removes organic matter (Sholberg and Owen 1990). Chlorine is sensitive to pH (Dychdala 1983): Hypochlorite solutions with higher pH values (7.5 to 8.5) are more stable but less fungicidal, whereas at lower pH values (5.5 to 6.5) the solutions are less stable but more fungicidal.

Chlorine dioxide can replace hypochlorite in some sanitizing processes, because several disadvantages limit the use of chlorine, including its unpleasant odor. Chlorine dioxide is not corrosive and is effective over a wide pH range (Spotts and Peters 1980). Recently in precisely controlled tests in water or as a foam, chlorine dioxide was found to be effective against common postharvest decay fungi on fruit packinghouse surfaces (Roberts and Reymond 1994). Peracetic acid is another material that could be used (Mari et al. 1999). It has greater stability and faster biocidal properties than chlorine dioxide but is more corrosive.

The search goes on for effective and economical sanitizing agents. New and old products alike are continually being evaluated under present-day packing operations. Interest in ozone has been rekindled with development of more efficient ozone generators. Acetic acid in the form of a gas can be used as a sanitizing agent on several crops (Sholberg 1998). It was as effective as SO_2 in preventing gray mold decay in table grapes stored for 2 months (Sholberg et al. 1996).

Postharvest Treatments. Products or treatments used to control postharvest decay can be classified as either chemical or biological and should be selected only after proper consideration of the following conditions (Ogawa and Manji 1984):

- Type of pathogen involved in the decay
- Location of the pathogen in the produce
- Best time for application of the treatment
- Maturity of the host
- Environment during storage, transportation, and marketing of produce

Chemical Control

Several fungicides are currently used as postharvest treatments for control of a wide spectrum of decay-causing microorganisms. However, when compared with preharvest pest-control products, the number is very small. Many products formerly used after harvest are no longer permitted because of concerns with residues and possible toxic effects, the most notable being products that contain benomyl. Other products are no longer as effective because of development of resistance by the target pathogen. For example, intensive and continuous use of fungicides for control of blue and green mold on citrus has led to resistance by the causal pathogens of these diseases (Eckert 1988). Resistance has been reported in many other crops to several different fungicides with different modes of action (Delp 1988). Resistance development continues to be a major problem and has resulted in the Fungicide Resistance Action Committee (FRAC), a cooperative effort among various producers of fungicides to delay resistance by recommending specific management guidelines (FRAC 1998).

Examples of chemicals currently used for postharvest treatments are thiabendazole, dichloran, and imazalil. However, resistance to thiabendazole and imazalil is widespread (Holmes and Eckert 1999), and their use as effective materials is declining. Preservatives or antimicrobial food additives are not generally thought of as postharvest treatments, but they do control decay and, in some cases, are the only means of control. These products include sodium benzoate, the parabens, sorbic acid, propionic acid, SO_2, acetic acid, nitrites and nitrates, and antibiotics such as nisin (Chichester and Tanner 1972). In California, for example, gray mold of stored table grapes is prevented by fumigation with SO_2 (Luvisi et al. 1992). The demand for new postharvest fungicide treatments is strong, especially since the loss of iprodione in 1996.

Fludioxinil was granted an emergency registration in 1998 to curb potential losses in nectarines, peaches, and plums (Forster and Adaskaveg 1999). Not all postharvest pathogens are currently controlled by materials that are available. For example, *Mucor piriformis*, a major postharvest pathogen of apples and winter pears in the Pacific Northwest is not controlled by any registered fungicide (Spotts and Dobson 1989). There is a dire need for new fungicide treatments that could in part be alleviated by using biological control agents (Wisniewski and Wilson 1992, Utkhede and Sholberg 1993).

Biological Control

Postharvest biological control is an approach that offers several advantages over conventional biological control (Wilson and Pusey 1985, Pusey 1996), such as the following:

- Exact environmental conditions can be established and maintained.
- The biocontrol agent can be targeted much more efficiently
- Expensive control procedures are cost effective on harvested food.

Several biological control agents have been developed, and a few have actually been registered for use on fruit crops. The first biological control agent developed for postharvest use was a strain of *Bacillus subtilis* (Pusey and Wilson 1984). It controlled peach brown rot, but when a commercial formulation of the bacterium was made, adequate disease control was not obtained (Pusey 1989). More recently, a strain of *Pseudomonas syringae* van Hall was found that controlled both blue and gray mold of pome fruit (Janisiewicz and Marchi 1992). It was subsequently registered and is now sold commercially for postharvest disease control (Janisiewicz and Jeffers 1997).

Other bacterial microorganisms have been developed for postharvest disease control. For example, strains of *Bacillus pumilus* and *Pseudomonas fluorescens* have been identified that exhibit successful control of *B. cinerea* in field trials of strawberry (Swalding and Jeffries 1998). Yeasts such as *Pichia guilliermondii* (Wisniewski et al. 1991) and *Cryptoccocus laurentii*, which occur naturally on apple leaves, buds, and fruit (Roberts 1990), were the first to be applied for control of postharvest decay on fruit. The yeast *Candida oleophilia* has been registered for control of postharvest decay on fruit crops. The yeasts *Cryptococcus infirmo-minutus* and *Candida sake* successfully control brown rot and blue mold on sweet cherry (Spotts et al. 1998) and on three diseases of apple (Vinas et al. 1998), respectively.

Though there is no doubt that biocontrols are effective, they do not always give consistent results. This could be because biocontrol efficacy is directly affected by the amount of pathogen inoculum present (Roberts 1994). Compatibility with chemicals used during handling is also important. Indications are that biological control agents must be combined with other strategies if they are to provide acceptable disease control.

Irradiation for Postharvest Decay Control

Though ultraviolet light has a lethal effect on bacteria and fungi that are exposed to the direct rays, there is no evidence that it reduces decay of packaged fruits and vegetables (Hardenburg et al. 1986). Low doses of ultraviolet light irradiation (254 nm UV-C) reduced postharvest brown rot of peaches (Stevens et al. 1998). In this case, the low-dose ultraviolet light treatments had two effects on brown rot development: reduction in the inoculum of the pathogen and induced resistance in the host. However, it has not become a practical postharvest treatment as yet and requires more research.

Gamma radiation has been studied for controlling decay, disinfecting, and extending the storage life and shelf-life of fresh fruits and vegetables. Dosages of 1.5 to 2 kilograys (kGy) and, in some cases, 3.0 kGy (300 krad) have been effective in controlling decay in several products (Hardenburg et al. 1986). A dose of 250 grays (Gy) has an adverse effect on grapefruits, increasing skin pitting, scald, and decay. Low doses of 150 Gy for fruit flies and 250 Gy for codling moth are acceptable quarantine procedures (Meheriuk and Gaunce 1994). Commercial application of gamma radiation is limited by the cost and size of equipment needed for treatment and by uncertainty about consumers' acceptance of irradiated foods (Hardenburg et al. 1986). Gamma irradiation may be used more in the future once methyl bromide is no longer available to control insect infestation in stored products. All uses of methyl bromide are being phased out to avoid any further damage to the protective layer of ozone surrounding the earth.

Effect of Storage Environment on Postharvest Decay

Commercial producers and handlers modify temperature, RH, and atmospheric composition during prestorage, storage, and transit to control decay (Spotts 1984). For optimum decay control, two or more factors often are modified simultaneously.

Temperature and RH. Proper management of temperature is so critical to postharvest disease control that all other treatments can be considered as supplements to refrigeration (Sommer 1989). Fruit rot fungi generally grow optimally at 20 to 25 ºC (68 to 77 °F) and can be conveniently divided into those with a growth minimum of 5 to 10 ºC (41 to 50 °F) and those with a growth minimum of -6 to 0 ºC (21 to 32 °F). Fungi with a minimum growth temperature below -2 ºC (28 °F) cannot be completely stopped by refrigeration without freezing the fruit. However, temperatures as low as possible are desirable because they significantly slow growth and thus reduce decay.

High temperature may be used to control postharvest decay on crops that are injured by low temperatures, such as mango, papaya, pepper, and tomato (Spotts 1984). Though hot water generally is more effective, hot air has been used to control decay in crops that are injured by hot water. Heating of pears at temperatures from 21 to 38 ºC (70 to 100 °F) for 1 to 7 days reduced postharvest decay (Spotts and Chen 1987). Decay in 'Golden Delicious' apples was reduced by exposure to 38 ºC (100 °F) for 4 days (Sams et al. 1993) and virtually eliminated when treated after inoculation (Fallik et al. 1995, Klien et al. 1997). Heat treatment eliminates incipient infections and improves coverage by fungicides (Couey 1989). The primary obstacle to the widespread use of heat to control postharvest fruit diseases or insect infestation is the sensitivity of many fruit to the temperatures required for effective treatment.

Both low and high RH have been related to postharvest decay control. Perforated polyethylene bags for fruit and vegetable storage create RH about 5 to 10% above that in storage rooms. Though shrivel and weight loss are reduced, decay may increase (Spotts 1984). Crops with well-developed cuticle and epidermis, such as apples and pears, tolerate lower RH levels, which helps prevent storage decay. Often fungal spore germination is inhibited at low RH, and small differences in RH can have significant effects in relation to the degree of postharvest decay (Spotts and Peters 1981).

Modified or Controlled Atmospheres. Alterations in O_2 and CO_2 concentrations are sometimes provided around fruit and vegetables (Spotts 1984). With close control of these gases, the synthetic atmosphere is commonly called a "controlled atmosphere"; the term "modified atmosphere" is used when there is little possibility of adjusting gas composition during storage or transportation (Sommer 1989). Because the pathogen respires as does produce, lowering O_2 or raising CO_2 above 5% can suppress pathogenic growth in the host. In crops such as stone fruits, a direct suppression occurs when fungal respiration and growth are reduced by the high CO_2 of the modified atmosphere. For example, CO_2 added to air has been widely used in the transport of 'Bing' cherries, primarily to suppress gray mold and brown rot. Low O_2 does not appreciably suppress fungal growth until the concentration falls below

2%. Important growth reductions result if O_2 is lowered to 1% or less, though there is a danger that the crop will start respiring anaerobically and develop off flavors. Other technologies that have been tested for lowering postharvest decay with limited success are storage and transport under low O_2 and the use of carbon monoxide (Spotts 1984, Sommer 1989).

Postharvest Diseases of Fruits

Fruit crops are attacked by a wide range of microorganisms in the postharvest phase (Snowdon 1990, Ogawa and English 1991). Actual disease only occurs when the attacking pathogen starts to actively grow in the host. Diseases are loosely classified according to their signs and symptoms. Signs are visible growths of the causal agents, and symptoms the discernible responses produced by the host. In many diseases there is local discoloration and disruption of tissue, with the formation of obvious lesions. Postharvest diseases are caused primarily by microscopic bacteria and fungi, with fungi the most important causal agent in fruit crops.

Fungi are further subdivided into classes and are described as “lower fungi” (characterized by the production of sporangia giving rise to numerous sporangiospores) or “higher fungi” (described as ascomycetes, deuteromycetes, and basidiomycetes.) Ascomycetes are exemplified by fruiting bodies that release sexual spores when mature. Deuteromycetes, a form of ascomycete, only release asexual spores. They are more common than the sexual ascomycete stage in postharvest crops. Deuteromycetes are further subdivided into hyphomycetes and coelomycetes based on spore and structural characteristics. The agonomycetes contain important soil pathogens that form survival structures known as “sclerotia,” which allow them to survive in the absence of the host. These fungi and the rust and smut fungi are examples of basidiomycetes. Table 1 lists many important diseases of fruit crops according to host and causal agents.

Postharvest Diseases of Vegetables

Postharvest diseases of vegetables are caused by microscopic fungi and bacteria (Snowdon 1992, Howard et al. 1994). Bacteria are more common as pathogens of vegetables than fruit because, in general, vegetables are less acidic than fruit. Bacteria are visible under the light microscope as mostly single-celled rods. Bacteria are capable of very rapid multiplication under the right conditions of pH, temperature, and nutrition. They are classified according to their size, shape, reaction to certain stains, and behavior on various growth media (Krieg and Holt 1984). The term “vegetable” encompasses a range of plant parts, and the common definition is a culinary one, denoting consumption as a savory rather than as a dessert food (Snowdon 1992). Many vegetables are fruits in the botanical sense, notable examples being tomatoes, peppers, squashes, and cucumbers. Table 2 lists many of the important diseases of vegetable crops according to host and causal agents.

Table 1. Important postharvest diseases of fruit

Fruit	Disease	Causal agent	Fungal class/type
Avocado	Anthracnose	*Glomerella cingulata*	Pyrenomycete
	Cercospora spot	*Pseudocercospora purpurea*	Hyphomycete
	Dothiorella rot	*Botryosphaeria ribis*	Loculoascomycete
	Scab	*Sphaceloma persae*	Coleomycete
	Stem-end rots	*B. theobromae*, *Phomopsis perseae*, *Thyronectria pseudotrichia*	Deuteromycetes
Banana	Anthracnose	*Colletotrichum musae*	Coelomycete
	Cigar-end rot	*Trachysphaera fructigena*, *Verticillium theobromae*	Deuteromycetes
	Crown rot	*C. musae*, *Fusarium pallidoroseum*, *V. theobromae*	Deuteromycetes
	Finger rot	*B. theobromae*	Coelomycete
	Pitting disease	*Pyricularia grisea*	Hyphomycete
	Sigatoka disease	*Mycosphaerella* spp.	Loculoascomycete
Berries	Gray mold	*Botrytis cinerea*	Hyphomycete
	Leak	*Mucor* spp.	Zygomycete
	Leather rot	*Phytophthora* spp.	Oomycete
Citrus	Alternaria rot	*Alternaria* spp.	Hyphomycete
	Anthracnose	*C. gloeosporioides*	Coelomycete
	Bacterial canker	*Xanthomonas campestris*	Bacterium
	Black pit	*Pseudomonas syringae*	Bacterium
	Black spot	*Phyllosticta citricarpa*	Coelomycete
	Blue mold	*Penicillium italicum*	Hyphomycete
	Brown rot	*Phytophthora* spp.	Oomycete
	Greasy spot	*Mycosphaerella citri*	Loculoascomycete
	Green mold	*P. digitatum*	Hyphomycete
	Scab	*Elsinoe fawcettii*	Loculoascomycete
	Sour rot	*Geotrichum candidum*	Hyphomycete
	Stem-end rots	*D. gregaria*, *Phomopsis citri*, *B. theobromae*	Coelomycete
Kiwifruit	Gray mold	*B. cinerea*	Hyphomycete
Grape	Aspergillus rot	*Aspergillus niger*	Hyphomycete
	Blue mold	*Penicillium* spp.	Hyphomycete
	Gray mold	*B. cinerea*	Hyphomycete
	Rhizopus rot	*Rhizopus* spp.	Zygomycete

Table 1. Important postharvest diseases of fruit—*Continued*

Fruit	Disease	Causal agent	Fungal class/type
Mango	Anthracnose	*C. gloeosporioides*	Coelomycete
	Botryodiplodia rot	*B. theobromae*	Coelomycete
	Stem-end rots	*B. theobromae, Phomopsis* spp.	Coelomycete
Papaya	Anthracnose	*C. gloeosporioides*	Coelomycete
	Black rot	*Phoma caricae-papayae*	Coelomycete
	Phytophthora rot	*P. palmivora*	Oomycete
	Rhizopus rot	*R. stolonifer*	Zygomycete
	Stem-end rot	*B. theobromae, Phomopsis* spp.	Coelomycete
Pineapple	Black rot	*Thielaviopsis paradoxa*	Hyphomycete
	Fruitlet core rot	*Fusarium moniliforme, P. funiculosum*	Hyphomycete
Pome fruit (apple, pear)	Bitter rot	*C. gloeosporioides*	Coelomycete
	Black rot	*Sphaeropsis malorum*	Coelomycete
	Blue mold	*Penicillium expansum, Penicillium* spp.	Hyphomycete
	Brown rot	*Monilinia* spp.	Hyphomycete
	Bull's-eye rot	*Cryptosporiopsis curvispora*	Hyphomycete
	Gray mold	*B. cinerea*	Hyphomycete
	Moldy core	*Alternaria* spp., others	Hyphomycete
	Mucor rot	*Mucor piriformis*	Zygomycete
	White rot	*D. gregaria*	Coelomycete
Stone fruit (cherry, etc.)	Alternaria rot	*A. alternata*	Hyphomycete
	Blue mold	*P. expansum*	Hyphomycete
	Brown rot	*Monilinia* spp.	Hyphomycete
	Rhizopus rot	*Rhizopus* spp.	Zygomycete

Table 2. Important postharvest diseases of vegetables

Vegetable	Disease	Causal Agent	Fungal Class/Type
Bulbs	Bacterial soft rot	*Erwinia caratovora*	Bacterium
(onion, garlic)	Black rot	*Aspergillus niger*	Hyphomycete
	Blue mold rot	*Penicillium* spp.	Hyphomycete
	Fusarium basal rot	*Fusarium oxysporum*	Hyphomycete
	Neck rot	*Botrytis* spp.	Hyphomycete
	Purple blotch	*Alternaria porri*	Hyphomycete
	Sclerotium rot	*Sclerotium rolfsii*	Agonomycete
	Smudge	*Colletotrichum circinans*	Coelomycete
Crucifers	Alternaria leaf spot	*Alternaria* spp.	Hyphomycete
(cabbage, etc.)	Bacterial soft rot	*E. caratovora*	Bacterium
	Black rot	*Xanthomonas campestris*	Bacterium
	Downy mildew	*Peronospora parasitica*	Oomycete
	Rhizoctonia rot	*Rhizoctonia solani*	Agonomycete
	Ring spot	*Mycosphaerella brassicicola*	Loculoascomycete
	Virus diseases	Cauliflower mosaic virus, turnip mosaic virus	Virus
	Watery soft rot	*Sclerotinia* spp.	Discomycete
	White blister	*Albugo candida*	Oomycete
Cucurbits	Anthracnose	*Colletotrichum* spp.	Coelomycete
(cucumber, etc.)	Bacterial soft rot	*Erwinia* spp.	Bacterium
	Black rot	*Didymella bryoniae*	Loculoascomycete
	Botryodiplodia rot	*Botryodiplodia theobromae*	Coelomycete
	Charcoal rot	*Macrophomina phaseolina*	Coelomycete
	Fusarium rot	*Fusarium* spp.	Hyphomycete
	Leak	*Pythium* spp.	Oomycete
	Rhizopus rot	*Rhizopus* spp.	Zygomycete
	Sclerotium rot	*Sclerotium rolfsii*	Agonomycete
	Soil rot	*R. solani*	Agonomycete
Legumes	Alternaria blight	*A. alternata*	Hyphomycete
(peas, beans)	Anthracnose	*Colletotrichum* spp.	Coelomycete
	Ascochyta pod spot	*Ascochyta* spp.	Coelomycete
	Bacterial blight	*Pseudomonas* spp., *Xanthomonas* spp.	Bacteria
	Chocolate spot	*B. cinerea*	Hyphomycete
	Cottony leak	*Pythium* spp.,	Oomycete
		Mycosphaerella blight, *M. pinodes*	Loculoascomycete
	Rust	*Uromyces* spp.	Hemibasidiomycete
	Sclerotium rot	*S. rolfsii*	Agonomycete
	Soil rot	*R. solani*	Agonomycete
	White mold	*Sclerotinia* spp.	Discomycete

Table 2. Important postharvest diseases of vegetables—*Continued*

Vegetable	Disease	Causal Agent	Fungal Class/Type
Roots/tubers			
Carrots	Bacterial soft rot	*Erwinia* spp., *Pseudomonas* spp.	Bacteria
	Black rot	*A. radicina*	Hyphomycete
	Cavity spot	Disease complex	Soil fungi
	Chalaropsis rot	*Chalara* spp.	Hyphomycete
	Crater rot	*R. carotae*	Agonomycete
	Gray mold rot	*B. cinerea*	Hyphomycete
	Sclerotium rot	*S. rolfsii*	Agonomycete
	Watery soft rot	*Sclerotinia* spp.	Discomycete
Potatoes	Bacterial soft rot	*Erwinia* spp.	Bacteria
	Blight	*Phytophthora infestans*	Oomycete
	Charcoal rot	*S. bataticola*	Agonomycete
	Common scab	*Streptomyces scabies*	Actinomycete
	Fusarium rot	*Fusarium* spp.	Hyphomycete
	Gangrene	*Phoma exigua*	Coelomycete
	Ring rot	*Clavibacter michiganensis*	Bacterium
	Sclerotium rot	*S. rolfsii*	Agonomycete
	Silver scurf	*Helminthosporium solani*	Hyphomycete
	Watery wound rot	*Pythium* spp.	Oomycete
Sweet potatoes	Black rot	*Ceratocystis fimbriata*	Pyrenomycete
	Fusarium rot	*Fusarium* spp.	Hyphomycete
	Rhizopus rot	*Rhizopus* spp.	Zygomycete
	Soil rot	*Streptomyces ipomoeae*	Actinomycete
	Scurf	*Monilochaetes infuscans*	Hyphomycete
Solanaceous plants (tomato, pepper, eggplant)	Alternaria rot	*A. alternata*	Hyphomycete
	Anthracnose	*Colletotrichum* spp.	Coelomycete
	Bacterial canker	*C. michiganensis*	Bacterium
	Bacterial speck	*Pseudomonas syringae*	Bacterium
	Bacterial spot	*X. campestris*	Bacterium
	Fusarium rot	*Fusarium* spp.	Hyphomycete
	Gray mold rot	*B. cinerea*	Hyphomycete
	Late blight	*P. infestans*	Oomycete
	Phoma rot	*Phoma lycopersici*	Hyphomycete
	Phomopsis rot	*Phomopsis* spp.	Coelomycete
	Phytophthora rot	*Phytophthora* spp.	Oomycete
	Pleospora rot	*Stemphylium herbarum*	Hyphomycete
	Rhizopus rot	*Rhizopus* spp.	Zygomycetes

Table 2. Important postharvest diseases of vegetables—*Continued*

Vegetable	Disease	Causal Agent	Fungal Class/Type
	Sclerotium rot	*S. rolfsii*	Agonomycete
	Soil rot	*R. solani*	Agonomycete
	Sour rot	*Geotrichum candidum*	Hyphomycete
	Watery soft rot	*Sclerotinia* spp.	Discomycete
Miscellaneous			
Artichokes	Gray mold	*Botrytis cinerea*	Hyphomycete
	Watery soft rot	*Sclerotinia sclerotiorum*	Discomycete
Asparagus	Bacterial soft rot	*Erwinia* or *Pseudomonas* spp.	Bacteria
	Fusarium rot	*Fusarium* spp.	Hyphomycete
	Phytophthora rot	*Phytophthora* spp.	Oomycete
	Purple spot	*Stemphylium* spp.	Hyphomycete
Celery	Bacterial soft rot	*Erwinia* or *Pseudomonas* spp.	Bacteria
	Brown spot	*Cephalosporium apii*	Hyphomycete
	Cercospora spot	*Cercospora apii*	Hyphomycete
	Gray mold	*Botrytis cinerea*	Hyphomycete
	Licorice rot	*Mycocentrospora acerina*	Hyphomycete
	Phoma rot	*Phoma apiicola*	Coelomycete
	Pink rot	*Sclerotinia* spp.	Discomycete
	Septoria spot	*Septoria apiicola*	Coelomycete
Lettuce	Bacterial rot	*Erwinia, Pseudomonas, Xanthomonas* spp.	Bacteria
	Gray mold rot	*B. cinerea*	Hyphomycete
	Rhizoctonia rot	*R. solani*	Agonomycete
	Ringspot	*Microdochium panattonianum*	Hyphomycete
	Septoria spot	*S. lactucae*	Coelomycete
	Stemphylium spot	*Stemphylium herbarum*	Hyphomycete
	Watery soft rot	*Sclerotinia* spp.	Discomycete

New Directions for Postharvest Plant Pathology

Postharvest plant pathology has changed its emphasis in the last decade. Food safety has emerged as a key element in decay control programs. Continued failure to effectively control certain postharvest diseases and the need for more environmentally friendly crop control materials require a new approach to disease control. Integrated postharvest decay control is the concept that offers the most promise for the future. Society can no longer rely on one or two control strategies but must enlist the entire spectrum of strategies to reduce postharvest losses.

Food Safety Issues

The two most important causes of unsafe food are microbial toxins (Hsieh and Gruenwedel 1990) and contamination of horticultural products by fecal coliforms (Gould 1973). The microbial toxins can be subdivided into bacterial toxins and toxins produced by fungi or mycotoxins. An example of a microbial toxin that is extremely toxic are the botulinum toxins produced by the anaerobic bacterium *Clostridium botulinum*.

Interest in toxins produced by fungi was stimulated by the death of 100,000 turkey poults in England in 1960. Aflatoxins produced by fungi in the peanut meal used to feed the birds was the cause. Studies have since shown aflatoxins to be potent carcinogens that may occur in nuts and grain (Phillips 1984, Ellis et al. 1991). Other toxins have been identified that are produced by the same fungi that cause postharvest decay. For example, patulin produced by *Penicillium* and *Aspergillis* spp. can be found in apple and pear products. Patulin is toxic to many biological systems but its role in causing animal and human disease is unclear (Hsieh and Gruenwedel 1990).

Studies on contamination of horticultural products by fecal coliforms has increased dramatically because of documented incidences of food poisoning from apple juice and seed sprouts. Definite interactions have been shown between plant pathogens and foodborne human pathogens such as *Salmonella* and *Listeria*. A study involving more than 400 samples each of healthy and soft-rotted commodities collected in retail markets indicated that the presence of *Salmonella* on produce affected by bacterial soft rot was twice that of healthy samples (Wells and Butterfield 1997). Controlled experiments with potato, carrot, and pepper tissues inoculated with a strain of *Salmonella* confirmed that bacterial soft rot infection increased multiplication of *Salmonella* by at least three- to ten-fold compared with multiplication on uninfected tissues. Similarly, populations of *Listeria monocytogenes*, inoculated into decayed apple tissue, continually increased on fruit decayed by *Glomerella cingulata* but did not survive after 5 days on fruit decayed by *Penicillium expansum* (Conway et al. 2000). The pH of the decayed area declined from pH 4.7 to 3.7 in the case of *P. expansum* but increased from pH 4.7 to 7.0 in the case of *G. cingulata*. This pH modification may be responsible for affecting growth of the foodborne pathogen.

Contamination of produce with human pathogens is an important issue that must be addressed along with limiting decay caused by postharvest pathogens and maintaining product quality.

Integrated Control of Postharvest Diseases

Effective and consistent control of storage diseases depends on integration of the following practices:

- Select disease-resistant cultivars where possible.
- Maintain correct crop nutrition by use of leaf and soil analysis.
- Irrigate based on crop requirements and avoid overhead irrigation.
- Apply preharvest treatments to control insects and diseases.
- Harvest crop at the correct maturity for storage.
- Apply postharvest treatments to disinfest and control diseases and disorders on produce.

- Maintain good sanitation in packing areas and keep dump-water free of contamination.
- Store produce under conditions least conducive to growth of pathogens.

Integration of cultural methods and biological treatments with yeast biocontrols has been studied on pears (Sugar et al. 1994). It was found that early harvest, low fruit nitrogen, high fruit calcium, yeast or yeast plus fungicide treatment, and controlled atmosphere storage all reduced severity of blue mold and side rot. These results demonstrated that unrelated cultural and biological methods that influenced pear decay susceptibility can be combined into an integrated program to substantially reduce decay.

In another example of an integrated strategy, 'Gala' apples were heat-treated at 38 °C (100 °F) for 4 days, followed by calcium infiltration with 2% $CaCl_2$, and then treated with the microbial antagonist, *Pseudomonas syringae* (Conway et al. 1999). The combined strategy was much more effective than any single strategy for two reasons. First, heat treatment reduced the pathogen population on the fruit surface but did not provide any residual protection. Second, the residual protection was provided by calcium, and the biocontrol agent added to the control provided by the heat treatment.

As a general rule, alternatives to chemical control are often less effective than many fungicides. It is highly unlikely that any one alternative method alone will give the same level of control as fungicides. Therefore, it will generally be necessary to combine several alternative methods to develop an integrated strategy to successfully reduce postharvest decay.

References

Blanpied, G.D., and A. Purnasiri. 1968. *Penicillium* and *Botrytis* rot of McIntosh apples handled in water. Plant Dis. Rep. 52:865-867.

Bulit, J., and B. Dubos. 1988. Botrytis bunch rot and blight. *In* R.C. Pearson and A.C. Goheen, eds., Compendium of Grape Diseases, pp. 13-15. APS Press, St. Paul, MN.

Campbell, C.L. 1998. Food security and plant pathologists. Phytopathol. News 32:70.

Cappellini, R.A., and M.J. Ceponis. 1984. Postharvest losses in fresh fruits and vegetables. *In* H.E. Moline, ed., Postharvest Pathology of Fruits and Vegetables: Postharvest Losses in Perishable Crops, pp. 24-30. Bull. 1914 (Pub NE-87), University of California, California Agricultural Experiment Station, Davis, CA.

Chichester, D.F., and F.W. Tanner. 1972. Antimicrobial food additives. *In* T.E. Furia, ed., CRC Handbook of Food Additives, vol. 1, pp. 115-184. CRC Press, Boca Raton, FL.

Conway, W.S. 1982. Effect of postharvest calcium treatment on decay of 'Delicious' apples. Plant Dis. 66:402-403.

Conway, W.S. 1984. Preharvest factors affecting postharvest losses from disease. *In* H.E. Moline, ed., Postharvest Pathology of Fruits and Vegetables: Postharvest Losses in Perishable Crops, pp. 11-16. Bull. 1914 (Pub NE-87), University of California, California Agricultural Experiment Station, Davis, CA.

Conway, W.S. 1989. Altering nutritional factors after harvest to enhance resistance to postharvest disease. Phytopathology 79:1384-1387.

Conway, W.S., W.J. Janisiewicz, J.D. Klein, and C.E. Sams. 1999. Strategy for combining heat treatment, calcium infiltration, and biological control to reduce postharvest decay of 'Gala' apples. HortScience 34:700-704.

Conway, W.S., B. Leverentz, R.A. Saftner, et al. 2000. Survival and growth of *Listeria monocytogenes* on fresh-cut apple slices and its interaction with *Glomeralla cingulata* and *Penicillium expansum*. Plant Dis. 84:177-181.

Couey, H.M. 1989. Heat treatment for control of postharvest diseases and insect pests of fruits. HortScience 24:198-202.

Delp, C.J. 1988. Fungicide Resistance in North America, pp. 11-16. APS Press, St. Paul, MN.

Dennis, C. 1983. Postharvest Pathology of Fruits and Vegetables. Academic Press, London, UK.

Dychdala, G.R. 1983. Chlorine and chlorine compounds. *In* S.S. Block, ed., Disinfection, Sterilization, and Preservation, 3rd ed., pp. 157-182. Lea & Febiger Co., Philadelphia, PA.

Eckert, J.W., and N.F. Sommer. 1967. Control of diseases of fruits and vegetables by postharvest treatment. Ann. Rev. Plant Pathol. 5:391-432.

Eckert, J.W. 1988. Dynamics of benzimidazole-resistant penicillia in the development of postharvest decay of citrus and pome fruits. *In* C.J. Delp, ed., Fungicide Resistance in North America, pp. 31-35. APS Press, St. Paul, MN.

Ellis, W.O., J.P. Smith, B.K. Simpson, and J.H. Oldham. 1991. Aflatoxins in food: occurrence, biosynthesis, effects on organisms, detection, and methods of control. Crit. Rev. Food Sci. Nut. 30:403-439.

Fallik, E., S. Grinberg, M. Gambourg, et al. 1995. Prestorage heat treatment reduces pathogenicity of *Penicillium expansum* in apple fruit. Plant Pathol. 45:92-97.

Forster, H., and J.E. Adaskaveg. 1999. Fludioxinil, a new reduced risk postharvest fungicide for management of fungal decays of stonefruit. Phytopathology 89:S26.

FRAC [Fungicide Resistance Action Committee]. 1998. 1998 Status Report and Recommended Fungicide Resistance Management Guidelines. Global Crop Protection Federation, Brussels, Belgium.

Gould, W.A. 1973. Micro-contamination of horticultural products. HortScience 8:116-119.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Harvey, J.M. 1978. Reduction of losses in fresh fruits and vegetables. Ann. Rev. Phytopath. 16:321-341.

Holmes, G.J., and J.W. Eckert. 1999. Sensitivity of *Penicillium digitatum* and *P. italicum* to postharvest citrus fungicides in California. Phytopathology 89:716-721.

Howard, R.J., J.A. Garland, and W.L. Seaman. 1994. Diseases and Pests of Vegetable Crops in Canada: An Illustrated Compendium. The Entomological Society of Canada and The Canadian Phytopathological Society, Ottawa, Ontario, Canada.

Hsieh, D.P., and S.H. Gruenwedel. 1990. Microbial toxins. *In* C. Winter, J. Seiber, and C. Nuckton, eds., Chemicals in the Human Food Chain, pp. 239-267. Van Nostrand Reinhold, New York, NY.

Janisiewicz, W.J., and A. Marchi. 1992. Control of storage rots on various pear cultivars with a saprophytic strain of *Pseudomonas syringae*. Plant Dis. 76:555-560.

Janisiewicz, W.J., and S.N. Jeffers. 1997. Efficacy of commercial formulation of two biofungicides for control of blue mold and gray mold of apples in cold storage. Crop Prot. 16:629-633.

Jeffries, P., and M.J. Jeger. 1990. The biological control of postharvest diseases of fruit. Biocontrol News Info. 11:333-336.

Kader, A.A. 1985. Biochemical and physiological basis for effects of controlled and modified atmospheres on fruits and vegetables. Food Technol. 40:99-104.

Kelman, A. 1989. Introduction: the importance of research on the control of postharvest diseases of perishable food crops. Phytopathology 79:1374.

Klien, J.D., W.S. Conway, B.D. Whitaker, and C.E. Sams. 1997. *Botrytis cinerea* decay in apples is inhibited by postharvest heat and calcium treatment. J. Amer. Soc. Hort. Sci. 122:91-94.

Krieg, N.R., and J.G. Holt. 1984. Bergey's Manual of Systemic Bacteriology, vol. 1. Williams and Wilkins, Baltimore, MD.

Luvisi, D.A., H.H. Shorey, J.L. Smilanick, et al. 1992. Sulfur Dioxide Fumigation of Table Grapes. Bull. 1932, University of California, Division of Agriculture and Natural Resources, Davis, CA.

Mari, M., T. Cembali, E. Baraldi, and L. Casalini. 1999. Peracetic acid and chlorine dioxide for postharvest control of *Monilinia laxa* in stone fruits. Plant Dis. 83:773-776.

Meheriuk, M., and A.P. Gaunce. 1994. Temperate fruits. *In* R.E. Paull and J.W. Armstrong, eds., Insect Pests and Fresh Horticultural Products: Treatments and Responses, pp. 291-307. CAB Intl, Wallingford, UK.

Ogawa, J.M., and B.T. Manji. 1984. Control of postharvest diseases by chemical and physical means. *In* H.E. Moline, ed., Postharvest Pathology of Fruits and Vegetables: Postharvest Losses in Perishable Crops, pp. 55-66. Bull. 1914 (Pub NE-87), University of California, California Agricultural Experiment Station, Davis, CA.

Ogawa, J.M., and H. English. 1991. Diseases of Temperate Zone Tree Fruit and Nut Crops. Pub. no. 3345, University of California, Division of Agriculture and Natural Resources, Davis, CA.

Ogawa, J.M., J.E. Adaskaveg, and K.E. Conn. 1992. Efficacy of iprodione wax/oil mixtures for control of postharvest decay of fruit caused by *Rhizopus* and *Alternaria* spp. Phytopathology 82:1064.

Phillips, D.J. 1984. Mycotoxins as a postharvest problem. *In* H.E. Moline, ed., Postharvest Pathology of Fruits and Vegetables: Postharvest Losses in Perishable Crops, pp. 50-54. Bull. 1914 (Pub NE-87), University of California, California Agricultural Experiment Station, Davis, CA.

Pierson, C.F., M.J. Ceponis, and L.P. McColloch. 1971. Market Diseases of Apples, Pears, and Quinces. Agriculture Handbook 376, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Pusey, P.L., and C.L. Wilson. 1984. Postharvest biological control of stone fruit brown rot by *Bacillus subtilis*. Plant Dis. 68:753-756.

Pusey, P.L. 1989. Use of *Bacillus subtilis* and related organisms as biofungicides. Pesticide Sci. 27:133-140.

Pusey, P.L. 1996. Micro-organisms as agents in plant disease control. *In* L.G. Copping, ed., Crop Protection Agents from Nature: Natural Products and Analogues, pp. 426-443. Royal Society of Chemistry, Cambridge, United Kingdom.

Roberts, R.G. 1990. Biological control of gray mold of apple by *Cryptoccus laurentii*. Phytopathology 80:526-530.

Roberts, R. 1994. Integrating biological control into postharvest disease management strategies. HortScience 29:758-762.

Roberts, R.G., and S.T. Reymand. 1994. Chlorine dioxide for reduction of postharvest pathogen inoculum during handling of tree fruits. Appl. Environ. Micro. 60:2864-2868.

Sams, C.E., W.S. Conway, J.A. Abbott, et al. 1993. Firmness and decay of apple following postharvest pressure infiltration of calcium and heat treatment. J. Amer. Soc. Hort. Sci. 118:623-627.

Sams, C.E. 1994. Management of postharvest disease resistance in horticultural crops: introduction to the colloquium. HortScience 29:746.

Sholberg, P.L., and G.R. Owen. 1990. Populations of propagules of *Penicillium* spp. during immersion dumping of apples. Can. Plant Dis. Surv. 70:11-14.

Sholberg, P.L., A.G. Reynolds, and A.P. Gaunce. 1996. Fumigation of table grapes with acetic acid to prevent postharvest decay. Plant Dis. 80:1425-1428.

Sholberg, P.L. 1998. Fumigation of fruit with short-chain organic acids to reduce the potential of postharvest decay. Plant Dis. 82:689-693.

Sholberg, P.L., and K.E. Bedford. 1999. Use of cyprodinil for control of *Botrytis cinerea* on apple. Phytopathology 89:S72.

Snowdon, A.L. 1990. Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 1, General Introduction and Fruits. CRC Press, Boca Raton, FL.

Snowdon, A.L. 1992. Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables. CRC Press, Boca Raton, FL.

Sommer, N.F. 1989. Suppressing postharvest disease with handling practices and controlled environments. *In* J.H. LaRue and R.S. Johnson, eds., Peaches, Plums, and Nectarines Growing and Handling for Fresh Market, pp. 179-190. Pub. no. 3331, University of California, Department of Agriculture and Natural Resources, Davis, CA.

Spotts, R.A., and B.B. Peters. 1980. Chlorine and chlorine dioxide for control of ‘d’Anjou’ pear decay. Plant Dis. 64:1095-1097.

Spotts, R.A., and B.B. Peters. 1981. The effect of relative humidity on spore germination of pear decay fungi and ‘d’Anjou’ pear decay. Acta Hort. 124:75-78.

Spotts, R.A. 1984. Environmental modification for control of postharvest decay. *In* H.E. Moline, ed., Postharvest Pathology of Fruits and Vegetables: Postharvest Losses in Perishable Crops, pp. 67-72. Bull. 1914 (Pub NE-87), University of California, California Agricultural Experiment Station, Davis, CA.

Spotts, R.A., and P.M. Chen. 1987. Prestorage heat treatment for control of decay of pear fruit. Phytopathology 77:1578-1582.

Spotts, R.A., and R.L. Dobson. 1989. Effects of the experimental fungicide RH 886 on *Mucor piriformis*. Pesticide Sci. 25:391-399.

Spotts, R.A. 1990. Bull’s-eye rot. *In* A.L. Jones and H.S. Aldwinckle, eds., Compendium of Apple and Pear Diseases, pp. 56. APS Press, St. Paul, MN.

Spotts, R.A., L.A. Cervantes, T.J. Facteau, and T. Chand-Goyal. 1998. Control of brown rot and blue mold of sweet cherry with preharvest iprodione, postharvest *Cryptococcus infirmo-miniatus,* and modified packaging. Plant Dis. 82:1158-1160.

Spotts, R.A., L.A. Cervantes, and E.A. Mielke. 1999. Variability in postharvest decay among apple cultivars. Plant Dis. 83:1051-1054.

Stevens, C., V.A. Khan, J.Y. Lu, et al. 1998. The germicidal and hormetic effects of UV-C light on reducing brown rot disease and yeast microflora of peaches. Crop Protection 17:75-84.

Sugar, D., T.L. Righetti, E.E. Sanchez, and H. Khemira. 1992. Management of nitrogen and calcium in pear tree for enhancement of fruit resistance to postharvest decay. HortTechnol. 2:382-387.

Sugar, D., R.G. Roberts, R.J. Hilton, et al. 1994. Integration of cultural methods with yeast treatment for control of postharvest fruit decay in pear. Plant Dis. 78:791-795.

Sugar, D. and R. Spotts. 1995. Preharvest strategies to reduce postharvest pear decay. Tree Fruit Postharvest Journal 6(2):13-14.

Swalding, I.R., and P.J. Jeffries. 1998. Antagonistic properties of two bacterial biocontrol agents of grey mould disease. Biocontrol Sci. Technol. 8:439-448.

Utkhede, R.S., and P.L. Sholberg. 1993. Biological control of diseases of temperate fruit trees. Curr. Top. Bot. Res. 1:313-334.

Vinas, I., J. Usall, N. Texido, and V. Sanchis. 1998. Biological control of major postharvest pathogens in apple with *Candida sake*. Int. J. Food Micro. 40:9-16.

Wells, J.M., and J.E. Butterfield. 1997. *Salmonella* contamination associated with bacterial soft rot of fresh fruits and vegetables in the marketplace. Plant Disease 81:867-872.

Wilson, C.L., and P.L. Pusey. 1985. Potential for biological control of postharvest plant diseases. Plant Disease 69:375-378.

Wisniewski, M., C. Biles, S. Droby, et al. 1991. Mode of action of the postharvest biocontrol yeast *Pichia guilliermondii.* 1. Characterization of attachment to *Botrytis cinerea.* Physiol. Molec. Plant Pathol. 39:245-258.

Wisniewski, M.E., and C.L. Wilson. 1992. Biological control of postharvest diseases of fruits and vegetables: recent advances. HortScience 27:94-98.

Flavor

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Introduction

The quality of fresh produce has traditionally been based on external characteristics of size, color, and absence of surface defects. Fruit and vegetable breeders select for color, size, disease resistance, yield, and other easily quantified horticultural traits. Because flavor and texture characteristics were not a part of the selection process, improvements in these quality attributes have not kept pace with the more easily quantified traits. Public and industry organizations are increasingly concerned with the public's growing dissatisfaction over the flavor and texture of some horticultural produce.

Flavor and aroma are perhaps the most elusive and subjective of quality traits. Flavor is taste plus odor and is mainly composed of sweetness, sourness, and aroma, which correspond to sugars, acids, and volatiles. Other components of flavor include bitterness related, for example, to sesquiterpene lactones in chicory (Peters and Amerongen 1998), saltiness due to various natural salts, and astringency related to flavonoids, alkaloids (DeRovira 1997), tannins (Taylor 1993), and other factors. The perception of sweetness—that is, sugars—one of the most important components of fruit or vegetable flavor, is modified by sourness or acid levels and aroma compounds. The contribution of aroma to the flavor quality of fresh produce has gained increasing attention.

Genetics is the primary determinant of flavor of fresh produce (Cunningham et al. 1985, Baldwin et al. 1991b, 1992), with preharvest environment (Romani et al. 1983), cultural practices (Wright and Harris 1985), harvest maturity (Fellman et al. 1993, Maul et al. 1998, Baldwin et al. 1999a), and postharvest handling (Mattheis et al. 1995; Fellman et al. 1993; Baldwin et al. 1999a,b) having lesser effect. Fruit such as apples and bananas that continue to ripen after harvest are termed climacteric, while those such as citrus and strawberries that do not ripen after harvest are termed nonclimacteric. The flavor quality of nonclimacteric fruit generally declines after harvest, while climacteric fruit can reach their best flavor after harvest. Climacteric fruit develop better quality if harvested after the start of ripening, while fruit of both will be inferior in quality if harvested immature, even if held under optimal postharvest conditions.

Human perception of flavor is exceedingly complex. Taste is the detection of nonvolatile compounds (in concentration of parts per hundred) by several types of receptors in the tongue for sugars or polyalcohols, hydronium ions, sodium ions, glucosides and alkaloids, etc. These correspond to the perception of sweet, sour, salty and bitter tastes in food. Aroma compounds can be detected in parts-per-billion concentrations and are detected by olfactory nerve endings in the nose (DeRovira 1997). The brain processes information from these senses to give an integrated flavor experience. This integration makes it difficult to determine the relative importance of each input since the brain can interpret changes in aroma as changes in taste (O'Mahony 1995) or vice versa. For example, the levels of aroma compounds influenced panelist perception of sweetness and sourness for tomatoes (*Lycopersicon esculentum* Mill.) (Baldwin et al. 1998). Conversely, levels of taste components influenced panelist perception of aromatic descriptors in mango (*Mangifera indica* L.) (Malundo et al. 2000a). The perception of certain combinations of chemicals is synergistic, while others combinations mute our perception in a process called masking. In contrast to masking is anesthetization or blanking, in which olfactory receptors become overloaded. Lighter-aroma volatiles (for example, top notes—low molecular weight, polar, hydrophilic compounds) are perceived first and generally have the major impact on perception, while heavier compounds are perceived later: for example, background notes—high molecular weight, nonpolar, hydrophobic compounds (DeRovira 1997).

Sensory Evaluation

Human perception of flavor can be determined by sensory evaluation by taste panels. Consumer preference and acceptance vary due to socioeconomic, ethnic, and geographical background, often necessitating the segmenting of subpopulations for a particular study (O'Mahony 1995). Generally a large number of panelists (for example, 50 to 100) rank their perceptions on a traditional 9-point hedonic scale, but sometimes a simple 3-point scale including the descriptive terms outstanding, acceptable, and unacceptable can be effective for tomato fruit evaluation. In one study, adaptation of logistic regression from medical science proved useful, in which a 0 or 1 indicates whether the consumer would or would not purchase a mango *(Mangifera indica)*. The consumer was asked to base their decision on flavor, which was then related to chemical constituents (Malundo et al. 2000b). Difference testing can be used to measure slight differences between foods (usually due to one particular aspect of flavor) and is considered a narrow-band approach. Descriptive analysis measures intensities of a set of sensory attributes and is considered a broadband approach (O'Mahony 1995). Panelists are trained to detect a range of flavor attributes and score their intensity, generally on a 150 mm unstructured line. Sensory studies for fresh produce can be used to identify optimal harvest maturity, evaluate flavor quality in breeding programs, determine optimal storage and handling conditions, assess effects of disinfestation or preconditioning techniques on flavor quality, and measure flavor quality over the postharvest life of a product.

Taste Components

Fructose, sucrose, and glucose are the sugars that affect the perception of sweetness in fruits and vegetables. Fructose is the sweetest, and glucose is less sweet than sucrose. A single "sucrose equivalent" value is the weighted average of these various sugars in a sample (Koehler and Kays 1991). Sugar content is commonly accepted to be synonymous with SSC (soluble solids content), and an inexpensive refractometer can easily measure SSC. However, the quantification of individual sugars requires complicated laboratory analysis. Breeders often select for higher SSC in an attempt to increase sweetness. In some fruits, such as orange *(Citrus sinensis)*, SSC relates to sweetness; while in others, such as tomato and mango, the relationship is not linear (Baldwin et al. 1998, 1999a, Malundo et al. 2000a).

Organic acids, such as citrate in citrus and tomatoes, tartaric acid in grapes (*Vitis* sp.), and malic acid in apples *(Malus pumila)*, give fruit and vegetables their sour flavor. Some fruits, like melon *(Cucumis melo)* or banana (*Musa* sp.), have very little acid (Wyllie et al. 1995). Different acids can affect sourness perception, depending on their chemical structure. An increase in carboxyl groups decreased acidity, while an increase in molecular weight or hydrophobicity increased sourness (Hartwig and McDaniel 1995). For example, acetic acid was perceived as more intensely sour than lactic or citric acid.

Acids can be measured individually by HPLC (Baldwin et al. 1991a,b), by titration (TA) with sodium hydroxide (Jones and Scott 1984), or by pH (Baldwin et al. 1998). Sometimes SSC, the ratio of SSC/TA, or pH relate better to sourness than TA itself (Baldwin et al. 1998, Malundo et al. 2000a).

Aroma Components

Volatiles that we can perceive contribute to food flavor. The level at which a compound can be detected by smell (the odor threshold) can be established in a background similar to a food medium as described by the Ascending Method of Limits of the American Society for Testing and Materials (ASTM 1991). Log odor units are calculated from the ratio of the concentration of a component in a food to its odor threshold. Compounds with positive odor units contribute to food flavor. Buttery (1993), for example, determined concentrations, odor thresholds, and log odor units for those tomato volatiles present at levels of 1 ppb or more (about 30 of > 400 identified compounds). However, the aroma perception of volatile compounds is affected by the medium of evaluation. For example, both the thresholds and descriptors of some volatile compounds in tomato were different if the background medium contained levels of methanol and ethanol similar to that found in fresh tomato homogenate or in deodorized homogenate itself than if the medium was water (Tandon et al. 2000) (table 1).

Table 1. Odor descriptors for tomato aroma compounds in deionized water, ethanol/methanol/deionized water mix and deodorized tomato homogenate

Aroma compound	Deionized water	EtOH/MeOH/water	Tomato homogenate
Hexanal	grassy/green	rancid/stale oil	stale/green/grassy
Trans-2-hexenal	floral/grass/apple	fruity/almond/vine	stale/green/vine
Cis-3-hexenol	leafy/cut grass	fresh-cut grass	green/celery
Hexanol	mint/grass	alcohol	glue/oil
6-methyl-5-hepten-2-one	raw greens/nutty	alcohol/paint	sweet/floral
Cis-3-hexenal	grass/tomato-like	alcohol/paint	tomato/citrus
2-isobutylthiazole	fermented/plastic	alcohol/tomato-like	pungent/bitter
2-pentenal	vine/organic solvent	acetone/medicine	stale/oil
Acetone	glue/alcohol	alcohol/nutty/spoilt	green
β-ionone	sweet/perfume-like	sweet	sweet/floral
Geranylacetone	sweet/paint/sharp	sweet/floral/leafy	sweet/citrus/ester
3-methylbutanol	earthy/watermelon rind	glue/mint/cinnamon	sweet/fresh
Phenylethanol	floral/roses	alcohol	alcohol/nutty
3-methylbutanal	bug spray/alcohol	fruity/green/leafy	stale/rotten
1-penten-3-one	glue/oil/pungent	nutty/glue/alcohol	fresh/sweet
Ethanol	earthy/stale	pungent/rancid	—
Methanol	earthy/stale	—	—

Source: Tandon et al. 2000

Aroma compounds are often only released upon cell disruption when previously compartmentalized enzymes and substrates interact (Buttery 1993). Some aroma compounds are bound to sugars as glycosides (celery *[Apium graveolens]*, lettuce *[Lactuca sativa]*), or glucosinolates (cabbage *[Brassica oleracea]*, radish *[Raphanus sativus]*). This linkage can be cleaved by enzyme action or heat during cooking. Other aromatic compounds are breakdown products of lipids, amino acids, lignin, or pigments (Buttery and Ling 1993).

Measurement of aroma compounds is difficult and time consuming. Earlier studies employed the classical flavor isolation procedures of steam distillation and solvent extraction (Teranishi and Kint 1993). The disadvantage of this method is that it can qualitatively and quantitatively modify the flavor profile of a sample (Schamp and Dirinck 1982). This method is not easily applied to large numbers of samples, and internal standards must be incorporated to determine recovery. The resulting concentration of material, however, allows identification of compounds by gas chromatography-mass spectrometry (GC-MS). Investigators have employed purge-and-trap headspace sampling methods, which involve trapping and concentrating volatile components on a solid support. Volatiles are later released from the trap using heat for analysis by GC-MS. This method is excellent for quantification and identification of aroma compounds (Schamp and Dirinck 1982, Teranishi and Kint 1993).

Static headspace methods are said to more closely reflect the true flavor profile; but compounds are present at low levels, and some may not be detected. Cryofocusing (cold trap) of static headspace volatiles (Teranishsi and Kint 1993) reduces this problem, since samples are concentrated without heating that may cause adulteration. This method has been used for quantification of orange juice volatiles (Moshonas and Shaw 1997). The newest method is solid-phase micro-extraction (SPME), a rapid sampling technique in which volatiles interact with a fiber-coated probe inserted into the sample headspace. The probe is then transferred to a GC injection port where the volatiles are desorbed. It has been used on apples, tomatoes (Song et al. 1997), and strawberries (Song et al. 1997, Golaszewski et al. 1998).

Aside from GC and GC-MS methods, there are new sensors available that have a broad range of selectivity. These sensor arrays, called "electronic noses," are useful to discriminate among samples based on the interaction of volatile components with the various sensors. The resulting response pattern allows a particular sample or flavor component(s) to be detected by pattern recognition. However, these instruments do not give information that leads to identification and quantification of individual compounds. Five basic sensor technologies have been commercialized to date: metal oxide semiconductors, metal oxide semiconductor field effect transistors, conducting organic polymers, piezoelectric crystals (bulk acoustic wave), and quartz crystal microbalance. The next generation of electronic noses may use fiberoptic, electrochemical, and bimetal sensors (Schaller et al. 1998).

Relating Sensory to Chemical Data

Chemical analysis of flavor compounds provides little insight into the actual flavor experience. However, sensory attributes, preferences, and decisions can be statistically related to chemical components in foods (Martens et al. 1994). Some important or abundant flavor compounds in selected fruits and vegetables are shown in table 2. Correlation of physical measurements with sensory analysis gives meaning to instrumental data, as was shown with apple and tomato (Baldwin et al. 1998). For example, linear regression established relationships between levels of sesquiterpene lactones and bitterness in chicory (Peters and Amerongen 1998). Multivariate methods require large data sets, but nonlinear regression techniques such as principal component or discriminate analysis yielded useful results for citrus (Moshonas and Shaw 1997), strawberry *(Fragaria ananassa)* (Shamaila et al. 1992), and tomato (Maul et al. 1998). Differences between samples were found based on measurement of volatiles or other flavor compounds.

Alternatively, sniff ports (olfactometry detectors) can be used with GCs, allowing a person to determine if odors are detectable as well as their relative intensity as the volatile components are separated by the GC column. This technique was used on apples (Cunningham et al. 1985, Young et al. 1996). Descriptive terms can be assigned to the respective peaks on the GC chromatogram that have odor activity (Acree 1993). The drawback to this method is that the interactive effects of volatile compounds with each other and with sugars and acids, both chemically and in terms of human perception, are eliminated.

Factors That Can Affect Flavor of Fruits and Vegetables

Effect of Genetics on Flavor

Fruit and vegetable varieties differ in flavor based on sensory and chemical analysis. “Charm” analysis combines separation on a GC column with a sniff port to assign biological activity (odor activity) to individual aroma components as they are identified and quantified by GC (Cunningham et al. 1985). This study with 40 cultivars showed that apple aroma was not the result of the same compounds in every cultivar, although some common volatile compounds were important in all cultivars.

Important aroma-specific compounds for strawberry included ethyl butanoate, methyl butanoate, γ-decalactone, and 2-heptanone (Larsen et al. 1992). Strawberry cultivars differed in flavor intensity and sweetness, according to a trained sensory panel (Podoski et al. 1997). Concentrations of several important compounds, including α- and ß-ionones, were higher in wild compared to cultivated raspberries (*Rubus* sp.). In addition, numerous aroma compounds were found only in wild berries, all of which may contribute to the stronger and more pleasant aroma of wild berries (Martin and MacLeod 1990). In tomato, the TA/SSC (Stevens et al. 1977) and levels of flavor volatiles varied significantly among varieties (Baldwin et al. 1991a,b). Insertion of the *rin* gene to reduce ethylene production and slow tomato fruit softening resulted in some deterioration in flavor quality (Baldwin et al. 2000) and reduction in flavor volatiles (Baldwin et al. 1992, 2000). Flavor appears to be related to ethylene production (Baldwin et al. 1991a, 2000). Transgenic fruit with antisense aminocyclopropanecarboxylic acid (ACC) synthase (an enzyme in the ethylene biosynthetic pathway) had lowered levels of many important flavor volatiles (Baldwin et al. 2000). Fruit with antisense pectinmethylesterase (which demethylates pectin in cell walls) had lowered levels of methanol, while those with downregulated phytoene synthase (phytoene is a precursor of carotenoids) had lowered levels of carotenoid-derived volatiles (Baldwin et al. 2000).

Effect of Preharvest Factors

Preharvest factors such as sunlight, water availability, fertilization, and chemical applications affect crop growth and can affect internal quality characteristics of the harvested product, including flavor. Preharvest treatment with aminoethoxyvinylglycine (AVG) suppressed volatile production in pears by 50%, which was reversed by ethylene exposure (Romani et al. 1983); and heavy rains prior to harvest dilute flavor compounds in tomato. Fruit from tomato plants treated with increased levels of N and K fertilizer scored lower in sensory analysis and showed increased levels of TA, SSC, and several volatiles (Wright and Harris 1985). Preharvest mite control resulted in sweeter and more flavorful field grown strawberries than those receiving no treatments, according to a trained sensory panel (Podoski et al. 1997).

Effect of Harvest Maturity

Horticultural crops should be harvested at optimal eating quality, but practical considerations dictate that they are harvested at a stage that minimizes physical damage during shipping and handling and maximizes shelf-life. The climacteric stage at harvest affected ester formation in apples (Fellman et al. 1993). Harvest maturity affected both the sensory and chemical analysis of ripened tomato fruit (Maul et al. 1998). Tomatoes harvested at the immature green stage resulted in ripened fruit with lower volatile levels than mature-green-harvested tomatoes. Harvest maturity also affected consumer acceptability for mango and trained descriptive panel ratings for sweetness, sourness, and various aroma descriptors. Fruit harvested later were sweeter and less sour and generally had more intense aroma characteristics (Baldwin et al. 1999a).

Effect of Postharvest Handling

Various techniques are used to extend the shelf-life of fruits and vegetables after harvest, to control postharvest decay, and to eliminate pests (quarantine treatments). These storage techniques and treatments involve cold, heat, irradiation, chemical applications, and different storage atmospheres.

Tomato fruit stored at 36, 41, 50, and 55 °F (2, 5, 10, and 13 °C) had reduced levels of important volatiles and had less-ripe aroma and flavor as well as more off flavors compared to fruit stored at 68 °F (20 °C), as quantified by a trained descriptive panel (Maul et al. 2000). Subjection of fruit to heat treatments for preconditioning and decay control (McDonald et al. 1996) resulted in altered aroma volatile profiles. Heat treatment of apples to reduce physiological and pathological disorders inhibited emission of volatile esters important to apple flavor (Fallik et al. 1997). Levels of fructose and glucose, but not sucrose, decreased with increased storage time and storage temperature for muskmelon. However, sensory analysis did not find differences in flavor or sweetness between stored and freshly harvested melons (Cohen and Hicks 1986).

CA storage altered flavor of apples, and, if prolonged, reduced volatile emission compared to air-stored fruit, especially lipid-derived esters (Mattheis et al. 1995). Low-O_2 storage decreased ester content and the enzymatic activity responsible for ester biosynthesis in apples (Fellman et al. 1993). However, when atmospheres induced anaerobic metabolism, large concentrations of ethanol and acetaldehyde accumulated. The altered synthesis of fruit volatiles resulted in increased amounts of ethyl acetate and certain ethyl esters at the expense of others. Sensory analysis of CA-stored apples revealed that intensity of fruity and floral descriptors decreased after 10 weeks in CA, while sourness and astringency were higher compared to apples stored in air. CA storage also increased certain volatiles in tomato, compared to air-stored fruit (Crouzet et al. 1986).

Use of packaging and edible coatings can create a modified atmosphere (MA) with reduced O_2 and elevated CO_2 levels, similar to that of CA. Lowering O_2 and raising CO_2 can maintain the quality of many fresh fruits and vegetables for extended periods. However, exposure of fresh produce to O_2 levels below their tolerance level can increase anaerobic respiration and lead to the development of off flavors. Use of edible coatings affects flavor and the level of volatile flavor compounds in citrus (Cohen et al. 1990), apple (Saftner et al. 1999), and mango fruit (Baldwin et al. 1999b). The coating barrier probably induced anaerobic respiration and the synthesis of ethanol and acetaldehyde and entrapped volatiles, including ethanol and acetaldehyde (Baldwin et al. 1999b). In broccoli, sulfur-containing volatiles, including methanethiol and dimethyl disulfide, are produced in response to anaerobic conditions that can be created by MAP (Dan et al. 1997). Storing strawberries in MAP altered volatile profiles depending on conditions (CO_2, mixed gases, or air), enabling separation of the samples using multivariate statistics (Shamaila et al. 1992). Fruit treated with CO_2 had the greatest change in volatile levels. This was confirmed by another study in which strawberry fruit stored in a CO_2-saturated atmosphere exhibited significant changes in volatile levels and phenylalanine ammonia lyase (PAL) activity (Dourtoglou et al. 1995). The amino acid phenylalanine is the precursor to a number of volatiles through a pathway in which PAL is the key enzyme.

In addition to CA, other gaseous treatments of fruits and vegetables have been reported. Use of ethylene to synchronize ripening has been practiced for years on banana and tomato, as well as for degreening of citrus. Ethylene gassing of tomato fruit alters volatile levels (McDonald et al. 1996). Treatment of apple fruit with 1-methylcyclopropene (1-MCP) and methyl jasmonate inhibited both ethylene production and production of many volatile alcohols and esters, including the formation of esters from alcohols (Fan and Mattheis 1999). Treatment of bananas with 1-MCP also suppressed volatile production and composition, resulting in an increase in alcohols and a decrease in related esters (Golding et al. 1999). Application of acetaldehyde and ethanol vapors to blueberries, tomatoes, and pears increased their sugar content, sugar-acid ratio, and hedonic sensory rating (Paz et al. 1981).

Other chemical treatments of fresh produce may also affect flavor. For example, pressure infiltration of apples with calcium chloride transiently reduced levels of important flavor volatiles (Saftner et al. 1999).

Flavor of Some Popular Fruits and Vegetables

Apple. Sucrose is the major sugar in apples, though it is slowly hydrolyzed to glucose and fructose during latter ripening stages. The major organic acid is malate, although some citrate is also present (Knee 1993). Eleven aroma compounds contribute to apple aroma in most of the 40 cultivars, while 27 other compounds contributing to flavor where found only in certain genetic types (Cunningham et al. 1985). Loss of apple flavor after long-term CA storage is a major problem, probably due to the reduction of volatile synthesis during storage (Mattheis et al.1995).

Peach *(Prunus persica)*. The main sugar in peaches is sucrose, but cultivars differ greatly in glucose:fructose:sorbitol ratios, which may contribute to differences in flavor. The major organic acids are malate and citrate, with malate levels declining and citrate levels increasing as fruit ripen (Brady 1993). Aroma of peaches and nectarines is distinguished by the presence of γ- and δ-lactones (peach-like and coconut-like, respectively), although other esters and aldehydes contribute to peach flavor (Do et al. 1969, Crouzet et al. 1990). γ-Lactones from C-5 to C-12, δ-lactones, and unsaturated lactones represent more than 25% of the volatiles, with γ-lactone being the second most abundant component after benzaldehyde. γ-Undecalactone, although rarely reported in natural extracts, has a distinct peach odor. It has been named "peach aldehyde" and is used in peach flavor formulations (Crouzet et al. 1990). Ethyl hexanoate and 3-methylbutanoate, linalool, α-terpineol, 6-pentyl-α-pyrone (coconut odor), and benzyl alcohol are also considered important (Crouzet et al. 1990).

Small Fruits

Strawberry. In most berry fruits sucrose, glucose, and fructose are present in roughly equivalent concentrations (Manning 1993), and citrate is the major organic acid. More than 200 volatile compounds have been identified in strawberry. C-6 aldehydes such as hexanal and *trans*-2-hexenal are found, as well as lipoxygenase and hydroperoxide lyase. Lipoxygenase acts on linolenic acid to form 13- and 9-hydroperoxides, which are cleaved by hydroperoxide lyase to form hexanal and *cis*-3-hexenal. The *cis*-3-hexenal is then isomerized to *trans*-2-hexenal (Perez et al. 1999), as was reported for tomato (Galliard et al. 1977, Riley et al. 1996). 2,5-Dimethyl-4-hydroxy-3(2H)-furanone (furaneol) and its methyl ether (mesifuran) are important aroma components in both strawberry and tomato and are considered to be glycosidically bound in both fruits (Roscher et al. 1997). Of more than 100 volatile compounds identified from strawberry, furaneol, ethyl hexanoate, and ethyl butanoate are considered to be the character-impact compounds (Zabetakis and Holden 1997). Sensory analysis of strawberry juice showed that furaneol was positively related to fresh flavor and negatively related to off flavors, while α-terpineol was inversely related to fresh flavor (Golaszewski et al. 1998).

Raspberry *(Rubus idaeus, R. ursinus)*. The main sugars in raspberry are sucrose, glucose, and fructose, with citric as the major organic acid (Robbins and Fellman 1993). At least 200 volatile compounds have been identified in raspberry (Honkanen and Hirvi 1990, Dourtoglou et al. 1995). Impact flavor compounds for raspberry are 1-(*p*-hydroxyphenyl)-3-butanone, *cis*-3-hexenol, α- and β-ionones, α-irone, and mesifurane. Other abundant volatiles include geraniol, nerol, and linalool among others (Paterson et al. 1993). The "raspberry ketone," or character-impact volatile for raspberry, is 4-(4-hydroxyphenyl)-butan-2-one (Larsen and Poll 1990). It had the lowest threshold (therefore the largest contribution to flavor), followed by α-ionone, β-ionone, geraniol, linalool, and benzyl alcohol. Furaneol, linalool, and ethyl hexanoate were important general aroma compounds, while ethyl butanoate, methyl butanoate, γ-decalactone, and 2-heptanone were important cultivar-specific compounds (Larsen et al. 1992). The most potent flavor compounds identified using a retronasal aroma simulator in raspberries were β-damascenone, diacetyl, 1-hexen-3-one, 1-nonen-3-one, 1-octen-3-one, and *cis*-3-hexenal (Roberts and Acree 1996).

Blackberry *(Rubus laciniata)*. Fresh blackberry fruit contain 245 aroma compounds (Georgilopoulos and Gallois 1987). The most abundant were heptan-2-ol, para-cymen-8-ol, heptan-2-one, hexanol, α-terpineol, pulegone, octanol, isoborneol, mytenol, 4-terpineol, carvone, elemincine, and nonanol. Though heptan-2-ol is an important flavor compound with an intense fruit taste with herbaceous nuances, no single volatile was identified as blackberry-like (Marton and MacLeod 1990). Some compounds in blackberry fruit and leaves are glycosidically bound, such as benzyl alcohol, benzoic acid, 3-hydroxy-7,8-dihydro-β-ionol, and *cis*-3-hexenol among others (Humpf and Schreier 1991).

Blueberry *(Vaccinium)*. Blueberries have glucose and fructose as their major soluble sugars and citric, malic, and quinic acids (Eck 1986). The odor-impact compounds for high-bush blueberry *(Vaccinium myrtillus)* are *trans*-2-hexenal, *trans*-2-hexenol, and linalool, but also include geraniol, citronellol, hydroxycitronellol, farnesol, and farnesyl acetate. Most volatiles are present below their threshold concentrations, but hydroxycitronellol was described by sensory panelists as blueberry-like. Rabbit-eye blueberries *(V. ashei)* have a different aroma than high-bush. Some aroma volatiles unique to rabbit-eye blueberries include 1-penten-2-one, γ-terpinene, carveol, acetone, *cis*-caran-3-ol, ecineralone, α-cedrene, sabinol, geranyl formate, linalyl acetate, undecan-2-one, tridecan-2-one, ethyl acetate, ethyl tetradecanoate, dimethyl octanedioate, toluene, *p*-cymene, and β-ionone, among others (Honkanen and Hirvi 1990).

Grape *(Vitis)*. Glucose and fructose are the predominant sugars in grapes, while tartaric and malic acids account for 90% of the TA (Kanellis and Roubelakis-Angelakis 1993). Grapes show an increase in free and glycosylated aroma compounds at the end of ripening, after sugar accumulation has slowed (Coombe and McCarthy 1997). This process is different from that of other berries and has been termed "engusting." The volatiles in wine grapes are the most complex and are classified into five groups, of which the first four have glycosylated forms: monoterpene (abundant in "floral" grapes), norisoprenoid, benzenoid, aliphatic, and methoxypyrazine. The accumulation of flavor volatiles occurs late in the berry-ripening cycle, well after accumulation of sugar as observed in Muscat berries (Park et al. 1991). Different varieties have distinctive aroma character. For example, Muscat odor is mainly composed of monoterpenes such as linalool and geraniol (Webb 1981, Kanellis and Roubelakis-Angelakis 1993). Carbernet Sauvignon, a *V. vinifera* cultivar, contains methoxyisobutylpyrazine, which has a strong, green-bell-pepper-like aroma (Webb 1981). Benzyl and 2-phenylethyl alcohols, ethers, aldehydes, and hydrocarbons also contribute to aroma. American grapes *(V. labruscana* and *V. rotundifolia)* are not suitable for wine production because they possess what has been termed "foxy" and candy-like odors due to compounds like methyl anthranylate, aminoacetophenone, furaneol, and methyl furaneol. ß-Phenylethanol, with its rose-like odor, was found to be important for muscadine *(V. rotundifolia)* aroma (Flora and Nakayama 1981). The *V. vinifera* grapes exhibit a mild aroma that is more desirable for wine production (Shure and Acree 1995).

Banana *(Musa).* Sucrose is the predominant sugar in banana initially, but as ripening proceeds glucose and fructose accumulate. Malic, citric, and oxalic acids are the predominant organic acids, with the astringent taste of unripe bananas being attributed in part to oxalate levels (Seymour 1993). The characteristic aroma of bananas arises from a complex mixture of compounds including short-chain fatty acids such as acetates, butanoates, and 3-methylbutyl esters. Recently, nonvolatile glycoside precursors were shown to release glycosidically bound volatiles from banana pulp by ß-glucosidase, including decan-1-ol, 2-phenylethanol, 3-oxy-pentanoic acid, 3-methylbutanoic acid, and benzoic acid (Perez et al. 1997). Esters account for about 70% of the volatile compounds and acetates and butyrates predominate (Seymour 1993). 3-Methylbutyl acetate, however, is considered to dominate banana flavor as the key odor-impact volatile (Berger 1991), along with butanoate and 3-methylbutanoate (Engel et al. 1990). Unusual phenol derivatives eugenol, 5-methoxyeugenol, eugenol-methylether, and elemicin contribute background notes for the full-bodied mellow aroma of ripe bananas (Engle et al. 1990).

Citrus Fruits

Sweet Orange *(Citrus sinensis).* The major sugar in most citrus types is sucrose, with varying levels of glucose and fructose. The major acid is citrate. Typical orange aroma is attributed to alcohols, aldehydes, esters, hydrocarbons, ketones, and other components, of which more than 200 have been identified. Of these, esters and aldehydes are the primary contributors, followed by alcohols, ketones, and hydrocarbons (Bruemmer 1975). There is no single impact compound for orange. However, octanal, decanal, nonanal, dodecanal, ethylbutyrate, and limonene are likely contributors to flavor (Shaw and Wilson 1980, Shaw 1991).

Tangerine *(Citrus reticulata).* Analysis of tangerine essence revealed 34 volatile compounds that were odor contributors. However, no one compound was found to have a characteristic tangerine odor (Moshonas and Shaw 1972). Later studies suggested that the compounds thymol and methyl-*N*-methylanthranilate (dimethylanthranilate) are odor-impact compounds for this fruit but that they are modified by the presence of monoterpene hydrocarbons. Nevertheless, dimethylanthranilate is the most potent flavor component (Shaw and Wilson 1980).

Grapefruit *(Citrus paradisi).* At least 126 volatile components have been identified in grapefruit (Demole et al. 1982). Nootkatone and 1-*p*-menthene-8-thiol may be key aroma-impact compounds for grapefruit (Demole et al. 1982), although aldehydes and esters are also important (Shaw and Wilson 1980).

Mango *(Mangifera indica).* The major sugars in mango are glucose, fructose, and sucrose, with sucrose predominating. The major acids are citric, malic, and sometimes tartaric at 0.1% to 0.4% TA (Nairain et al. 1997, Baldwin et al. 1999b) and 10 to 16 SSC (Baldwin et al. 1999b). Mango varieties differ in amount and type of volatile compounds present (more than 150 compounds identified), often depending on area of production. Asian mangoes have more oxygenated volatile compounds such as esters, furanones, and lactones, giving some varieties pineapple- or peach-like aromas (Narain et al. 1997), while western mangoes that are hybrids of Asian stock have higher levels of certain hydrocarbons such as 3-carene (MacLeod and de Troconis 1982, Wilson et al. 1986, Narain et al. 1997).

Pineapple *(Ananas comosus).* Besides banana and possibly mango, pineapple is the most popular fruit from the tropics. SSC can range from 11° to 17° Brix, and the major sugars are glucose, fructose, and sucrose, with sucrose predominating (Salunkhe and Desai 1984, Shukor et al. 1998). The major acids are citrate and malate with about 0.1 to 0.6% titratable acidity (Salunkhe and Desai 1984, Shukor et al. 1998). More than 120 volatiles have been identified in green and ripened pineapples with esters dominating at more than 80% of the total volatiles (Shukor et al. 1998). Contributing aroma volatiles, based on odor thresholds, show that pineapple aroma is also dominated by esters such as ethyl 2-methylbutanoate, ethyl acetate, ethyl hexanoate, ethyl butanoate, methyl heptanoate, and others.

Melons *(Cucumis melo).* Sucrose is the principal sugar in most melon types, although high levels of fructose may be present in some watermelon cultivars. Melons contain citrate and malate, or only malate in watermelon (Seymour and McGlasson 1993). Ethyl 2-methylbutanoate and methyl-2-methylpropanoate are among the most significant contributors to flavor of muskmelon cultivar ‘Makdimon,’ one of the *C. mello reticulatus* cultivars that exhibit strong characteristic aromas. Muskmelon and watermelon also have *cis*-non6-enal and *cis*,*cis*-nona-3,6,-dien-1-ol, respectively. The former has a strong melon-like aroma, while the latter is reminiscent of watermelon rind. 4-Oxononanal and 2-hydroxy-5-pentyltetrahydrofuran have fruity and green odors and contribute to watermelon aroma. The volatile *cis*-non6-enyl acetate has a pleasant honeydew-melon-like aroma (Engle et al. 1990). Other varieties have ethyl-2-methylpropanoate, 2-methylbutyl acetate, 2-methylpropyl acetate, and the thioether esters (Wyllie et al. 1995).

Tomato *(Lycopersicon esculentum).* The SSC/TA ratio (De Bruyn et al. 1971) or the content of SSC or TA are important for flavor (Stevens et al. 1977, Jones and Scott 1984). The major sugars are glucose and fructose in roughly equal amounts, while citrate and malate are the major organic acids, with citrate predominating (Baldwin et al. 1991a,b, Hobson and Grierson 1993). However, more than 400 volatile compounds were identified, of which 16 or so have odor thresholds that would indicate that they contribute to flavor (Buttery 1993, Buttery and Ling 1993). Of these, there is no clear odor-impact compound. Buttery (1993) suggested that a combination of *cis*-3-hexenal, hexanal, 1-penten-3-one, 3-methylbutanal, *trans*-2-hexenal, 6-methyl-5-hepten-2-one, methyl salicylate, 2-isobutylthiazole, and β-ionone at the appropriate concentrations produces the aroma of a fresh ripe tomato. Of these, *cis*-3-hexenal and β-ionone have the highest odor units, and 2-isobutylthiazole is unique to tomato. Furaneol has an odor threshold indicating it may contribute to flavor (Buttery et al. 1995). Volatile production occurs at the same time that ethylene increase, carotenoid synthesis, and chlorophyll breakdown occur (Baldwin et al. 1991a). Enzymes important in volatile synthesis from lipids include lipoxygenase, hydroperoxide lyase (hydroperoxy cleavage), and alcohol dehydrogenase (Galliard et al. 1977, Riley et al. 1996). Amino acid precursors include alanine, isoleucine, leucine, phenylalanine, and valine (Buttery and Ling 1993). Glycosides are also precursors to some volatiles (Krammer et al. 1994). Furaneol is also reported to be important (seems it is found in every fruit). Genetically engineered fruit with down- or up-regulated alcohol dehydrogenase expression exhibited altered levels of some related volatiles (Speirs et al. 1998).

Table 2. Some important or abundant flavor compounds in selected fruits and vegetables

Fruit and references	Major sugars	Major acids	Important aroma compounds
Apple			
Fellman et al. 1993	sucrose	malic	β-damascenone
Honkanen and Hirvi 1990	glucose	citric	butyl hexanoate
Knee 1993	fructose		isoamyl hexanoate
Mattheis et al. 1995			hexyl hexanoate
Young et al. 1996			ethyl butanoate
			propyl butanoate
			hexyl butanoate
			butylacetate
			2-ethyl-1-butyl acetate
			ethyl acetate
			butanol
Peach			
Brady 1993	sucrose	malic	benzaldehyde
Crouzet et al. 1990	glucose	citric	benzyl alcohol
Do et al. 1969	fructose		nonanol
			sorbitol
			linalool
			ethyl hexanoate
			3-methylbutanoate
			α-terpineol
			γ-hexalactone
			δ-decalactone
			γ-undecalactone
			δ-undecalactone
			γ-dodecalactone
			δ-dodecalactone
			α-pyrone
			6-pentyl-α-pyrone
Strawberry			
Golaszewski et al. 1998	sucrose	citric	hexanal
Honkanen et al. 1980	glucose		*cis*-3-hexanal
Manning 1993	fructose		*trans*-2-hexanal
Perez et al.1999			furaneol
Roscher et al. 1997			mesifuran
Zabetakis and Holden 1997			ethyl hexanoate
			ethyl butanoate
			methyl butanoate
			ethyl-2-methyl propanoate

Table 2. Some important or abundant flavor compounds in selected fruits and vegetables —*Continued*

Fruit and references	Major sugars	Major acids	Important aroma compounds
Raspberry			
Dourtoglou et al. 1995	sucrose	citric	H-(4-hydroxyphenyl-butan-2-one)
Honkanen and Hirvi 1990	glucose		(raspberry ketone)
Larsen and Poll 1990	fructose		α-ionone
Larsen et al. 1992			β-ionone
Paterson et al. 1993			geraniollinalool
Robbins and Fellman 1993			benzyl alcohol
Roberts and Acree 1996			ethyl hexanoate
			ethyl butanoate
			methyl butanoate
			γ-decalactone
			2-heptanone
			cis-3-hexanal
			β-damascenone
Grape (references for all grape types)			
Coombe and McCarthy 1997			
Flora and Nakayama 1981			
Kanellis and Roubelakis -Angelakis 1993			
Park et al. 1991			
Shure and Acree 1995			
Webb 1981			
Concord	glucose	tartaric	methyl anthranilate
(*Vitis labruscana*)	fructose	malic	0-aminoacetophenone
			furaneol
			methyl furaneol
			β-damascenone
Muscadine			β-phenylethanol
(V. rotundifolia)			butyl alcohol
			hexyl alcohol
			hexanal
			trans-2-hexenal
			isoamyl alcohol
			acetaldehyde
			isobutyraldehyde
			ethyl acetate
			ethyl propionate
			butyl acetate
			propyl acetate
			2-methylbutanol

Table 2. Some important or abundant flavor compounds in selected fruits and vegetables —*Continued*

Fruit and references	Major sugars	Major acids	Important aroma compounds
Muscat varieties			linalool
(*V. vinifera*)			geraniol
			methoxyisobutylpyrazine
Banana			
Berger 1991	sucrose	malic	decan-1-ol
Engel et al. 1990	glucose	citric	2-phenylethanol
Perez et al. 1997	fructose	oxalic	3-oxy-pentanoic acid
Seymour 1993			3-methylbutanoic acid
			3-methylbutyl acetate
			butanoate
			3-methylbutanoate
			eugenol
			5-methoxyeugenol
			eugenol-methylether
			elemicin
Sweet orange			
Bruemmer 1975	sucrose	citric	geranial
Shaw 1991	glucose		neral acetaldehyde
Shaw and Wilson 1980	fructose		decanal
			octanal
			nonanal
			ethyl acetate
			ethyl propionate
			ethyl butanoate
			methyl butanoate
			ethyl-2-methyl butanoate
			ethyl-3-hydroxy hexanoate
			linalool
			α-terpineol
			limonene
			myrcene
			α-pinene
			valencene
Tangerine			
Moshonas and Shaw 1972	sucrose	citric	acetaldehyde
Shaw and Wilson 1980	glucose		decanal
	fructose		octanal
			dimethyl anthranilate
			thymol
			α-sinensal
			γ-terpinene
			β-pinene

Table 2. Some important or abundant flavor compounds in selected fruits and vegetables —*Continued*

Fruit and references	Major sugars	Major acids	Important aroma compounds
Grapefruit			
Demole et al. 1982	sucrose	citric	acetaldehyde
Shaw and Wilson 1980	glucose		decanal
			ethyl acetate
			methyl butanoate
			ethyl butanoate
			1-*p*-menthene-8-thiol
			nootkatone
			limonene
			naringin
Mango			
Baldwin et al. 1999	sucrose	citric	ethyl butanoate
MacLeod and de Troconis 1982	glucose	malic	ethyl-2-butanoate
Nairain et al. 1997	fructose		hexanal
Wilson et al. 1986			cis-3-hexanal
			trans-2-hexanal
			γ-octalactone
			γ-dodecalactone
			furaneol
			α-pinene
			β-pinene
			3-carene
			myrcene
			limonene
			p-cymene
			terpinolene
			α-Copaene
			caryophyllene
Melon	sucrose	malic	ethylbutyrate
(Cantaloupe, Honeydew,	fructose	citric	ethyl-2-methyl butyrate
Watermelon)		(watermelon:	ethyl butyrate
Engle et al. 1990		malic only)	ethyl hexanoate
Seymour and McGlasson 1993			hexyl acetate
Wyllie et al. 1995			3-methylbutyl acetate
			benzyl acetate
			cis-6-nonenyl acetate
			trans-6-nonenol
			cis,cis-3,6-nonadienol
			cis-6-nonenal
			4-oxononanal
			2-hydroxy-5-pentyltetra-hydrofuran
			cis-non6-enyl acetate
			methyl acetate
			ethyl acetate

Table 2. Some important or abundant flavor compounds in selected fruits and vegetables—*Continued*

Fruit and references	Major sugars	Major acids	Important aroma compounds
			isopropyl acetate
			ethyl propanoate
			ethyl isobutanoate
			propyl acetate
			butyl acetate
			methyl-2-methylbutanoate
			ethyl butanoate
			2-methylpropanoate
			2-methylbutyl acetate
			2-methylpropyl acetate
			methyl (methylthio) acetate
			ethyl (methylthio) acetate
			ethyl (methylthio) propanoate
Tomato			
Baldwin et al. 1991a,b	glucose	citric	hexanal
Buttery 1993	fructose	malic	*trans*-2-hexenal
Buttery and Ling 1993			*cis*-3-hexenal
Buttery et al. 1995, 1989			*cis*-3-hexenol
De Bruyn et al. 1971			β-ionone
Hobson and Grierson 1993			β-damascenone
			1-penten-3-one
			3-methylbutanal
			3-methylbutanol
			2-isobutylthiazole1-nitro-phenyl-ethane
			trans-2-heptenal
			phenylacetaldehyde
			6-methyl-5-hepten-2-one
			methyl salicylate
			geranylacetone

Conclusion

Flavor of fruits and vegetables is an important aspect of quality. Though difficult to define, qualify, and quantify, this elusive and complex trait is important to consumers and deserves more attention from both researchers and industry. Flavor quality of fresh and processed fruit and vegetable products will be an important factor in an increasingly competitive global market. Flavor maintenance becomes a challenge as shelf-life and marketing distances increase due to new storage, handling, and transport technologies. However, despite these issues the bottom line for flavor quality is still genetic. Breeders need more information and analytical tools in order to select for flavor quality. Use of wild material may be necessary in breeding programs to regain flavor characteristics that have been lost from some commodities. Use of molecular markers that relate to flavor may help identify important enzymes in flavor pathways. The effect of harvest maturity on flavor quality needs to be determined for each commodity. With the current focus on flavor quality and current advances in flavor chemistry, sensory techniques, and molecular biology, there are many opportunities to further efforts on behalf of flavor quality in fresh produce.

References

Acree, T.E. 1993. Bioassays for flavor. *In* T.E. Acree and R. Teranishi, eds., Flavor Science: Sensible Principles and Techniques, pp. 1-20. ACS Books, Washington, DC.

ASTM [American Society for Testing and Materials]. 1991. Determination of odor and taste thresholds by a force choice ascending concentration series methods of limits. ASTM Standard Practice E679, pp. 1-5. ASTM, Philadelphia, PA.

Baldwin, E.A., M.O. Nisperos, and M.G. Moshonas. 1991a. Quantitative analysis of flavor and other volatiles and for other constituents of two tomato varieties during ripening. J. Amer. Soc. Hort. Sci. 116:265-269.

Baldwin, E.A., M.O. Nisperos-Carriedo, and M.G. Moshonas. 1991b. Quantitative analysis of flavor parameters in six Florida tomato varieties (*Lycopersicon esculentum* Mill). J. Agric. Food Chem. 39:1135-1140.

Baldwin, E.A., M.O. Nisperos-Carriedo, and J.W. Scott. 1992. Levels of flavor volatiles in a normal cultivar, ripening inhibitor and their hybrid. Proc. Fla. State Hort. Soc. 104:86-89.

Baldwin, E.A., J.W. Scott, M.A. Einstein, et al. 1998. Relationship between sensory and instrumental analysis for tomato flavor. J. Amer. Soc. Hort. Sci. 12:906-915.

Baldwin, E.A., T.M.M. Malundo, R. Bender, and J.K. Brecht. 1999a. Interactive effects of harvest maturity, controlled atmosphere and surface coatings on mango (*Mangifera indica* L.) flavor quality. HortScience 34:514.

Baldwin, E.A., J.K. Burns, W. Kazokas, et al. 1999b. Effect of two edible coatings with different permeability characteristics on mango (*Mangifera indica* L.) ripening during storage. Postharv. Biol. Technol. 17:215-226.

Baldwin, E.A., J.W. Scott, C.K. Shewmaker, and W. Schuch. 2000. Flavor trivia and tomato aroma: biochemistry and possible mechanisms for control of important aroma components. HortScience 35:1013-1022.

Berger, R.G. 1991. Fruits. *In* H. Maarse, ed., Volatile Compounds in Foods and Beverages, pp. 283-304. Marcel Dekker, New York, NY.

Brady, C.J. 1993. Grape. *In* G.B. Seymour, J.E. Taylor, and G.A. Tucker, eds., Biochemistry of Fruit Ripening, pp. 379-404. Chapman and Hall, New York, NY.

Bruemmer, J.H. 1975. Aroma substances of citrus fruits and their biogenesis. *In* F. Drawart, ed., Symposium on Fragrance and Flavor Substances, pp. 167-176. Verlag Hans Carl, Nuremburg, Germany.

Buttery, R.G. 1993. Quantitative and sensory aspects of flavor of tomato and other vegetable and fruits. *In* T.E. Acree and R. Teranishi, eds., Flavor Science: Sensible Principles and Techniques, pp. 259-286. ACS, Washington, DC.

Buttery, R.G., and L.C. Ling. 1993. Volatiles of tomato fruit and plant parts: relationship and biogenesis. *In* R. Teranishi, R. Buttery, and H. Sugisawa, eds., Bioactive Volatile Compounds from Plants, American Chemical Society Symposium Series no. 525, pp. 23-34. ACS Books, Washington, DC.

Buttery, R.G., G.R. Takeoka, and L.C. Ling. 1995. Furaneol: odor threshold and importance to tomato aroma. J. Agric. Food Chem. 43:1638-1640.

Cohen, E., Y. Shalom, and I. Rosenberger. 1990. Postharvest ethanol buildup and off-flavor in Murcott tangerine fruits. J. Amer. Soc. Hort. Sci. 115:775-778.

Cohen, R.A., and J.R. Hicks. 1986. Effect of storage on quality and sugars in muskmelon. J. Amer. Soc. Hort. Sci. 111:553-557.

Coombe, B.G., and M.G. McCarthy. 1997. Identification and naming of the inception of aroma development in ripening grape berries. Aust. J. Grape and Wine Res. 3:18-20.

Crouzet, J., P. Etievant, and C. Bayonove. 1990. Stone fruit: apricot, plum, peach, cherry. *In* I.D. Morton and A.J. Macleod, eds., Food Flavors, Part C, The Flavor of Fruits, pp. 43-91. Elsevier, New York, NY.

Crouzet, J., A. Signoret, J. Coulibaly, and M.H. Roudsari. 1986. Influence of controlled atmosphere storage on tomato volatile components. *In* G. Charalambous, ed., The Shelf-Life of Foods and Beverages, pp. 355-367. Elsevier, Amsterdam, The Netherlands.

Cunningham, D.G., T.E. Acree, J. Barnard, et al. 1985. Charm analysis of apple volatiles. Food Chem. 19:137-147.

Dan, K., S. Todoriki, M. Nagata, and I. Yamashita. 1997. Formation of volatile sulfur compounds in broccoli stored under anaerobic condition. J. Japan Soc. Hort. Sci. 65:867-875.

Demole, E., P. Enggist, and G. Ohloff. 1982. 1-*p*-Menthene-8-thiole: A powerful flavor impact constituent of grapefruit juice (*Citrus paradisi* Macfadyen). Helv. Chim. Acta 65:1785-1794.

DeRovira, D. 1997. Manual - Flavor Nomenclature Workshop: An Odor Description and Sensory Evaluation Workshop. Flavor Dynamics, Inc., Somerset, NJ.

De Bruyn, J.W., F. Garretsen, and E. Kooistra. 1971. Variation in taste and chemical composition of the tomato (*Lycopersicon esculentum* Mill). Euphytica 20:214-227.

Do, J.Y., D.K Salunkhe, and L.E. Olson. 1969. Isolation, identification and comparison of the volatiles of peach fruit as related to harvest maturity and artificial ripening. J. Food Sci. 34:618-621.

Dourtoglou, V., A. Gally, V. Tychopoulos, et al. 1995. Effects of storage under CO_2 atmosphere on the volatiles, phenylalanine ammonia-lyase activity and water soluble constituents of strawberry fruits. *In* G. Charalamous, ed., Food Flavors: Generation, Analysis, and Process Influence, pp. 1379-1394. Elsevier, New York, NY.

Eck, P. 1986. Blueberry. *In* S.P. Monselise, ed. CRC Handbook of Fruit Set and Development, pp. 75-85. CRC Press, Boca Raton, FL.

Engle, K.H., J. Heidlas, and R. Tressl. 1990. The flavour of tropical fruits (banana, melon, pineapple). *In* I.D. Morton and J.D. MacLeod, eds., Food Flavors, Part C, The Flavor of Fruits, pp. 195-219. Elsevier, Amsterdam, The Netherlands.

Fallik, E., D.D. Archbold, T.R. Hamilton-Kemp, et al. 1997. Heat treatment temporarily inhibits aroma volatile compound emission from Golden Delicious apples. J. Agric Food Chem. 45:4038-4041.

Fan, X., and J.P Mattheis. 1999. Impact of 1-methylcyclopropene and methyl jasmonate on apple volatile production. J. Agric. Food Chem. 47:2847-2853.

Fellman, J.K., J.P. Mattheis, M.E. Patterson, et al. 1993. Study of ester biosynthesis in relation to harvest maturity and controlled-atmosphere storage of apples (*Malus domestica* Borkh.). Proceedings of the 6th International Controlled Atmosphere Research Conference, Ithaca, NY, June 1993, pp. 500-507. Natural Resource, Agriculture, and Engineering Service, Cornell University, Ithaca, NY.

Flora, L.F., and T.O.M. Nakayama. 1981. Quality characteristics of muscadine grape products. *In* R. Teranishi and H. Barrera-Benitez, eds., Quality of Selected Fruits and Vegetables of North America, pp. 21-27. American Chemical Society, Washington, DC.

Galliard, T., J.A. Matthew, A.J. Wright, and M.J. Fishwick. 1977. The enzymic breakdown of lipids to volatile and nonvolatile carbonyl fragments in disrupted tomato fruits. J. Sci. Food Agric. 28:863-868.

Georgilopoulos, D.N., and A.N. Gallois. 1987. Aroma compounds of fresh blackberries (*Rubus laciniata* L.). Z. Lebensm Unters. Forsch. 184:374-380.

Golaszewski, R., C.A. Sims, S.F. O'Keefe, et al. 1998. Sensory attributes and volatile components of stored strawberry juice. J. Food Sci. 63:734-738.

Golding, J.B., D. Shearer, W.B. McGlasson, and S.G. Wyllie. 1999. Relationships between respiration, ethylene, and aroma production in ripening banana. J. Agric. Food Chem. 47:1646-1651.

Hartwig, P., and M. McDaniel. 1995. Flavor characteristics of lactic, malic, citric, and acetic acids at various pH levels. J. Food Sci. 60:384-388.

Hobson, G., and D. Grierson.1993. Tomato. *In* G.B. Seymour, J.E. Taylor, and G.A. Tucker, eds., Biochemistry of Fruit Ripening, pp. 405-442. Chapman and Hall, New York, NY.

Honkanen, E., and T. Hirvi. 1990. The flavour of berries. *In* I.D. Morton and J.D. MacLeod, eds., Food Flavors: Part C, The Flavor of Fruits, pp. 125-193. Elsevier, Amsterdam, The Netherlands.
\

Honkanen, E., T. Pysalo, and T. Hirvi. 1980. The aroma of Finnish wild raspberries. Z. Lebensm. Unters. Forsch. 171:180-182.

Humpf, H.U., and P. Schreier. 1991. Bound aroma compounds from the fruit and the leaves of blackberry (*Rubus laciniata* L.). J. Agric. Food Chem. 39:1830-1832.

Jones, R.A., and S.J. Scott. 1984. Genetic potential to improve tomato flavor in commercial F1 hybrids. J. Amer. Soc. Hort. Sci. 109:318-321.

Kanellis, A.K., and K.A. Roubelakis-Angelakis. 1993. Grape. *In* G.B. Seymour, J.E. Taylor, and G.A. Tucker, eds., Biochemistry of Fruit Ripening, pp. 190-234. Chapman and Hall, New York, NY.

Knee, M. 1993. Apple. *In* G.B. Seymour, J.E. Taylor, and G.A. Tucker, eds., Biochemistry of Fruit Ripening, pp. 325-346. Chapman and Hall, New York, NY.

Koehler, P.E., and S.J. Kays. 1991. Sweet potato flavor: Quantitative and qualitative assessment of optimum sweetness. J. Food Qual. 14:241-249.

Krammer, G.E., G.R. Takeoka, and R.G. Buttery. 1994. Isolation and identification of 2,5-dimethyl-4-hydroxy-3(2H)-furanone glucoside from tomatoes. J. Agric. Food Chem. 42:1595-1597.

Larsen, M., and L. Poll. 1990. Odour thresholds of some important aroma compounds in raspberries. Z. Lebensm. Unters. Forsch. 191:129-131.

Larsen, M., L. Poll, and C.E. Olsen. 1992. Evaluation of the aroma composition of some strawberry (*Fragaria ananassa* Duch) cultivars by use of odor threshold values. Z. Lebensm. Unters. Forsch 195:536-539.

MacLeod, A.J., and N.G. de Troconis. 1982. Volatile flavor components of mango fruit. Phytochemistry 21:2523-2526.

Malundo, T.M.M., R.L. Shewfelt, G.O. Ware, and E.A. Baldwin. 2001. Sugars and acids influence flavor properties of mango. J. Amer. Soc. Hort. Sci. 126:115-121.

Malundo, T.M.M., R.L. Shewfelt, G.O. Ware, and E.A. Baldwin. 2001. Alternative methods for consumer testing and data analysis used to identify critical flavor properties of mango (*Mangifera indica* L.). J. Sens. Stud. 16:199-214.

Manning, K. 1993. Soft fruit. *In* G.B. Seymour, J.E. Taylor, and G.A. Tucker, eds., Biochemistry of Fruit Ripening, pp. 347-377. Chapman and Hall, New York, NY.

Martens, M., E. Risvik, and H. Martens. 1994. Matching sensory and instrumental analyses. *In* J.R. Piggott and A. Paterson, eds., Understanding Natural Flavors, pp. 60-76. Blackie Academic Professional/Chapman and Hall, Gasgow, UK.

Mattheis, J.P., D.A. Buchanan, and J.K. Fellman. 1995. Volatile compound production by Bisbee Delicious apples after sequential atmosphere storage. J. Agric. Food Chem. 43:194-199.

Maul, F., S.A. Sargent, M.O. Balaban, et al. 1998. Aroma volatile profiles from ripe tomatoes are influenced by physiological maturity at harvest: an application for electronic nose technology. J. Amer. Soc. Hort. Sci. 123:1094-1101.

Maul, F., S.A. Sargent, C.A. Sims, et al. 2000. Recommended storage temperatures affect tomato flavor and aroma quality. J. Food Sci. 65:1228-1237.

McDonald, R.E., T.G. McCollum, and E.A. Baldwin. 1996. Prestorage heat treatments influence free sterols and flavor volatiles of tomatoes stored at chilling temperature. J. Amer. Soc. Hort. Sci. 12:531-536.

Marton, I.D., and A.J. MacLeod. 1990. Food Flavors: Part C. The Flavor of Fruits. Elsevier, New York, NY.

Moshonas, M.G., and P.E. Shaw. 1972. Analysis of volatile flavor constituents from tangerine essence. J. Agric. Food Chem. 20:70-71.

Moshonas, M.G., and P.E. Shaw. 1997. Dynamic headspace gas chromatography combined with multivariate analysis to classify fresh and processed orange juices. J. Ess. Oil Res. 9:133-139.

Narain, N., P.S. Bora, R. Narain, and P.E. Shaw. 1997. Quantitative determination of 46 volatile constituents in fresh, unpasteurized orange juices using dynamic headspace gas chromatography. *In* P. Shaw, H. Chan, and S. Nagy, eds., Tropical and Subtropical Fruits, vol. 1, pp. 1-77. AgScience, Auburndale, FL.

O'Mahony, M. 1995. Sensory measurement in food science: Fitting methods to goals. Food Tech. Apr:72-82.

Park, S.K., J.C. Morrison, D.O. Adams, and A.C. Noble. 1991. Distribution of free and glycosidically bound monoterpenes in the skin and mesocarp of Muscat of Alexandria grapes during development. J. Agric. Food Chem. 39:514-518.

Paterson, A., J.R. Piggott, and J. Jiang. 1993. Approaches to mapping loci that influence flavor quality in raspberries. *In* M.J. Comstock, ed., Food Flavor and Safety - Molecular Analysis and Design, pp. 109-117. ACS Symp. Ser. 528, American Chemical Society, Washington, DC.

Paz, O., H.W. Janes, B.A. Prevost, and C. Frenkel. 1981. Enhancement of fruit sensory quality by postharvest applications of acetaldehyde and ethanol. J. Food Sci. 47:270-276.

Perez, A.G., A. Cert, J.J. Rios, and J.M. Olias. 1997. Free and glycosidically bound volatile compounds from two banana cultivars: Valery and Pequena Enana. J. Agric. Food Chem. 45:4393-4397.

Perez, A.G., C. Sanz, R. Olias, and J.M. Olais. 1999. Lipoxygenase and hydroperoxide lyase activities in ripening strawberry fruits. J. Agric. Food Chem. 47:249-253.

Peters. A.M., and A. Van Amerongen. 1998. Relationship between levels of sesquiterpene lactones in chicory and sensory evaluation. J. Amer. Soc. Hort. Sci. 123:326-329.

Podoski, B.W., C.A. Sims, S.A. Sargent, et al. 1997. Effects of cultivar, modified atmosphere, and preharvest conditions on strawberry quality. Proc. Fla. State Hort. Soc. 110:246-252.

Riley, J.C.M., C. Willemot, and J.E. Thompson. 1996. Lipoxygenase and hydroperoxide lyase activities in ripening tomato fruit. Postharv. Biol. Technol. 7:97-107.

Robbins, J.A., and J.K. Fellman. 1993. Postharvest physiology, storage and handling of red raspberry. Postharv. News Info. 4:53-59.

Roberts, D.D., and T.E. Acree. 1996. Effects of heating and cream addition on fresh raspberry aroma using a retronasal aroma simulator and gas chromatography olfactometry. J. Agric. Food Chem. 44:3919-3925.

Romani, R., J. Labavitch, T. Yamashita, et al. 1983. Preharvest AVG treatment of 'Bartlett' pear fruit: effects on ripening, color change, and volatiles. J. Amer. Soc. Hort. Sci. 108:1046-1049.

Roscher, R., P. Schreier, and W. Schwab. 1997. Metabolism of 2,5-dimethyl-4-hydroxy-3(2H)-furanone in detached ripening strawberry fruits. J. Agric. Food Chem. 45:3202-3205.

Saftner, R.A., W.S. Conway, and C.E. Sams. 1999. Postharvest calcium infiltration alone and combined with surface coating treatments influence volatile levels, respiration, ethylene production, and internal atmospheres of 'Golden Delicious' apples. J. Amer. Soc. Hort. Sci. 124:553-558.

Salunkhe, D.K., and B. Desai. 1984. Postharvest Biotechnology of Fruits, vol. II. CRC Press, Boca Raton, FL.

Schaller, E., J.O. Bosset, and F. Escher. 1998. 'Electronic noses' and their application to food. Lebens. Wiss. Technol. 31:305-316.

Schamp, N., and P. Dirinck. 1982. The use of headspace concentration on Tenax for objective evaluation of fresh fruits. *In* G. Charalambous, ed., Chemistry of Foods and Beverages, pp. 25-47. Academic Press, New York, NY.

Seymour, G.B. 1993. Banana. *In* G.B. Seymour, J.E. Taylor, and G.A. Tucker, eds., Biochemistry of Fruit Ripening, pp. 83-106. Chapman and Hall, New York, NY.

Seymour, G.B., and W.B. McGlasson. 1993. Melons. *In* G.B. Seymour, J.E. Taylor, and G.A. Tucker, eds., Biochemistry of Fruit Ripening, pp. 273-290. Chapman and Hall, New York, NY.

Shamaila, M., W.D. Powrie, and B.J. Skura. 1992. Analysis of volatile compounds from strawberry fruit stored under modified atmosphere packaging (MAP). J. Food Sci. 57:1173-1176.

Shaw, P.E. 1991. Fruits II. *In* H. Maarse, ed., Volatile Compounds in Foods and Beverages, pp. 305-328. Marcel Dekker, New York, NY.

Shaw, P.E., and C.W. Wilson. 1980. Importance of selected volatile components to natural orange, grapefruit, tangerine, and mandarin flavors. *In* S. Nagy and J.A. Attaway, eds., Citrus Nutrition and Quality, pp. 167-190. ACS Symp. Ser. no. 143, American Chemical Society, Washington, DC.

Shukor, A.R., A. Faridah, H. Abdullah, and Y.K. Chan. 1998. Pineapple. *In* P.E. Shaw, H.T. Chan, and S. Nagy, eds., Tropical and Subtropical Fruits, vol. 1, pp. 137-190. AgScience, Auburndale, FL.

Shure, K.B., and T.E. Acree. 1995. In vivo and in vitro flavor studies of *Vitis labruscana* cv. Concord. *In* R.L. Rouseff and M.M. Leahy, eds., Fruit Flavors: Biogenesis, Characterization, and Authentication, pp. 127-133. American Chemical Society, Washington, DC.

Song, J., B.D. Gardner, J.F. Holland, and R.M. Beaudry. 1997. Rapid analysis of volatile flavor compounds in apple fruit using SPME and GC/time of flight spectrometry. J. Agric. Food Chem. 45:1801-1807.

Speirs, J., E. Lee, K. Holt, et al. 1998. Genetic manipulation of alcohol dehydrogenase levels in ripening tomato fruit affects the balance of some flavor aldehydes and alcohols. Plant Physiol. 117:1047-1058.

Stevens M.A., A.A. Kader, M. Albright-Holton, and M. Algazi. 1977. Genotypic variation of flavor and composition in fresh market tomatoes. J. Amer. Soc. Hort. Sci. 102:680-689.

Tandon, K.S., E.A. Baldwin, and R.L. Shewfelt. 2000. Aroma perception of individual volatile compounds in fresh tomatoes (*Lycopersicon esculentum* Mill.) as affected by the medium of evaluation. Postharvest Biol. Technol. 20:261-268.

Taylor, J.E. 1993. Exotics. *In* G.B. Seymour, J.E. Taylor, and T.A. Tucker, eds., Biochemistry of Fruit Ripening, pp. 151-187. Chapman and Hall, London, UK.

Teranishi, R., and S. Kint. 1993. Sample preparation. *In* T. Acree and R. Teranshi, eds., Flavor Science: Sensible Principles and Techniques, pp. 137-167. ACS Books, Washington, DC.

Webb, A.D. 1981. Quality factors in California grapes. *In* R. Teranishi and Harrera-Benitez, eds., Quality of Selected Fruits and Vegetables of North America, pp. 1-9. American Chemical Society, Washington, DC.

Wilson, C.W., P.E. Shaw, and R.J. Knight. 1986. Importance of selected volatile compounds to mango (*Mangifera indica* L.) flavor. *In* B.M. Lawrence, B.D. Mookherjee, and B.J. Willis, eds., Flavors and Fragrances: A World Perspective, Proceedings of the 10th International Congress on Essential Oils, Fragrances and Flavors, November 1986, Washington, DC., pp. 283-294. Elsevier Science Publishers, Amsterdam, The Netherlands.

Wright, D.H., and N.D. Harris. 1985. Effect of nitrogen and potassium fertilization on tomato flavor. J. Agric. Food Chem. 33:355-358.

Wyllie, S.G., D.N. Leach, Y. Wang, and R.L. Shewfelt. 1995. Key aroma compounds in melons: their development and cultivar dependence. *In* R.L. Rouseff and M.M. Leahy, eds., Fruit Flavors: Biogenesis, Characterization, and Authentication, pp. 248-257. ACS Symposium Series 596, American Chemical Society, Washington, DC.

Young, H., J.M. Gilbert, S.H. Murray, and R.D. Ball. 1996. Causal effects of aroma compounds on Royal Gala apple flavors. J. Sci. Food Agric. 71:329-326.

Zabetakis, I., and M.A. Holden. 1997. Strawberry flavor: analysis and biosynthesis. J. Sci. Food Agric. 74:421-434.

Food Safety

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Introduction

Data from the U.S. Center for Disease Control and Prevention (CDC) between 1973 and 1987 indicate that there were 3,699 foodborne illness outbreaks in the United States. Only 2% were associated with fruits and vegetables, and most of those were due to improper home canning. In general, produce is a low-risk food, and it is unlikely that one will become ill from eating raw fruits or vegetables. But a small risk does exist, and it is incumbent on all of those involved in the production and distribution of fresh produce to work to minimize those risks. Safety is the perception of acceptable risk, and if no risk is acceptable, then nothing can ever truly be safe. Many consumers feel that food products should have no risk associated with their consumption. Unfortunately, the reality is that reducing the risk of foodborne illness from consumption of fresh fruits and vegetables to absolute zero is an impossible task. It should also be kept in mind that the health benefits derived from eating at least 5 servings of fresh fruits and vegetables daily far outweigh the very small probability of contracting a foodborne illness.

Fruits and vegetables are unique foods, since they are often consumed raw or with minimal preparation. To date, there have been no effective intervention strategies developed that can completely eliminate food safety risks associated with consumption of uncooked produce. Therefore, preventing contamination with human pathogens, dangerous levels of chemical residues, or physical contaminants is the only way to ensure that these foods are wholesome and safe for human consumption.

Systems that ensure safety and wholesomeness of fruits and vegetables during postharvest handling and fresh-cut processing fall into four prevention programs: Good Agricultural Practices (GAPs), Good Manufacturing Practices (GMPs), Sanitation Procedures, and Hazard Analysis Critical Control Points (HACCPs).

The greatest risk to human health from consumption of uncooked produce is from pathogenic microorganisms. Raw agricultural products, such as fresh produce, should be expected to harbor a wide variety of microorganisms including the occasional pathogen. A vigorous population of nonpathogenic bacteria can be an excellent barrier to prevent the growth of pathogens, should they be present. Nonpathogenic bacteria also act as indicators of temperature abuse and age by spoiling the product. In the absence of spoilage, high levels of pathogens may occur, and the item may be consumed because it is not perceived as spoiled. There are four groups of human pathogens associated with fresh produce:

- Soil-associated pathogenic bacteria *(Clostridium botulinum* and *Listeria moncytogenes)*
- Fecal-associated pathogenic bacteria (*Salmonella* spp., *Shigella* spp., *E. coli* O157:H7, and others)
- Pathogenic parasites *(Cryptosporidium* and *Cyclospora)*
- Pathogenic viruses (hepatitis, norwalk virus, and others)

Many of these pathogens are spread from humans or domestic animals to food to humans. Fruits and vegetables may become contaminated by infected field workers, food preparers, consumers, cross-contamination, use of contaminated irrigation water, use of inadequately composted manure, or contact with contaminated soil. To minimize risks, growers should implement practices outlined in the “Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables” published by the Center for Food Safety and

Applied Nutrition, Food and Drug Administration (FDA 1998). This publication outlines Good Agricultural Practices (GAPs) which, when followed, can significantly reduce the risk of microbial hazards in produce. Growers should be aware that agricultural practices that may have been acceptable in years past may no longer be acceptable. In addition, fresh-cut processors should adhere to Good Manufacturing Practices (GMPs) 21 [CFR 100-169] to appropriately manage food safety risks during processing. Food handlers and consumers must act responsibly as they are the final link in the food safety chain.

Prevention of contamination is the only way to minimize true food safety risks and ensure food safety. Microbial testing cannot guarantee the absence of pathogens on fresh produce and, in fact, is unlikely to detect pathogens even when they are present. For example, if 5 fruit in a given lot of 100 individual fruit are harboring pathogens (5% contamination rate), how many fruit would have to be sampled to be 95% sure that one of the infected fruit was found? Table 1 shows that at 5% contamination rates, it would be necessary to test 60 fruit to have a 95% chance of finding the pathogen. It is surely not practical to test 60 out of every 100 fruits or vegetables. Yet testing fewer fruits results in a high likelihood that pathogens will be missed, even when they are present. For this reason, negative results from product pathogen testing have little value and can be misleading. Microbial testing can be an effective tool, but sampling the finished product is not an efficient, cost-effective approach. Sampling potential sources of contamination—such as irrigation water, cooling and process water, and food contact surfaces—and monitoring employee hygiene practices are more effective in preventing spread of human pathogens.

Table 1. Probability that a given number of samples will fail to detect microbial contaminants at specified contamination levels

Percent	**Number of Samples Analyzed**					
Contaminated	**5**	**10**	**15**	**20**	**30**	**60**
	-------------------%----------------					
10.0	41	65	79	88	96	>99
5.0	33	40	54	64	79	95
2.0	10	18	26	33	45	70
1.0	5	10	14	18	26	45
0.1	1	1	2	2	3	6

Source: U.S. Food and Drug Administration

Has the Problem Gotten Worse?

Scientists continue to discover new microorganisms that cause foodborne illness, and recent advances in diagnostics allow more rapid detection of smaller numbers of pathogens on foods. Detection methods for pathogenic microorganisms are faster and more sensitive, allowing investigators to better identify causes of outbreaks. In recent years, fresh produce sourcing has undergone significant changes, and centralized local production has been replaced with worldwide sourcing. Agricultural practices and hygienic conditions vary greatly among growing regions around the world, and increased global sourcing increases consumers exposure to diverse endemic microflora carried on fresh fruits and vegetables. Also, global sourcing means longer transportation and handling, giving pathogenic microorganisms additional time to proliferate and reach levels which can cause illness. Population demographics in North America have shifted, with a greater number of individuals that are older or who have compromised immune systems. They are at greater risk from foodborne illness, and the consequences of exposure can be deadly. All of these circumstances have resulted in increased foodborne illness awareness.

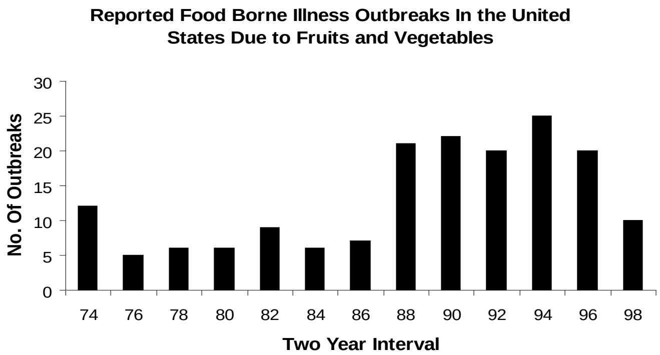

Figure 1. Increasing number of foodborne illness outbreaks associated with fresh produce in the United States. Source: CDC Food Borne Outbreak Surveillance System.

Intervention Strategies

Washing produce before preparation or consumption is recommended but does not guarantee that fresh produce is pathogen-free. Studies have demonstrated that washing produce in cold chlorinated water will reduce microbial populations by 2 or 3 logs (100- to 1000-fold), but sterility is not achieved, because microorganisms adhere to surfaces of produce and may be present in microscopic nooks and crannies on the surface of produce (Zhuang et al. 1995).

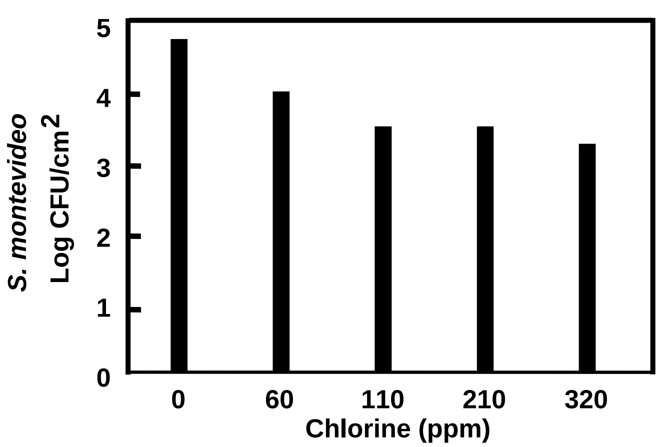

Figure 2. The effect of wash-water chlorine concentration on the fate of *Salmonella montevideo* on raw tomatoes. Adapted from Zhuang et al. 1995.

This is a problem since some pathogens, such as *E. coli* O157:H7, have an infectious dose of as few as 10 to 100 viable cells. To date, there are no wash-water treatments that can completely eliminate human pathogens from fresh produce. Product wash-water, if not properly sanitized, can become a source of microbiological contamination for every piece of product that passes through that water. It is a widespread misconception that chlorinated wash-water cleans or sterilizes produce as it is washed. Chlorinated wash-water does little more to clean produce than potable, nonchlorinated water. Chlorine does sanitize wash-water and maintains a low microbiological count in the water. In this way the water does not become a reservoir for mold spores and bacteria to infest produce.

Sodium or calcium hypochlorite is most commonly used in produce wash-water. The antimicrobial activity of these compounds depends on the amount of hypochlorous acid (HOCl) present in the water. This, in turn, depends on the pH of the water, the amount of organic material in the water, and, to some extent, the temperature of the water. Above pH 7.5, very little chlorine occurs as active hypochlorous acid, but rather as inactive hypochlorite (OCl^-). Therefore, the wash-water pH should be kept between 6.0 and 7.5 to ensure chlorine activity. If the pH falls below 6.0, chlorine gas may be formed, which is irritating to workers. Organic material in the water will reduce chlorine activity, so periodically replacing or filtering the water is important to maintain cleanliness.

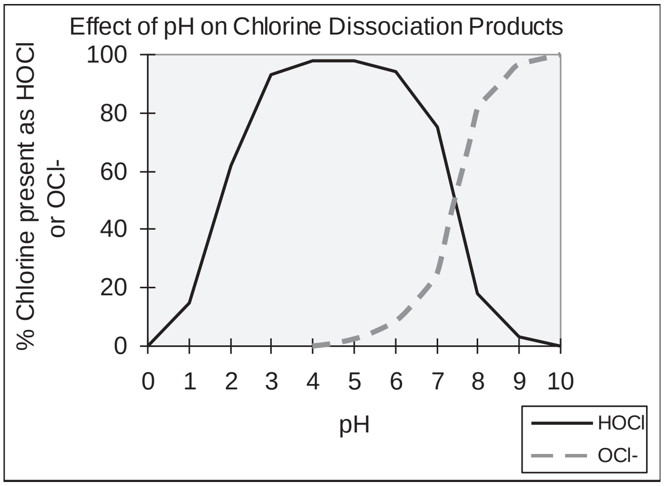

Figure 3. Effect of pH on chlorine dissociation products.

An effective wash-water sanitation system is becoming a necessity in the produce industry due to increased concerns with safety of fresh produce. Since water can be a source of contamination if the water itself becomes contaminated, the ability to ensure clean water is an essential element of a food safety program. Understanding how different sanitizers work and how they are measured and monitored is an important element in operating a food safety system in an effective and cost-efficient manner (See table 2.)

Irradiation and Cold Pasteurization

Use of nonthermal irradiation, often called cold pasteurization, has been advocated as a means to eliminate human pathogens from produce, similar to current allowable practices in the meat and poultry industry. To date this strategy has been ineffective for a number of reasons, including the expense of irradiating produce, a lack of facilities to treat produce, the damage susceptibility of many produce items to irradiation, and perceived consumer resistance to the use of irradiation for foods. Irradiation with a gamma source, such as cobalt 60, has been studied by many researchers. In the 30 years preceding 1983, more than a thousand published reports addressed irradiation of fruits and vegetables (Kader and Heintz 1983). The accumulated data suggest that irradiation may have some applications for disinfestation of fruits and vegetables but that irradiation alone will not resolve most microbiological issues. Different organisms vary in their sensitivity to ionizing radiation and many microbes will not be killed at the maximum allowable dose of 1 kGy (Brackett 1987).

Killing microbes with irradiation occurs when the irradiated energy interacts with water in microbial cells. Reactive chemicals are created that damage the cells' genetic material, or DNA. The ability of irradiation to kill a particular microbe is measured as the "D-value," the amount of energy needed to kill 90% of the cells of the microbe. Thus, a dosage of 2D would kill 99% of the cells, 3D kills 99.9% and so on. Of course, the D-value will differ for different microorganisms.

Insect pests and some parasites (*Cyclospora*, *Cryptosporidium*, etc.) have a relatively large amount of water and DNA in their cells and so are easily killed by irradiation. D-values for gamma irradiation of 0.1 kGy are typical. Thus, a dosage of 0.5 kGy would give a 5-log reduction. Bacteria (*E. coli*, *Salmonella*, *Listeria*, etc.) have less DNA and are more resistant to irradiation. D-values of 0.3 to 0.7 kGy are typical, depending on the bacterium. Thus, it would require 1.5 to 3.5 kGy to achieve a 5-log reduction of bacteria. At this time, the maximum allowable dosage for treating

Table 2. Activities and environmental sensitivities of wash-water sanitizers

Sanitizer	pH	Organic Matter	Biocidal Activity
Hypochlorites	6.0 - 7.5	Very sensitive	Oxidizer
Chlorine dioxide	6.0 - 10.0	Sensitive	Oxidizer
Ozone	6.0 - 10.0	Somewhat sensitive	Oxidizer
Peroxyacetic acid	1.0 - 8.0	Somewhat sensitive	Oxidizer
UV light	Not affected	Somewhat sensitive	Disrupts DNA

fruits and vegetables is 1.0 kGy. The implication is that gamma irradiation is not approved for use at dosages high enough to effectively eliminate pathogens from fresh produce. The Food Safety and Inspection Service (FSIS) has set the maximum absorbed dose levels for refrigerated and frozen meat at 4.5 kGy and 7.0 kGy, respectively, and 3.0 kGy for poultry.

Spore-forming bacteria (*Clostridium*, *Bacillus*, etc) are even more resistant to irradiation, and viruses (hepatitis, norwalk, etc.) are impossible to kill even with the dosages allowable for meat. Compared with the amount of radiation used in medical devices, the dosages approved for food are extremely low. Allowable doses of irradiation do not make food sterile. They do not always kill all the undesirable microorganisms if they are numerous to begin with. Also, an irradiated food can be recontaminated if mishandled. Consequently, while irradiation may have a future role in fruit and vegetable sanitation, it will never effectively guarantee pathogen-free produce, nor will it ever be a substitute for proper sanitation and food safety preventative programs. Different fruits and vegetables differ in the maximum dose that they will tolerate without unacceptable softening or loss of other quality parameters. However, the negative impacts of produce irradiation such as accelerated softening and technical issues (for example, nonhomogenous dosing) have hindered the commercialization of this technology.

However, it is unclear if irradiation will ever be capable of surface-sterilizing produce without irreparably damaging produce beyond salability. Irradiation dosages necessary to kill viruses and some bacteria are well in excess of the levels which induce damage to produce. Though irradiation has specific uses in produce, such as for phytosanitary and insect quarantine, its effectiveness as a food safety tool is limited. New irradiation technologies such as pulsed electric fields, pulsed UV light, or radio frequency technologies may yet play a role as tools for ensuring the food safety of produce.

Prevention

Good Agricultural Practices (GAPs)

In 1998 the FDA published “Guidance for Industry: Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables.” Though this document carries no regulatory or legal weight, due diligence requires producers to take prudent steps to prevent contamination of their crops. This document gives guidance on those prudent steps. A number of retail chains have begun to require independent third-party audits of producers based, in part, on this document.

The guide identifies eight food safety principles within the realm of growing, harvesting, and transporting fresh produce and suggests the reader “use the general recommendations in the guide to develop the most appropriate good agricultural and management practices for their operation.” The application of the principles is aimed at preventing contamination of produce with human pathogens. The following sections list the eight principles and implementation areas.

The following are the basic principles of GAPs:

- Prevention of microbial contamination of fresh produce is favored over reliance on corrective actions once contamination has occurred.
- To minimize microbial food safety hazards in fresh produce, growers or packers should use GAPs in those areas over which they have a degree of control, while not increasing other risks to the food supply or the environment.
- Anything that comes in contact with fresh produce has the potential of contaminating it. For most foodborne pathogens associated with produce, the major source of contamination is associated with human or animal feces.
- Whenever water comes in contact with fresh produce, its source and quality dictate the potential for contamination.
- Practices using manure or municipal

biosolid wastes should be closely managed to minimize the potential for microbial contamination of fresh produce.
- Worker hygiene and sanitation practices during production, harvesting, sorting, packing, and transport play a critical role in minimizing the potential for microbial contamination of fresh produce.
- All applicable local, State, and Federal laws and regulations, or corresponding or similar laws, regulations, or standards for operators outside the United States for agricultural practices should be followed.
- Accountability at all levels of the agricultural environment (farms, packing facility, distribution center, and transport operation) is important to a successful food safety program. There must be qualified personnel and effective monitoring to ensure that all elements of the program function correctly and to help track produce back through the distribution channels to the producer.

Land Use. The safety of food grown on any given parcel of land is influenced not only by the current agricultural practices but also by former land use practices. Heavy metals and pesticide residues may persist in soils for long periods of time. Soil should be tested to ensure that dangerously high levels of these compounds are not present. Former land use should also be investigated and documented to ensure that the production land was not formerly used for hazardous waste disposal or for industrial purposes that may have left behind toxic residues. If production land was previously used for agricultural purposes, pesticide use records should be reviewed to ensure that proper pesticide management practices were followed. Production acreage should not have recently been used as a feedlot or for animal grazing, because fecal contamination of the soil may persist.

Fertilizers. Improperly composted or uncomposted manure is a potential source of human pathogens. Human pathogens may persist in animal manure for weeks or even months. *E. coli* O157:H7 has been found to survive in uncomposted dairy manure incorporated into soil for up to 250 days (Suslow 1999). Proper composting via thermal treatment reduces the risk of potential foodborne illness. However, the persistence of many human pathogens in untreated agricultural soils is unknown. Use of inorganic fertilizers, which have been certified to be free of heavy metals and other chemical contaminants, is recommended.

Irrigation Water. Irrigation water is another potential vector by which contaminants may be brought into contact with fruits and vegetables. Deep-well water is less likely to be contaminated with human pathogens than surface water supplies. However, all irrigation water sources should be periodically tested for contamination by pesticides and human pathogens. The presence of *E. coli* is a useful indicator for fecal contamination and possible presence of human pathogens. Inexpensive test kits for generic *E. coli* are available from several vendors. Overhead irrigation systems are more likely than flood, furrow, or drip irrigation to spread contamination since contaminated water is applied directly to the edible portions of fruits and vegetables. Water used to mix or spray agricultural chemicals must be confirmed to be free of pathogens before use.

Pesticide Use. All pesticide use should be done in strict accordance with manufacturer's recommendations as well as Federal, State, and local ordinances. Monitoring and documentation of proper pesticide use should be done to prevent unsafe or illegal residues from contaminating fruits and vegetables. All pesticide applications should be documented, and proper records of application should be available and reviewed by management on a regular basis. Appropriately trained and licensed individuals should perform pesticide use recommendations and applications.

Harvest Operations. During harvest operations, field personnel may contaminate fresh fruits and vegetables by simply touching them with an unclean hand or knife blade. Portable field latrines equipped with hand-washing stations must be available and used by all harvest crew members. Training, monitoring, and enforcement of field worker hygiene practices, such as washing hands after using the bathroom, are necessary to reduce the risk of human pathogen contamination. Once harvested, produce should not be placed on soil before being placed in clean and sanitary field containers. Field harvesting tools should be clean and sanitary and should not be placed directly in contact with soil. Field containers should be cleaned and sanitized on a regular basis and should be kept free of contaminants such as mud, industrial lubricants, metal fasteners, or splinters. Plastic bins and containers are recommended as they are easier to clean and sanitize than wooden ones.

Sanitary Postharvest Handling of Produce. Depending on the commodity, produce may be field-packed in containers that will go all the way to the destination market, or it may be temporarily placed in bulk bins, baskets, or bags that will be transported to a packing shed. Employees, equipment, cold storage facilities, packaging materials, and any water that will contact the harvested produce must be kept clean and sanitary to prevent contamination.

Employee Hygiene. Gloves, hairnets, and clean smocks are commonly worn by packing house employees in export-oriented packing sheds. The cleanliness and personnel hygiene of employees handling produce at all stages of production and handling must be managed to minimize the risk of contamination. Adequate bathroom facilities and hand-washing stations must be provided and used properly to prevent contamination of produce by packing house employees. Shoe- or boot-cleaning stations may also be in place to reduce the amount of field dirt and contamination that enters the packing shed from field operations. Employee training in sanitary food handling practices should be done when an employee is hired, before beginning work, and on a regular basis thereafter. All training should be documented and kept on file.

Equipment. Food contact surfaces on conveyor belts, dump tanks, etc. should be cleaned and sanitized on a regularly scheduled basis with approved cleaning compounds. A 200 ppm (200 $\mu L\ L^{-1}$) NaOCl solution (bleach) is an example of a food-contact-surface sanitizer. Sanitizers should be used only after thorough cleaning with abrasion to remove organic material such as dirt or plant materials. Steam or high-pressure water should be used with care as it may create bacterial aerosols and actually help spread contamination throughout the packinghouse facility.

Cold Storage Facilities. Cold storage facilities, and in particular refrigeration coils, refrigeration drip pans, forced-air cooling fans, drain tiles, walls, and floors, should be cleaned and sanitized on a regular basis. The human pathogen *Listeria monocytogenes* can multiply at refrigerated temperatures in moist conditions and may contaminate produce if condensation from refrigeration units or ceilings drips on to the produce. A common environmental pathogen, *L. monocytogenes,* may get on walls, in drains, and into cooling systems. Comprehensive sanitation programs that target these areas are important in preventing establishment of this pathogen.

Packaging Materials. All packaging materials should be made of food-contact-grade materials to ensure that toxic compounds in the packaging materials do not leach out of the package and into the produce. Toxic chemical residues may be present in some packaging materials due to use of recycled base materials. Packages, such as boxes and plastic bags, should be stored in an enclosed storage area to protect them from insects, rodents, dust, dirt, and other potential sources of contamination. Plastic field bins and totes are preferred to wooden containers since plastic surfaces are more amenable to cleaning and sanitizing. Field bins should be cleaned and sanitized after every use. Wooden containers or field totes are almost impossible to sanitize since they have a porous surface and wooden or metal fasteners, such as nails from wooden containers, may accidentally be introduced into produce. Cardboard field bins, if reused, should be inspected for cleanliness and lined with clean plastic bags before reuse to prevent risk of cross-contamination.

Produce Wash-Water and Hydrocooling Water. All water that comes in contact with produce for washing, hydrocooling, or vacuum cooling must be potable. To achieve this, water should contain between 2 and 7 ppm (µL L^{-1}) free chlorine and have a pH between 6 and 7. Total chlorine up to 200 µL L^{-1} is allowed by law, though 50 to 100 ppm (µL L^{-1}) is usually sufficient if the pH of the water is between 6 and 7. Alternatively, an oxidation-reduction potential greater than 650 mV using any oxidative sanitizer will ensure that bacteria in the water are killed on contact. Chlorine use prevents cross-contamination of produce in the washing or hydrocooling system but it will not sterilize the produce. Rinsing produce with potable water will reduce the number of microorganisms present on the produce but will not remove all bacteria.

Refrigerated Transport. Produce is best shipped in temperature-controlled refrigerated trucks. Maintaining most perishables below 5 °C (41 °F), except for tropical fruit, will extend shelf-life and significantly reduce the growth rate of microbes, including human pathogens. Cut produce, including tropical fruits, should always be stored below 5 °C (41°F). Trucks used during transportation should be cleaned and sanitized on a regular basis. Trucks that have been used to transport live animals, animal products, or toxic materials should not be used to transport produce.

Recall and Traceback Plans. Recall of product is the last line of defense in a food safety emergency. This action may be initiated by the company, performed on a voluntary basis, or done at the request of the FDA because of a suspected hazard in the product. The FDA has defined three recall classifications and FDA actions. Class I is an emergency situation involving removal of products from the market that could lead to an immediate or long-term life-threatening situation and involve a direct cause-effect relationship; for example, *C. botulinum* in the product. Class II is a priority situation in which the consequences may be immediate or long term and may be potentially life threatening or hazardous to health; for example, *Salmonella* in food. Class III is a routine situation in which life-threatening consequences (if any) are remote or nonexistent. Products are recalled because of adulteration (filth in produce relating to aesthetic quality) or misbranding (label violation), and the product does not involve a health hazard. Every food provider should develop a recall or trace-back plan and an organizational structure that enable it to remove product from the market in a rapid and efficient manner.

Good Manufacturing Practices (GMPs)

GMPs ensure that food for human consumption is safe and has been prepared, packed, and held under sanitary conditions. GMPs are mandatory for the fresh-cut produce industry, but not mandatory for packinghouse or field operations that simply handle whole produce. However, though GMPs are not mandatory for packing sheds, they are mostly good common sense and are recommended for all produce-handling facilities.

The Code of Federal Regulations describes the conditions under which food must be processed and handled. The regulations cover general provisions, buildings and facilities, equipment, production and process controls, and defect action levels. Many of the GMPs are simple good sense, such as washing hands after using the restrooms and wearing hairnets when working with food. Unlike GAPs, GMPs are regulations and have the weight of law: A food processor *must* comply with GMPs. Copies of the Current GMPs (CGMP) can be obtained by subscribing to the Federal Register or by ordering 21 CFR 100-169 (Code of Federal Regulations, Title 21, Food and Drugs, Pt. 100-169). Submit a check or money order to Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402; or telephone the Government Printing Office at 202-783-3238 to order by credit card.

Personnel GMPs. Personnel working in food processing plants or packinghouses can be a significant source of food contamination. This includes production employees, maintenance employees, supervisors, and management. It is the responsibility of processing plant management to educate and train all food handlers about sanitary handling of foods. Employees experiencing diarrhea, vomiting, open skin sores, boils, fever, or disease should report these symptoms to their supervisor and should not be allowed to work with food products. All food handlers should have clean outer garments or frocks and thoroughly wash their hands before entering a food processing area, especially after toilet use. No jewelry (earrings, pendants, rings, etc.), pens, or wrist watches should be allowed in food processing areas, because these items may fall into food products unnoticed. Intact, clean, and sanitary gloves and hair restraints should be used by all personnel in food handling areas.

Physical Plant and Grounds. Food processing plants and produce packing houses should be constructed so as to segregate food handling activities from the outside environment. The physical building itself should have no openings or gaps which could allow entrance by rodents, insects, or birds. Surrounding grounds should be free of clutter such as equipment, litter, waste, refuse, or animal feces. No unpaved or dusty roads should be adjacent to food handling facilities, and areas surrounding the structure should be adequately drained so that no standing or pooled water is present. Vegetation surrounding the processing plant should be kept down to prevent the formation of breeding grounds for rodents. Rodent traps should be placed on the outside perimeter of the grounds and be inspected and serviced regularly.

Plant Construction and Design. The most important aspect of sanitary food plant and produce packinghouse design is sufficient space for sanitary operations. Processing areas should be designed for easy cleaning and sanitation. Floors, walls, and ceilings should be made of a cleanable, noncorrosive, nonabsorbent material and be in good repair. Floors should have rounded corner joints where they meet the wall to allow for easy cleaning. Processing plant floors should be constructed of sealed concrete or tile to withstand the physical and chemical abuses from machinery and cleaning chemicals. Equipment should be constructed of stainless steel to prevent corrosion. Overhead pipes, ducts, and fixtures should not be suspended over work areas, and horizontal surfaces of these items should be minimized to reduce accumulation of dust and water condensation. Where possible, overhead structures should be hidden above a false ceiling, and all hoses, pipes and electrical conduits should descend vertically from the ceiling so as to not provide horizontal surfaces for accumulation of filth. Adequate lighting should be provided and all light bulbs should be covered to ensure that broken glass cannot contaminate food products.

All water (rinse, flume, cleaning, ice, etc.) used in food processing must be of proper sanitary quality. Plumbing should be of adequate size and design to handle the amount of product being processed. Produce handling environments are usually wet; therefore, sloping floors with drains should be present to remove excess water from the processing area. Sanitary sewer lines should be separate from floor drains to ensure that cross-contamination of the processing area from sewage backflow does not occur.

An adequate number of toilets and hand-washing stations should be available to accommodate all employees. Restroom facilities should not open into processing areas. Hot running potable water, soap, and hand towels should be available at all times. Signs should be posted to instruct employees to wash their hands after using the restroom. Employee frocks, gloves, and knives should never be taken into the restrooms, and adequate storage space should be made available directly outside the restroom door for temporary storage of these items. Heating, ventilation, and air-conditioning (HVAC) systems may feature filtered positive air pressure in processing plants because of the potential for airborne pathogen contamination. HVAC units should blow air along the ceiling and down the walls to keep the walls dry and free of condensation.

Sanitation Procedures. Cleaning and sanitation are some of the most important programs in any food processing plant or packing shed. Cleaning is the removal, through physical action, of debris and filth. Sanitation is the application of antimicrobial compounds. Sanitation cannot be effective until surfaces are cleaned. Regular and scheduled equipment cleaning and sanitizing ensures that food products are being processed under hygienic conditions. Cleaning and sanitation is best done by a specially trained sanitation and cleaning crew and not by production personnel. A sanitation program in a food processing plant consists of two main elements: a master sanitation schedule and a monitoring program.

Master Sanitation Schedule. A written master sanitation schedule should be in place to ensure that all areas of a food processing plant or packing shed are cleaned and sanitized on a regular basis. The master sanitation schedule should detail the area to be cleaned, the sanitation method, tools, cleaning materials, and frequency of cleaning. There are five steps involved in cleaning and sanitizing:

1. Physical debris removal
2. Rinsing
3. Washing with detergent
4. Second rinsing
5. Sanitizing

It is critical that cleaning—that is, removal of debris and food particles—be done prior to any sanitation steps, because many sanitizers are inactivated by organic materials. Once gross or large pieces of food are removed, equipment should be rinsed with potable water to remove smaller particles. Then, soaps and detergents should be applied. Mild abrasion should be used to scrub equipment clean and remove caked-on food particles and biofilms (layers of bacteria). All soaps and detergents used should be approved for use on food contact surfaces. After cleaning, soaps and detergents should be removed by rinsing equipment with potable water. After rinsing, equipment should be sanitized to kill microbes. Sanitizing consists of rinsing all food contact surfaces with bactericidal compounds such as chlorine, iodine, or quaternary ammonia. Product manufacturer's directions for sanitizers and cleaning chemicals should be strictly followed.

Written sanitation standard operating procedures (SSOPs) for cleaning and sanitation should be prepared for specific pieces of equipment that are cleaned on a regular basis. This ensures that the equipment is cleaned properly regardless of who does the cleaning. SSOPs should specify the following:

- What: identifies task
- Why: purpose of task
- When: frequency of task
- Who: person responsible for task
- How: steps for completing task

A sample SSOP for sanitation of drains might take the following form:

Sanitation of Drains

Goal: Prevent build-up of contaminants (especially *Listeria monocytogenes*) in drains that could cross-contaminate product

Frequency: Daily

Procedure:

a. Remove all grates and coverings over drains.
b. Remove and dispose of all debris in drains.
c. Rinse drains and drain coverings to remove loose debris.
d. Mix chlorine-based soap as follows.
e. Apply soap to drains and drain coverings.
f. Scrub drains and drain coverings vigorously with brushes to remove invisible films.
g. Rinse thoroughly to remove soap. Must rinse thoroughly for sanitizing solution to be effective.
h. Mix quarternary ammonia sanitizer solution as follows.
i. Irrigate all drains and spray (or soak) coverings with sanitizer solution.
j. Replace grates and drain coverings.
k. The Sanitation Crew Chief then inspects all sanitized drains.
l. The Sanitation Crew Chief writes the time and date and signs the sanitation log for drains. If any drain does not pass inspection, the Crew Chief notes that in the log and the crew must rewash and resanitize until it passes inspection.

Cleaners and Sanitizers. There are numerous cleaning and sanitizing compounds available for use in food processing plants and packing sheds. These compounds fall into five categories:

- Chelators: tie up cations or salts; for example, EDTA (ethylenediaminetetraacetic acid)
- Alkalines: excellent detergents; for example, sodium hydroxide
- Acids: remove mineral deposits; for example, phosphoric acid
- Wetting agents: emulsify and penetrate soil; for example, alkyl sulfates
- Sanitizers: kill microbes; for example, sodium hypochlorite

Table 3. Comparison of common sanitizers

	Chlorine	Iodine	QUATS	Acid-anionic surfactants
Effectiveness against:				
Gram-positive bacteria, (lactics, clostridia, *Bacillus*, *Staphylococci*)	Good	Best	Good	Good
Gram-negative bacteria (*E. coli*, *Salmonella*, psychrotrophs)	Best	Good	Poor	Good
Yeast and molds	Best	Good	Good	Good
Spores	Best	Poor	Fair	Fair
Viruses	Best	Good	Poor	Poor
Effects on property:				
Corrosive	Fairly	Slightly	No	Slightly
Affected by hard water	No	Slightly	Type A*, No Type B†, Yes	Slightly
Irritating to skin	Yes, >100 $\mu L\ L^{-1}$	Not at levels used	No	Yes
Maximum level permitted by FDA without rinse	200 $\mu L\ L^{-1}$	25 $\mu L\ L^{-1}$	200 $\mu L\ L^{-1}$	200-400 $\mu L\ L^{-1}$ based on type
Affected by organic matter	Most affected	Somewhat	Least affected	Somewhat
Cost	Cheapest	Cheap	Expensive	Expensive
Tests for active residual	Simple	Simple	Difficult	Difficult
Stability in hot solution (>150 °F)	Unstable; some compounds stable	Highly unstable	Stable	Stable
Leaves active residue	No	Yes	Yes	Yes

Table 3. Comparison of common sanitizers—*Continued*

	Chlorine	Iodine	QUATS	Acid-anionic surfactants
Incompatible with—	Phenols, amines, soft metals	Starch, silver	Anionic wetting agents, soaps, wood, cloth, cellulose, nylon	Cationic surfactants, alkaline cleaners
Effective at neutral pH	Yes	No	Yes	No

Source: Adapted from Katsuyama and Strachan (1980)
*Type A: alkyl dimethyl benzyl ammonium chloride.
†Type B: methyl dodecyl benzyl trimethyl ammonium chloride.

Chlorine is by far the most commonly used sanitizer at 100 to 200 µL L^{-1}. It is important that water containing chlorine be free from organic matter and have a pH between 6.0 and 7.0. If either of these conditions is not met, then the chlorine is ineffective.

Monitoring Program. Before processing or packing begins, sanitation crew performance should be evaluated on a daily basis to ensure that conditions are hygienic. Visual inspection should be performed to ensure that no food particles or foreign matter are present on processing equipment. In particular, areas that are difficult to clean should be inspected, such as the underside of conveyors and peeling equipment. Unfortunately, visual inspection is not enough to ensure that equipment has been sanitized properly. The number of microbes present on processing equipment after sanitation operations should be determined on a regular basis to evaluate sanitation crew performance. Such determination can be made using one of three methods: petri contact plate, surface swabbing, or bioluminescence.

Petri Contact Plate. Plastic petri plates or films contain sterile agar with growth media for microbes and the type of microbes that will grow on these plates is determined by the type of medium used. In this method, petri plates or films are pressed up against food contact surfaces and the location is noted. The plates are then incubated in the laboratory; if microbes were present on the sampled surfaces, they will grow on the agar. A low bacteria count per square centimeter means that the sanitation crew is doing a good job at cleaning and sanitizing. If the number of microbes dramatically increases, an evaluation of sanitation procedures is in order.

Surface Swabbing. A variation of the petri plate method is to use sterile swabs to collect samples from food contact surfaces. Wet sterile swabs are used to brush an area of a food contact surface. The swab is then placed in a container with sterile solution. Bacteria are counted after incubation as above. Swabs and films for environmental sampling are commercially available from several companies.

Bioluminescence. The contact petri plate or swab methods are good for monitoring sanitation crew performance, but results are not available immediately. Another microbe detection method, called bioluminescence, is capable of detecting the presence of microbes immediately. This method relies on measuring the amount of ATP (adenosine triphosphate) that is present on food contact surfaces. ATP is present in all living cells and thus is a good indicator of the presence of organic material. This test is similar to the swab testing method except that the cleanliness of equipment is determined within minutes after the swab is taken.

In this test, equipment is swabbed and the amount of ATP present is determined by a chemical test kit. These test kits are available from a number of suppliers. Bioluminescence test results are available immediately and can determine if cleaning and sanitation procedures must be repeated before processing or packing begins.

Hazard Analysis Critical Control Points (HACCPs)

HACCP is a food safety system developed by the Pillsbury Company to reduce risk associated with food eaten by astronauts during space flights. HACCP is a system for the prevention of physical, chemical, or microbial contamination of food. The prime function of HACCP is to prevent identified hazards in food preparation through control of the process. HACCP functions as the final stage of an integrated food safety program and includes Good Agricultural Practices (GAPs), Good Manufacturing Practices (GMPs), and Sanitation Standard Operating Procedures (SSOPs). In fact, HACCP can only be effective if these programs are in place and functioning properly. There is no minimum or maximum number of Critical Control Points (CCPs) in any given operation. What is important is that all potential hazards be addressed through prerequisite programs or HACCP. Those hazards that can be controlled or minimized through quantitative control of a process may be designated CCPs and included in a HACCP program. Fresh-cut processors may have as few as two Critical Control Points (CCPs) in a perfectly adequate HACCP plan.

HACCP is a systems approach to ensure safety of a food product; it is not a means of ensuring food quality. Prevention of physical, chemical, and microbial contamination of produce during packing or processing is essential to ensure production of a safe product. It is recommended that each produce handling operation identify an individual for formal HACCP training and to be in charge of a team responsible for implementing the HACCP program. HACCP programs should be as simple as possible, without an excessive number of CCPs. Each HACCP program is unique and must be tailored to the specific operation.

There are seven basic steps in an HACCP program:

1. Conduct a hazard analysis
2. Determine CCPs to control the identified hazards
3. Establish critical limits for each CCP
4. Establish CCP monitoring requirements
5. Establish corrective actions to be taken when a CCP is outside critical limits
6. Establish record-keeping systems to document the HACCP program
7. Establish procedures to verify that the HACCP program is functioning as intended.

Assessment of Hazards

Each unit operation should be evaluated to identify potential sources of microbial, chemical, and physical hazards that may be introduced into produce. Areas that should be evaluated are growing and harvesting operations, packing shed operations, packaging material and storage areas, and all steps in distribution. This process is best accomplished by a team consisting of both management and production personnel. (Example: Hydrocooling water contamination, microbial or chemical.)

Determination of CCPs to Control the Identified Hazards

The next step in developing a HACCP program is to draw a flow diagram for the specific operation and then determine where each of the identified hazards may be prevented. Each point that will be monitored to control a specific hazard may be designated a CCP. (Example: A chlorine injection system on a hydrocooler.)

Establishment of CCP Limits

Once CCPs have been identified, critical limits must be set to determine when corrective actions need to be taken. Limits must be observable and measurable. (Example: Hydrocooler water must have a chlorine level of 100 to 150 µL L^{-1} total chlorine and a pH of 6.0 to 7.5.)

Establishment of CCP Monitoring Procedures

It is critical to define clearly how often monitoring will be done, how measurements will be taken, and what documentation will be prepared. (Example: Hydrocooler water pH and chlorine levels will be monitored hourly using a test kit and continuously with a strip chart recorder that has been calibrated daily; hourly pH and chlorine level measurements will be recorded in writing; and the records will be made available for inspection at the hydrocooler.)

Corrective Action When Deviations From Critical Limits Occur

When a deviation from the prescribed limits occurs, corrective action must be taken to eliminate potential contamination. All deviations and corrective actions must be documented in writing. (Example: Chlorine levels are determined to be below 25 µL L^{-1}. Hydrocooling of product is stopped, chlorine levels are adjusted, and all products that had been hydrocooled since the last time the system was verified to be within critical limits are disposed of.)

HACCP Recordkeeping Systems

All paperwork related to the HACCP system must be kept in an orderly and accessible manner. Paperwork kept should include production records (for example, supplier audits), harvesting records (for example, harvest dates and lot numbers), CCP monitoring records, and deviation file (HACCP deviations and corrective actions taken).

HACCP Verification

Periodic HACCP plan review, including review of CCP records, deviations, and random sampling must be conducted to ensure that the HACCP program is functioning properly.

Application of HACCP

When considering applying these principles to a farm operation, one can immediately see the difficulty in controlling naturally occurring hazards. For example, bird droppings in an orchard may potentially represent a hazard from the spread of *E. coli* O157:H7 or *Salmonella* spp. However, it may not be a CCP because there is no way to prevent that hazard by controlling a process. Furthermore, there is no way to quantify and measure bird droppings to know if they are within critical limits. The same would also be true of *Clostridium botulinum* spores in soil. Though they may represent a potential hazard, it would not be appropriate to establish soil as a CCP because it is not practical to measure the spores in soil or to control them through any known process. In fact, most agricultural hazards cannot, and should not, be prevented through HACCP. Instead, the use of GAPs has been identified by the FDA and the produce industry as a more appropriate way to address these hazards.

Another example is a cold storage room in a packinghouse where condensed water from refrigeration coils may contain the bacterium *Listeria monocytogenes* and could drip on the product. This is certainly a significant hazard, but is it a CCP? It would not be practical to develop a process to prevent water from dripping or to quantify and monitor water dripping from refrigeration coils. A more appropriate way to deal with this hazard is through SSOPs. Refrigeration coils and drip pans should be cleaned and sanitized according to a predetermined schedule to prevent the growth of *L. monocytogenes* in the condensate. This way, the hazard is prevented more effectively and more simply than by designating a CCP.

There is no minimum or maximum number of CCPs in any given operation. What is important is that all potential hazards be addressed through prerequisite programs or through HACCP. Those hazards that can be controlled or minimized through quantitative control of a process may be designated CCPs and included in a HACCP program. Fresh-cut processors may have as few as two CCPs in an adequate HACCP plan.

The Fresh-Cut Industry

Consumers expect that fresh-cut processors will manufacture wholesome and nutritious foods. To do this, fresh-cut processors must have systems in place to ensure that products being manufactured do not have physical, chemical, or microbial contaminants introduced during processing and packaging. If such systems are not in place, consumers are at risk and a single incidence of personal injury traced back to a specific food manufacturer may put that company out of business and result in criminal prosecution of the owners and management. Ensuring that food products are manufactured in a safe and wholesome manner does add cost to the final product. However, the long-term success of every food processor depends on its ability to consistently produce safe products. Food safety should not be confused with food quality. Food safety programs simply ensure that food products are safe to consume and prevent injury to consumers. Food safety does not begin at the processing plant receiving dock and the production of raw ingredients should be done following GAPs.

Fresh-cut produce can be damaged through peeling, cutting, slicing, or shredding. These same operations can transfer pathogenic microbes from the surface of the intact produce to the internal tissues. Injured cells and released cell fluids provide a nourishing environment for microbial growth. Maintaining low temperature throughout distribution is critical to maintaining quality of fresh-cut fruits and vegetables. Low temperatures reduce enzymatic reactions and greatly slow down the multiplication of spoilage organisms. Low temperatures also prevent the multiplication of most foodborne pathogens, with the exception of *Listeria monocytogenes* and a few others that are capable of growing, albeit slowly, at refrigerated temperatures.

Emphasis should be placed on preventing contamination by pathogens. The best way to prevent the introduction of pathogens into fresh-cut produce is by employing GAPs, GMPs, SSOPs, and, in some cases, by implementing an effective HACCP program. Such a program identifies potential points of contamination and ensures that those potential hazards are controlled and monitored to enhance safety. HACCP and food safety do not begin and end at the doors of the handling facility. They require that the produce handler work with both suppliers and customers to maintain food safety throughout the production, distribution, and marketing chain.

Sprouts—A Special Case

Over the past several years, sprouts have become a common fresh produce item linked to foodborne illness. A scientific advisory group to the FDA has recognized sprouts as a special problem. This is because bacterial pathogens that may be present at very low levels on sprout seeds at the time of sprouting can multiply to very high levels during the 3- to 5-day sprouting process.

Most sprout outbreaks have been caused by seed that was contaminated with a bacterial pathogen before sprouting began. Pathogens can survive for months under dry conditions used for seed storage. Though contaminated alfalfa seeds have been identified as the source in many outbreaks, clover, radish, and bean sprouts have also been associated with outbreaks. Any type of sprout seed may potentially be contaminated with bacterial pathogens before sprouting.

The FDA published guidelines for sprout processors to reduce the potential for foodborne illness related to sprouts. The guidelines include treatment of seeds in a sanitizer solution (currently a special allowance for 20,000 $\mu L\ L^{-1}$ chlorine) prior to sprouting, as well as testing of the sprout wash-water for *Salmonella*, *E. coli* O157:H7, and *L. monocytogenes* prior to harvest.

The FDA has published two related documents, entitled "Guidance for Industry: Reducing Microbial Food Safety Hazards for Sprouted Seeds" and "Guidance for Industry: Sampling and Microbial Testing of Spent Irrigation Water During Sprout Production." These guidelines are intended to provide recommendations to suppliers of seed for sprouting and to sprout producers about how to reduce microbial food safety hazards found in the production of raw sprouts. The guidelines are also intended to help ensure that sprouts are not a cause of foodborne illness and that those in the sprout industry comply with food safety provisions of the Federal Food, Drug, and Cosmetic Act.

References

Brackett, R.E. 1987. Microbiological consequences of minimally processed fruits and vegetables. J Food Quality 10:195-205.

FDA. 1998. Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables. Food Safety Initiative Staff, HFS-32, U.S. Food and Drug Administration, Center for Food Safety and Applied Nutrition, 200 C Street, Washington, DC.

Kader, A.A., and C.M. Heintz. 1983. Gamma irradiation of fresh fruits and vegetables - an indexed reference list (1965-1982). Postharvest Hort Ser. no. 4, University of California, Department of Pomology, Davis, CA.

Katsuyama, A.M., and J.P. Strachan. 1980. Principles of Food Processing Sanitation. The Food Processors Institute, Washington, DC.

Suslow, T. 1999. Addressing animal manure management issues for fresh vegetable production. Perishables Handling 98:7-9.

Zhuang, R.Y., L.R. Beuchat, and F.J. Angulo. 1995. Fate of *Salmonella montevideo* on and in raw tomatoes as affected by temperature and treatment with chlorine. Appl. Environ. Microbiol. 61: 2127-2131.

Further Reading

Guidance for Industry: Reducing Microbial Food Safety Hazards for Sprouted Seeds, October 27, 1999, Federal Register, vol. 64, no. 207. (U.S. Food and Drug Administration, Center for Food Safety and Applied Nutrition, 200 C Street, Washington, DC.; http://www.gpo.gov/fdsys/pkg/FR-1999-10-27/pdf/99-27976.pdf

Guidance for Industry: Sampling and Microbial Testing of Spent Irrigation Water During Sprout Production, October 27, 1999, Federal Register, vol. 64, no. 207. (U.S. Food and Drug Administration, Center for Food Safety and Applied Nutrition, 200 C Street, Washington, DC.; http://www.gpo.gov/fdsys/pkg/FR-1999-10-27/pdf/99-27976.pdf

FDA. 1998. Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables. Food Safety Initiative Staff, HFS-32, U.S. Food and Drug Administration, Center for Food Safety and Applied Nutrition, 200 C Street, Washington, DC. http://www.fda.gov/downloads/Food/GuidanceComplianceRegulatoryInformation/GuidanceDocuments/ProduceandPlanProducts/UCM169112.pdf

Beuchat, L.R. 1998. Surface Decontamination of Fruits and Vegetables Eaten Raw: A Review. World Health Organization, Geneva, Switzerland.

Current Good Manufacturing Practices (GMPs) Regulations 21 CFR 100-169. Superintendent of Documents, U.S. Government Printing Office, 732 North Capitol Street, NW, Washington, DC.

Nutritional Quality and Its Importance to Human Health

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Fruits, nuts, and vegetables play a significant role in human nutrition, especially as sources of dietary fiber, minerals, and vitamins—C (ascorbic acid), A, thiamine (B_1), niacin (B_3), pyridoxine (B_6), folacin (also known as folic acid or folate), B_9, and E (Quebedeaux and Bliss 1988, Quebedeaux and Eisa 1990, Craig and Beck 1999, Wargovich 2000). Their contribution as a group is estimated at 91% of vitamin C, 48% of vitamin A, 30% of folacin, 27% of vitamin B_6, 17% of thiamine, and 15% of niacin in the U.S. diet. Fruits and vegetables also supply 16% of magnesium, 19% of iron, and 9% of calories. Legume vegetables, potatoes, and tree nuts, such as almond, filbert, pecan, pistachio, and walnut, contribute about 5% of the per-capita availability of proteins in the U.S. diet, and their proteins are of high quality because they contain essential amino acids. Nuts are a good source of essential fatty acids, fiber, vitamin E, and minerals. Other important nutrients supplied by fruits and vegetables include riboflavin (B_2), zinc, calcium, potassium, and phosphorus. Fruits and vegetables remain an important source of nutrients in many parts of the world and offer advantages over dietary supplements because of low cost and wide availability.

Dietary supplements, while advantageous for conditions in which specific nutrients are needed in abundance such as iron deficiency, may be poorly absorbed. Climatic conditions, particularly temperature and light intensity, have an especially strong effect on the nutritional quality of fruits and vegetables (Mozafar 1994). Low temperatures favor synthesis of sugars and vitamin C (glucose being the precursor to ascorbic acid) and at the same time decrease the rate of ascorbic acid oxidation. Maximum β-carotene (vitamin A) content in tomatoes occurs at a temperature range of 15 to 21 ºC (59 to 70 ºF), but β-carotene content is reduced if temperatures are higher or lower than this range, principally due to the temperature sensitivity of lycopene, the precursor to β-carotene and lutein.

The B vitamins are crop specific when it comes to temperature sensitivity. Warm-season crops (beans, tomatoes, peppers, melons, etc.) produce more B vitamins at high (27 to 30 ºC, 81 to 86 ºF) than at low (10 to 15 ºC, 59 to 70ºF) temperatures. Conversely, cool season crops (broccoli, cabbage, spinach, peas, etc.) produce more B vitamins at low than at high temperatures. Light intensity has little effect on the B vitamins; but, as light intensity increases, vitamin C increases and total carotenoids (vitamin A precursors) and chlorophyll decrease (Gross 1991). Higher light intensities produce more sugars, leading to more vitamin C, and also increase plant temperatures, inhibiting β-carotene (vitamin A) production, which protects chlorophyll from photobleaching. Soil type, the rootstock used for fruit trees, mulching, irrigation, fertilization, and other cultural practices influence the water and nutrient supply to the plant, which can affect the composition and quality attributes (appearance, texture, taste, and aroma) of the harvested plant parts (Goldman et al. 1999). Other environmental factors that affect fruit and vegetable nutritional quality are altitude, soil pH and salinity, production practices (organic versus conventional and greenhouse versus field), ozone, insect injury, and plant diseases.

Maturity at harvest, fruit size, and harvesting method influence the commodity’s quality and extent of physical injuries. Delays between harvest and consumption or processing can result in losses of flavor and nutritional quality. The magnitude of these losses increases with exposure to temperature, relative humidity, and/or concentrations of O_2, CO_2, and C_2H_4 outside the ranges that are optimum for each commodity during the entire postharvest handling system (Lee and Kader 2000). Furthermore, processing and cooking methods can greatly affect the nutritional value of fruits and vegetables. For instance, water-soluble vitamins such as vitamin C and folate are lost when cooking water is discarded, while fat-soluble compounds such as lycopene may be stabilized or enhanced by cooking.

Fruits, nuts, and vegetables in the daily diet have been strongly associated with reduced risk for some forms of cancer, heart disease, stroke, and other chronic diseases (Quebedeaux and Bliss 1988, Quebedeaux and Eisa 1990, Produce for Better Health Foundation 1999, Prior and Cao 2000, Southon 2000, Wargovich 2000, Tomas-Barberan and Espin 2001, Hyson 2002, Goldberg 2003). Some components of fruits and vegetables (phytochemicals) are strong antioxidants and function to modify the metabolic activation and detoxification and disposition of carcinogens or even influence processes that alter the course of the tumor cell (Wargovich 2000). Though antioxidant capacity varies greatly among fruits and vegetables (Prior and Cao 2000, Perkins-Veazie and Collins 2001, Kalt 2002), it is better to consume a variety of commodities rather than limiting consumption to a few with the highest antioxidant capacity. The Dietary Guidelines for Americans, 2010 (USDA and HHS 2010) in part advises filling half your plate with fruits, vegetables, cooked beans, and grains. Such a healthy eating pattern also embodies food safety principles to avoid foodborne illness. In some countries, consumers are encouraged to eat up to 10 servings of fruits and vegetables per day.

There is increasing evidence that consumption of whole foods is better than isolated food components such as dietary supplements and nutraceuticals. For example, increased consumption of carotenoid-rich fruits and vegetables was more effective than carotenoid dietary supplements in increasing LDL oxidation resistance, lowering DNA damage, and inducing higher repair activity in human volunteers who participated in a study conducted in France, Italy, The Netherlands, and Spain (Southon 2000). In another study, adding antioxidant (vitamins A, C, and E) dietary supplements into the diet of cancer treatment patients who were eating a balanced diet of fruits and vegetables negatively affected their radiotherapy and chemotherapy (Seifried et al. 2003). High consumption of tomatoes and tomato products has been linked to reduced carcinogenesis, particularly prostate cancer, and has been thought to be due to the presence of lycopene, which gives red tomatoes their color (Giovannucci 2002). However, use of tomato powder effectively reduced prostate carcinogenesis in rats, while lycopene supplements, considered the primary active ingredient of tomatoes, had no effect (Boileau et al. 2003). Similar comparative studies are needed on other constituents of fruits and vegetables and on the bioavailability of nutrients taken as dietary supplements or as foods that contain these nutrients.

Examples of the phytochemicals in fruits and vegetables that have established or proposed positive effects on human health and their important sources are shown in tables 1 and 2. Some changes in these tables are likely as the results of additional studies on effects of phytochemicals and their bioavailability on human health become available in the next few years. Meanwhile it is important to evaluate the validity and dependability of the results of every study before reaching conclusions for the benefit of consumers.

Table 1. Nutritive constituents of fruits and vegetables that have positive effects on human health and their sources

Constituent	Sources	Established or proposed effects on human wellness
Vitamin C (ascorbic acid)	Broccoli, cabbage, cantaloupe, citrus fruits, guava, kiwifruit, leafy greens, pepper, pineapple, potato, strawberry, tomato, watermelon	Helps prevent scurvy and cardiovascular disease; aids wound healing and immune system
Vitamin A (carotenoids)	Dark-green vegetables (such as collards, spinach, and turnip greens), orange vegetables (such as carrots, pumpkin, and sweet potato), orange-flesh fruits (such as apricot, cantaloupe, mango, nectarine, orange, papaya, peach, persimmon, and pineapple), tomato	Helps prevent night blindness, chronic fatigue, psoriasis, heart disease, stroke, and cataracts
Vitamin K	Nuts, lentils, green onions, crucifers (cabbage, broccoli, brussel sprouts, etc.), leafy greens	Aids synthesis of procoagulant factors; helps prevent osteoporosis
Vitamin E (tocopherols)	Nuts (such as almonds, cashew nuts, filberts, macadamias, pecans, pistachios, peanuts, and walnuts), corn, dry beans, lentils and chickpeas, dark-green leafy vegetables	Helps prevent heart disease, LDL oxidation, cancer, and diabetes; aids immune system
Fiber	Most fresh fruits and vegetables, nuts, cooked dry beans and peas	Helps prevent diabetes and heart disease
Folate (folicin or folic acid)	Dark-green leafy vegetables (such as spinach, mustard greens, butterhead lettuce, broccoli, brussels sprouts, and okra), legumes (cooked dry beans, lentils, chickpeas, and green peas), asparagus	Helps prevent birth defects, cancer, and heart disease; aids nervous system
Calcium	Cooked vegetables (such as beans, greens, okra, and tomatoes), peas, papaya, raisins, orange, almonds, snap beans, pumpkin, cauliflower, rutabaga	Helps prevent osteoporosis; helps lower blood pressure; aids muscles, skeleton, and teeth

Table 1. Nutritive constituents of fruits and vegetables that have positive effects on human health and their sources—*Continued*

Constituent	Sources	Established or proposed effects on human wellness
Magnesium	Spinach, lentils, okra, potato, banana, nuts, corn, cashews	Helps prevent osteoporosis; aids nervous system, teeth, and immune system
Potassium	Baked potato or sweet potato, banana and plantain, cooked dry beans, cooked greens, dried fruits (such as apricots and prunes), winter (orange) squash, cantaloupe	Helps prevent hypertension (high blood pressure), stroke, and arteriosclerosis

Table 2. Nonnutritive plant constituents that may be beneficial to human health

Constituent	Compound	Sources	Established or proposed effects on human wellness
Phenolic compounds			
Proanthocyanins	Tannins	Apple, grape, cranberry, pomegranate	Help prevent cancer
Anthocyanidins	Cyanidin, malvidin, delphinidin, pelargonidin, peonidin, petunidin	Red, blue, and purple fruits (such as apple, blackberry, blueberry, cranberry, grape, nectarine, peach, plum & prune, pomegranate, raspberry, and strawberry)	Help prevent heart disease, cancer initiation, diabetes, cataracts, and allergies; help lower blood pressure
Flavan-3-ols	Epicatechin,	Apples, apricots, blackberries, plums, raspberries, strawberries	Help prevent platelet aggregation and cancer
Flavanones	Hesperetin, naringenin, eriodictyol	Citrus (oranges, grapefruit, lemons, limes, tangerines, etc.)	Help prevent cancer
Flavones	Luteolin, apigenin	Celeriac, celery, peppers, rutabaga, spinach, parsley, artichoke, guava, pepper	Help prevent cancer, allergies, and heart disease
Flavonols	Quercetin, kaempferol, myricetin, rutin	Onions, snap beans, broccoli, cranberry, kale, peppers, lettuce	Help prevent heart disease and cancer initiation; are capillary protectants
Phenolic acids	Caffeic acid, chlorogenic acid, coumaric acid, ellagic acid	Blackberry, raspberry, strawberry, apple, peach, plum, cherry	Help prevent cancer; help lower cholesterol
Carotenoids			

Table 2. Nonnutritive plant constituents that may be beneficial to human health—*Continued*

Constituent	Compound	Sources	Established or proposed effects on human wellness
Lycopene		Tomato, watermelon, papaya, Brazilian guava, autumn-olive, red grapefruit	Help prevent cancer, heart disease, and male infertility
α-Carotene		Sweet potatoes, apricots, pumpkins, cantaloupes, green beans, lima beans, broccoli, brussel sprouts, cabbage, kale, kiwifruit, lettuce, peas, spinach, prunes, peaches, mango, papaya, squash, carrots	Help prevent/slow tumor growth
β-Carotene		Cantaloupes, carrots, apricots, broccoli, leafy greens (lettuce, swiss chard, etc.), mango, persimmon, red pepper, spinach, sweet potato	Help prevent cancer
Xanthophylls	Lutein, zeaxanthin, β-cryptoxanthin	Sweet corn, spinach, corn, okra, cantaloupe, summer squash, turnip greens	Help prevent macular degeneration
Monoterpenes	Limonene	Citrus (grapefruit, tangerine, etc.)	Help prevent cancer
Sulfur compounds	Glucosinolates, isothiocyanates, indoles, allicin, diallyl isulphide	Broccoli, brussels sprouts, mustard greens, horseradish, garlic, onions, chives, leeks	Help prevent cancer and diabetes; help lower cholesterol and blood pressure

References

Boileau, T.W., Z. Liao, S. Kim, et al. 2003. Prostate carcinogenesis in N-methyl-N-nitrosourea (NMU)-testosterone-treated rats fed tomato powder, lycopene, or energy-restricted diets. J. Natl. Cancer Inst. 95:1578-86.

Craig, W., and L. Beck. 1999. Phytochemicals: health protective effects. Can. J. Diet. Pract. Res. 60:78-84.

Giovannucci, E. 2002. A review of epidemiologic studies of tomatoes, lycopene, and prostate cancer. Exp. Biol. Med. (Maywood) 227:852-9.

Goldberg, G., ed. 2003. Plants: Diet and Health. The Report of a British Nutrition Foundation Task Force. Blackwell Science, Oxford, United Kingdom.

Goldman, I.L., A.A. Kader, and C. Heintz. 1999. Influence of production, handling, and storage on phytonutrient content of foods. Nutr. Rev. 57:S46-S52.

Gross, J. 1991. Pigments in Vegetables: Chlorophylls and Carotenoids. AVI Book, Van Nostrand Reinold, New York, NY.

Hyson, D. 2002. The Health Benefits of Fruits and Vegetables: A Scientific Overview for Health Professionals. Produce for Better Health Foundation, Wilmington, DE

Kalt, W. 2002. Health functional phytochemicals of fruits. Hort. Rev. 27:269-315.

Lee, S.K. and A.A. Kader. 2000. Preharvest and postharvest factors influencing vitamin C content of horticultural crops. Postharv. Biol. Technol. 20:207-220.

Mozafar, A. 1994. Plant Vitamins: Agronomic, Physiological and Nutritional Aspects. CRC Press, Boca Raton, FL.

Perkins-Veazie, P., and J.K. Collins. 2001. Contribution of nonvolatile phytochemicals to nutrition and flavor. HortTechnology 11:539-546.

Prior, R.L., and G. Cao. 2000. Antioxidant phytochemicals in fruits and vegetables: diet and health implications. HortScience 35:588-592.

Produce for Better Health Foundation. 1999. Dietary Guidelines: The Case for Fruits and Vegetables First. The Foundation, Wilmington, DE.

Quebedeaux, B., and F.A. Bliss, eds., 1988. Horticulture and Human Health. Contributions of Fruits and Vegetables, Proceedings of the 1st International Symposium on Horticulture and Human Health, Arlington VA, April 12-15, 1987, pp. 243. Prentice Hall, Englewood Cliffs, NJ.

Quebedeaux, B., and H.M. Eisa. 1990. [Horticulture and Human Health: Contributions of Fruits and Vegetables, Proc. 2nd Intl. Symp. Hort. and Human Health.] HortScience 25:1473-1532.

Seifried, H.E., S.S. McDonald, D.E. Anderson, et al. 2003. The antioxidant conundrum in cancer. Cancer Res. 63:4295-4298.

Southon, S. 2000. Increased fruit and vegetable consumption within the EU: potential health benefits. Food Res. Intl. 33:211-217.

Tomas-Barberan, F.A., and J.C. Espin. 2001. Phenolic compounds and related enzymes as determinants of quality in fruits and vegetables. J. Sci. Food Agric. 81:853-876.

USDA and HHS. 2010. U.S. Department of Agriculture and U.S. Department of Health and Human Services. Dietary Guidelines for Americans, 2010. 7th Edition, U.S. Government Printing Office, December 2010, Washington, DC.

Wargovich, M.J. 2000. Anticancer properties of fruits and vegetables. HortScience 35:573-575.

Annual Culinary Herbs

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Scientific Names and Introduction

Culinary herbs include basil (*Ocimum basilicum* L.), chervil, salad chervil (*Anthriscus cerefolium* L. [Hoffm.]), coriander, cilantro, Chinese parsley (*Coriandrum sativum* L.), dill (*Anethum graveolens* L.), and savory/summer savory (*Satureja montana* L.). Leaves of annual herbs are typically used, though roots of coriander are also. Herbs are grown in both the field and greenhouse.

Quality Characteristics and Criteria

Herbs should appear fresh and green: no yellowing, decay, insect, or mechanical damage. Leaves should be uniform in size. Flavor and aroma should be strong and characteristic of the herb. There are purple forms of basil that should have a rich color.

Horticultural Maturity Indices

Annual herbs should be harvested before flowering. Basil still maintains its quality with some flowers.

Grades, Sizes, and Packaging

There are no market grades or sizes for fresh herbs. They may be tied or bunched with a rubberband, packaged in plastic bags or clamshells, then packed in corrugated cartons. Perforated polyethylene liners will prevent dehydration and maintain quality.

Precooling Conditions

With the exception of basil, herbs should be cooled to just above 0 °C (32 °F) as soon as possible after harvest. Vacuum cooling is recommended (Aharoni et al. 1988). Basil should be cooled to no lower than 12 °C (54 °F).

Optimum Storage Conditions

Chervil, coriander, dill, and savory should be stored at 0 °C (32 °F) and 95 to 100% RH. Postharvest life ranges from 1 week for chervil (Gorini 1981) to 2 weeks for coriander and dill and up to 3 weeks for savory. Basil should be stored at 12 °C (54 °F) and 95 to 100% RH (Aharoni et al. 1993). At this temperature and RH, quality can be maintained for 2 weeks (Lange and Cameron 1994).

Controlled Atmosphere (CA) Considerations

A 5 to 10% O_2 + 4 to 6% CO_2 CA is only moderately beneficial for fresh herbs (Saltveit 1997). However, MAP lengthens the shelf-life of coriander (Loiza and Cantwell 1997), chervil (Aharoni et al. 1993), and basil (Lange and Cameron 1998).

Retail Outlet Display Considerations

Use of water sprinklers is acceptable. Basil should not be displayed at temperatures below 12 °C (54 °F) because of chilling sensitivity. Other herbs should be displayed at 0 °C (32 °F) in refrigerated units.

Chilling Sensitivity

Chervil, coriander, dill, and savory are not sensitive to chilling and should be stored as cold as possible (0 °C [32 °F]) without freezing. Basil is susceptible to chilling injury if stored below 12 °C (54 °F). The primary symptom of chilling injury is browning or blackening of the leaves (Cantwell and Reid 1993).

Ethylene Production and Sensitivity

Annual herbs produce very little ethylene, but are highly susceptible to ethylene exposure (Cantwell 1997). Symptoms of ethylene damage include yellowing and leaf abscission (Cantwell and Reid 1993).

Respiration Rates

Temperature	Basil	Chervil	Coriander	Dill
	------------*mg CO_2 kg^{-1} h^{-1}*------------			
0 °C	36	12	22	22
5 °C	—	—	30	—
7.5 °C	—	—	46	—
10 °C	71	80	—	103
20 °C	176	170	—	324

Data from Cantwell and Reid (1993) and Loiza and Cantwell (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Yellowing and leaf abscission may occur due to ethylene exposure, especially if herbs are held at 10 °C (50 °F) or warmer. Basil is susceptible to chilling injury if held below 12 °C (54 °F), the main symptom being necrosis and browning or blackening of the leaves.

Postharvest Pathology

Molds and bacterial decay may develop, especially on mechanically damaged leaves or cut ends of stems. Low temperatures should be maintained throughout the cold chain to minimize pathological disorders and prolong shelf-life. Chilling increases the susceptibility of basil to decay.

Quarantine Issues

There are no quarantine issues.

Suitability as Fresh-Cut Product

Annual herbs are used in some packaged salad blends.

Special Considerations

High RH is used to prevent water loss and is especially important in maintaining the quality of fresh herbs.

References

Aharoni, N., O. Dvir, D. Chalupowisz, and Z. Aharon. 1993. Coping with postharvest physiology of fresh culinary herbs. Acta Hort. 344:69-78.

Aharoni, N., A. Reuveni, and O. Dvir. 1989. Modified atmospheres in film packages delay senescence and decay of fresh herbs. Acta Hort. 258:255-262.

Cantwell, M. 1997. Properties and recommended conditions for storage of fresh fruits and vegetables. *At* http://postharvest.ucdavis.edu.

Cantwell, M.I., and M.S. Reid. 1993. Postharvest physiology and handling of fresh culinary herbs. J. Herbs, Spices, Medicinal Plants 1:83-127.

Gorini, F. 1981. Vegetable schedules. 2. Leafy vegetables. Chervil. Informatore di Ortoflorofrutticoltura 22:3-4.

Lange, D.D., and A.C. Cameron. 1994. Postharvest shelf-life of sweet basil *(Ocimum basilicum).* HortScience 29:102-103.

Lange, D.D., and A.C. Cameron. 1998. Controlled atmosphere storage of sweet basil. HortScience 33:741-743.

Loaiza, J., and M. Cantwell. 1997. Postharvest physiology and quality of cilantro (*Coriandrum sativum* L.). HortScience 32:104-107.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, vol. 4, Vegetables and Ornamentals, pp. 98-117. Postharvest Hort. Ser. no. 18, University of California, Davis, CA.

Apple

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Scientific Name and Introduction

Malus × *domestica* Borkh., the apple, is a perennial of the Rosaceae family. The apple is thought to have arisen in the Caucasus region of southeastern Europe, and the tree is one of the hardiest temperate zone species. The edible part of the fruit is composed of fleshy tissue that surrounds the five ovaries, as well as some ovary or carpel tissue. The parenchyma of the fused bases of the calyx, corolla, and stamens constitutes the major edible part of the fruit, though this tissue is sometimes interpreted as being cortical. The skin surrounding the fleshy parenchyma tissue is made up of cuticle, epidermal, and hypodermal layers, with lenticels allowing gas diffusion across the skin. Cracks in the skin surface are also important for gaseous exchange. The diffusion characteristics of the skin can affect the tolerance of different varieties to storage conditions. Examples include 'Golden Delicious,' which tends to shrivel faster than other varieties because of breaks in the cuticle, and the Marshall 'McIntosh' strain, which is less tolerant to low O_2 in CA storage than other strains because of higher resistance of the skin to gas exchange.

Quality Characteristics

Quality consists of a combination of visual appearance, texture, and flavor. Modern consumers demand impeccable appearance, optimum texture, and firmness typical of the variety.

Skin Color. Each variety has specific commercial requirements for skin color ranging from green or yellow for varieties such as 'Golden Delicious' and 'Granny Smith' to red for varieties such as 'Red Delicious.' Bicolored apples such as 'Gala' and 'Braeburn' are also popular. Some varieties are currently marketable only if they meet strict standards for red color intensity and coverage. There is a tendency for wholesalers to gradually increase color standards, thereby encouraging growers to select redder strains of previously acceptable bicolored apples. Red color is not an indicator of fruit maturity or quality, however. With few exceptions, the ground (background) color requirement for apples is light green, as yellowness is regarded as an indication of overmature or senescent fruit. Consumers generally prefer 'Golden Delicious' apples that have a white skin color, rather than green or yellow. Consumers demand fully green 'Granny Smith' apples without a red blush and 100% red color for 'Red Delicious.'

Blemish. A high-quality apple in the marketplace is free from blemish, though there may be a greater tolerance for defects in certain markets such as organic outlets. Occurrences of physically induced damage such as bruising or stem-punctures and physiological and pathological disorders are not acceptable in any market. The prevalence of these defects can be affected greatly by variety characteristics such as stem length, skin tenderness, softness of the fruit, and genetically based resistance to physiological and pathological disorders. The density of the flesh and the skin thickness can also contribute to resistance of fruit to bruising under normal handling conditions, and susceptibility to bruising can determine the commercial success of a variety.

Texture. A universal constituent of quality regardless of variety is firmness. Consumers demand apples that are crisp and crunchy. Other textural or flavor components are secondary. All apples are not required to have the same firmness values, and optimum values depend on the characteristics of an individual variety. For example, a crisp 'Granny Smith' apple is often 80 to 98 N (18 to 22 lb-force), while a crisp 'Golden Delicious' is above 53 N (12 lb-force).

Flavor. Sweetness and acidity vary by variety. For example, the acidity of 'Granny Smith' apples is high (0.8 to 1.2% malate) while that of 'Red Delicious' is low (0.2 to 0.4%). Similarly, sugar content of apples also varies by variety. 'Fuji' apples can have 20% or more SSC.

Ethylene Production and Sensitivity

The apple is classified as a climacteric fruit, exhibiting increased respiration rates during maturation and ripening. This rise is associated with increases in internal concentrations of CO_2 and ethylene, respiration, and autocatalytic ethylene production. Endogenous ethylene production can vary greatly among varieties. In general, early season varieties have high ethylene production rates and ripen quickly, while late season ones have low ethylene production rates and ripen slowly. The timing of the climacteric and ripening of apple fruit is advanced by exposure to ethylene. Prevention or slowing of ethylene production, by affecting ethylene synthesis or perception, is a strategy for increasing fruit storability. This is achieved primarily by use of low storage temperatures and application of CA storage technologies (Watkins 2002, 2003). Methylcyclopropane (1-MCP) is available under the commercial name SmartFresh. 1-MCP is structurally related to ethylene, has a nontoxic mode of action, and is applied at very low levels with low measurable residues in food commodities.

Respiration Rates

In general, early season varieties have high respiration rates, while late season varieties have low respiration rates. The respiration rate of fruit is directly affected by temperature, and the respiratory climacteric is suppressed by storage temperatures below 10 °C (50 °F). The lowest temperatures for storage must be above freezing and above those at which chilling injury will develop.

Temperature	Summer apples	Fall apples
	mg CO_2 kg^{-1} h^{-1}	
0 °C	3 to 6	2 to 4
5 °C	5 to 11	5 to 7
10 °C	14 to 20	7 to 10
15 °C	18 to 31	9 to 20
20 °C	20 to 41	15 to 25

Data from Hardenburg et al. (1986).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Horticultural Maturity Indices

Maturity and Marketing Season. In general, an apple fruit harvested when less mature will have poor color and flavor and can be more susceptible to physiological disorders such as bitter pit and superficial scald. Fruit harvested overmature tend to be softer and more easily damaged, may have watercore, and may be more susceptible to diseases and physiological disorders such as senescent breakdown. The length of storage of apples generally can be increased by harvesting fruit before they are fully mature, but quality characteristics such as varietal flavor decrease as immaturity at harvest increases. Fruit harvested early in the harvest window for long-term storage (6 to 12 mo) tend to have less flavor than those allowed to ripen further on the tree but are acceptable if minimal flavor requirements are met along with good texture. The challenge is to decide appropriate harvest periods for each marketing period, which can range from immediate on-farm sales to marketing across the globe after 11 months of storage.

Harvest Maturity Indices. A wide range of indices have been tested over many years as possible indicators of harvest maturity. Several common methods have been outlined by Lau (1985). Ethylene, measured commonly as internal ethylene concentration, and the starch index, in which the degree of starch hydrolysis is estimated, have become the most widely used maturity indices. Since a rise in ethylene production is associated with initiation of ripening, it has been suggested that ethylene production or internal ethylene concentration (IEC) should be a major determinant of harvest decisions (Lau 1985). However, relationships between ethylene production and optimum harvest dates can be poor, and the timing, or presence, of increased ethylene production is a function of cultivar. Factors such as a growing region, orchard within a region, cultivar strain, growing season conditions, and nutrition are greatly affected within a cultivar (Watkins 2003). Therefore, ethylene production may not be relevant for determining harvest of some cultivars.

For some bicolored apples, background color is considered an important harvest index. In some cases, State regulations have been established to set minimal harvest maturities; for example, in California the starch index for 'Granny Smith.' While ethylene production is regarded as the only *physiological* indicator of apple fruit maturity, fruit of some varieties and growing regions are often harvested well before autocatalytic ethylene production occurs, and therefore this measurement is commercially irrelevant. However, in some regions ethylene is used to determine when fruit are too mature to be candidates for long-term storage. It is generally recognized that no single maturity index is appropriate across all varieties; growers have learned to rely on a combination of indices.

Other indices, such as flesh firmness and soluble sugar content, are quality indicators rather than maturity indicators, as they are influenced greatly by orchard factors; for example, fruit exposure to light. During the preharvest season, firmness falls and sugar content continues to increase. However, these quality indicators provide information that can be important to fruit performance in storage. Both indices are increasingly used in the marketplace as quality criteria by wholesalers, especially in Europe.

The three major apple-growing regions in the U.S. are the States of Washington, New York, and Michigan. They operate apple maturity programs in conjunction with their land grant universities. Currently in Washington, individual packinghouses conduct their own maturity programs inline with their marketing strategies. In each region, a wide range of maturity and quality indices are collected, and the optimum harvest period (harvest window) is established for each variety (Anonymous 1986, Blanpied and Silsby 1992, Beaudry et al. 1993. The strength of these programs lies not in reliance on absolute maturity indices, but in discussion with industry personnel on changes in maturity and quality occurring over the harvest period. In this way, full participation of extension personnel, growers, and storage operators can ensure that fruit of appropriate storage potential are directed towards short-, medium- or long-term storage.

Grades, Sizes, and Packaging

Grade Standards. U.S. grades are U.S. Extra Fancy, U.S. Fancy, and U.S. No. 1, based primarily on color requirements, but also on freedom from decay, disorders, and blemishes, as well as firmness of fruit (Childers et al. 1995). These Federal guidelines have been adopted by many States, but States may have additional grading and branding laws. Information pertaining to any State can be obtained from the local State Department of Agriculture. Washington State packers follow the grade standards of either U.S. Federal regulations or special Washington State Grade Standards promulgated by the Washington State Department of Agriculture in conjunction with USDA.

Cartons. Sizing is usually carried out by weight or fruit diameter but is independent of grade. Requirements for fruit size vary greatly by market, but in general, larger sizes bring greater returns. Most fruit are packed into bushel cartons, usually 40 lb (18.2 kg), depending on variety, and sold by count (fruit per carton). Apples are most often packed on four or five soft fiberboard trays made from recycled newspaper. In some cases, the tray is made of soft polystyrene. Cartons are often unvented. However, unvented cartons on pallet stacks will cool slowly, detrimentally affecting product longevity. Venting to improve cooling rates of fruit is becoming more common.

A two-layer carton that is wider, known as the 60×40 pack, is becoming more common in the United States and for export to Europe. It has the advantage of minimizing fruit handling as the cartons are placed directly onto display racks at retail.

Most apples are sold loose, though fruit are increasingly available in polyethylene bags of 3, 5, or 10 lb (1.4, 2.3, or 4.5 kg). These bags were originally used for marketing smaller fruit but are now used for all qualities and sizes. Bags are most often sold in warehouse-type retail stores. Consumer packages in which two to six apples, or a combination of fruits, are shrink-wrapped are becoming more popular in some retail outlets. Shrink-wrapped packages reduce the time consumers spend in the produce section and also reduce loss caused by consumer sorting and handling of individual fruit.

Cooling Conditions

The rate of cooling of apple fruit affects retention of quality, but its importance varies according to variety, harvest maturity, nutritional status of the fruit, and storage history. It is very important to rapidly cool apple varieties that mature in the early part of the harvest season (summer varieties) since they will soften more rapidly than those that mature in the later part of the harvest season.

Within a variety, apples tend to soften more rapidly at later stages of maturity than at earlier stages. Effects of slow cooling are magnified as storage length increases. Therefore, inadequate investment of resources at harvest to ensure rapid fruit cooling may not be apparent until late in the storage period when fruit may not meet minimum firmness standards for marketing. For example, a 1-day delay at 21 °C (70 °F) before cooling results in a 7- to 10-day loss of storage life for ‘McIntosh.’ The effects of delays before cooling of fruit, irrespective of timing of CA conditions, are illustrated for ‘Empire’ apples in table 1.

Table 1. Effect of cooling rate on firmness of rapid CA Empire apples

Days to cool to 0 °C	Days from harvest to 3% O_2	Flesh firmness (N) after removal from CA
1	4	63
7	4	58
14	4	52

Modified from Blanpied (1986).

Apple fruit can be cooled by room cooling, forced-air cooling, or hydrocooling. Forced-air cooling and hydrocooling systems can be used to rapidly reduce fruit temperatures, but they are not widely used for apples in the United States. Room cooling, in which normal air flow within the storage room cools the fruit, is the predominant method in most regions. However, air flows around rather than through bins of fruit, so this method is slow and inefficient. Rapid cooling is often difficult to accomplish when rooms are filled rapidly and refrigeration capacity was not designed for a large fruit load. This problem can be overcome in two ways. First, fruit can be separated and loaded into a number of rooms for precooling before being moved into long-term storage. A second option is to load only the quantity that can be handled by the existing refrigeration system.

When refrigeration capacity is a limiting factor, no more than two stacks of bins should be placed across the width of the storage room each day, and that should be reduced to one stack if the air temperature in the room is not down to 0 °C (32 °F) by the next morning (Bartsch and Blanpied 1990). Faster cooling will be obtained if bins are placed in the downstream discharge of the evaporator with pallet runners oriented in the same direction as the air flow. Additional bins of fruit should be stacked, no more than two high, in unfilled refrigeration rooms to cool overnight before loading into the CA room the next morning. These stacks should be placed randomly throughout the unfilled room to maximize air exchange with the fruit. Capacity to cool fruit depends on refrigeration capacity and room design. A qualified refrigeration engineer should assist in the development of a cooling program.

Maximizing quality maintenance of fruit requires attention to temperature not only immediately after harvest and during storage but also during packing, transport, and retail display. This combination of events is sometimes described as the “cold chain,” highlighting the importance of maintaining the links from harvest to consumer.

Excellent discussions of cooling can be found in Kader (1992), Thompson et al. (1998), and Bartsch and Blanpied (1990).

Optimum Storage Conditions

Apple producers have learned that apple fruit respond dramatically to both temperature and atmosphere modification. Rapid temperature reduction and the exacting maintenance of low temperatures close to the chilling point of the variety can provide good to medium quality product following 3 to 6 mo of storage and in some cases longer. However, modern commercial warehouses combine temperature management with CA for long-term storage of apples.

Regular Air Storage. The recommended conditions for commercial storage of apples are -1 °C to 4 °C (30 to 39 °F) and 90 to 95% RH, depending on variety. Typical storage periods for a number of varieties in air are shown in table 2. The acceptable duration of air storage has become shorter over the last several years as quality standards in the market have increased. Also, short-term CA storage is becoming more common as the period available for sale of air-stored fruit has decreased.

Table 2. Storage characteristics of several apple varieties

Variety	Potential months of storage		Superficial scald susceptibility	Comments
	0 ºC Air	CA*		
Braeburn	3-4	8-10	Slight	Sensitive to CO_2.
Cortland	2-3	4-6	Very high	Temperature sensitive; McIntosh conditions preferred; scald inhibitor essential.
Delicious	3	12	Moderate to very high	Sensitive to CO_2 >2%; scald inhibitor essential.
Empire	2-3	5-10	Slight	Avoid late harvest; temperature sensitive; scald inhibitor not required; CO_2 sensitive.
Fuji	4	12	Slight	Late harvested fruit may be CO_2 sensitive.
Gala	2-3	5-6	Slight	Loses flavor during storage.
Golden Delicious	3-4	8-10	Slight	Susceptible to skin shrivel.
Granny Smith	3-4	10-11	Very high	Sensitive to CO_2.
Idared	3-4	7-9	Slight	Temperature sensitive; tolerant to orchard freezing damage.
Jonagold	2	5-7	Moderate	Avoid late harvest; may develop scald.
Jonamac	2	3	Moderate	Loses flavor during storage.
Law Rome	3-4	7-9	Very high	Scald inhibitor essential.
Macoun	3	5-7	Slight	Can be stored with McIntosh.
McIntosh	2-3	5-7	Moderate	CO_2 sensitive; normal storage is sometimes shortened by excessive flesh softening; scald inhibitors recommended.

Table 2. Storage characteristics of several apple varieties—*Continued*

Variety	Potential months of storage		Superficial scald susceptibility	Comments
	0 ºC Air	CA*		
Mutsu	3-4	6-8	Slight	Green apples have low eating quality.
Spartan	3-4	6-8	Slight	Can be susceptible to high CO_2; susceptible to skin shrivel at 36 to 38 °F.
Stayman	2-3	5-7	High	Will tolerate CO_2 up to 5%, but usually stored in 2 to 3% CO_2; scald inhibitor essential; susceptible to skin shrivel.

* The potential months storage are for rapid CA and range from those obtained with standard CA to those obtained with low-O_2 and low-ethylene CA. Growing region affects storage periods obtained even under optimal CA conditions.

Temperatures for air-stored fruit are affected by sensitivity of the variety to low-temperature disorders. While lower temperatures usually result in firmer and greener fruit, some varieties such as 'McIntosh' can develop core browning, soft scald, and internal browning when held at temperatures below 3 °C (37 °F). However, these disorders typically develop only in fruit kept for more than several months, so risks of low-temperature injury are low for fruit kept in short-term storage (2 to 3 mo). An additional factor to consider in selecting storage temperatures is the effect of temperature on RH requirements. It is easier to maintain RH above 90% at 1 °C (34 °F) than at 0 °C (32 °F). Final decisions should be based on experience with the apple variety and advice of extension personnel.

Most apple varieties are not sensitive to chilling and should be stored as close to 0 °C (32 °F) as possible. However, varieties that are susceptible to low-temperature disorders should be stored at 2 to 3 °C (36 to 37 °F). Temperatures also should be increased for fruit stored in low-O_2 CA, since lower temperatures increase risk of low-O_2 injury.

Temperatures in storage rooms should be monitored throughout the storage period using thermocouples throughout the room (Bartsch and Blanpied 1990). It is dangerous to rely on a single thermometer at the door, as temperatures within stacks and throughout the room may be lower or higher than indicated by such readings. Faster fruit ripening and greater refrigeration usage result when fruit temperatures are too high (table 3). Excessive temperatures after packing due to lack of cooling or developing during transport to market can reduce quality at the consumer level. Fruit temperatures can increase during packing; failure to remove heat may result in subsequent loss of firmness during transport (Kupferman 1994, Watkins 1999).

Table 3. Rates of heat evolution by 10 apple varieties at different temperatures

Cultivar	**Temperature**				
	-1 °C	**0 °C**	**2.2 °C**	**3.3 °C**	**4.4 °C**
	---------------------- ***BTU ton^{-1} day^{-1}*** ----------------------				
Delicious	690	760	910	1,010	1,110
Golden Delicious	730	800	970	1,070	1,180
Jonathan	800	880	1,060	1,170	1,290
McIntosh	730	800	970	1,070	1,180
Northern Spy	820	900	1,090	1,200	1,320
Rome Beauty	530	580	700	780	850
Stayman Winesap	820	910	1,100	1,210	1,330
Winesap	530	590	710	780	860
Yellow Newton	510	570	690	760	840
York Imperial	610	670	810	900	990
Mean	680	750	900	1,000	1,100

* To convert BTU ton^{-1} day^{-1} to kJ ton^{-1} day^{-1}, multiply by 1.055.

Adapted from Tolle (1962).

Controlled Atmosphere (CA) Considerations

Apples are the predominant horticultural commodity stored under CA conditions, but the gas composition and storage temperature conditions are specific to variety, growing region, and sophistication of the equipment available for monitoring and controlling the atmospheres. Interactions occur between O_2, CO_2, and temperature. For example, low storage temperatures increase fruit susceptibility to low-O_2 injury. Also when very low O_2 levels are used, levels of CO_2 should be reduced to prevent CO_2 damage.

The wide range of recommended atmospheres has been reported by Kupferman (1997) and reflects the above factors as well as strategies employed by different industries. Information about CA recommendations for varieties in any growing region should be obtained from local extension personnel.

Until the mid 1970s, 8 to 10 days was often required to load a CA room and an additional 15 to 20 days was needed for fruit respiration to lower O_2 to 2.5 to 3%. Fruit quality resulting from these conditions gradually became unacceptable in the marketplace. Rapid CA is now standard practice in many apple industries. Nitrogen flushing equipment enables O_2 in CA rooms to be reduced to less than 5% within a day or two of harvest, though 4 to 7 days from the harvest of the first fruit and placing into the storage room with CA conditions is considered “rapid CA.” For certain varieties, fruit core temperatures must be reduced to predetermined thresholds *before* application of CA. Even when rooms are filled over extended periods, O_2 concentrations are usually lowered by flushing with N_2, and it is becoming more common to use N_2 flushing for resealing rooms that are opened briefly to remove some of the fruit required for marketing. Nitrogen used for flushing is either purchased in tanks or generated on site.

An RH of 90 to 95% is recommended for apples to prevent shrivel. The major causes of dehydration are small coil surface areas and frequent defrosting. When CA rooms are designed, the refrigeration engineer should demand the largest coil size feasible for the room. Operators have been reducing the number of defrost cycles to an absolute minimum to optimize RH in the room. Some operators reduce the O_2 to the minimum safe level and then raise the temperature to 1 to 2 °C (34 to 36 °F) to minimize the need to defrost. Some storage rooms are outfitted with high-pressure water vapor systems that add moisture to the room and are suited for operation at around 0 °C (32 °F). The air distribution system should be designed to prevent condensation of water droplets on fruit to prevent decay. The use of plastic, rather than wooden bins or poly tubes (bin liners), inside wooden bins has also helped minimize shrivel of ‘Golden Delicious.’

Once fruit have been cooled and CA conditions established, CA storage regimes fall into one of three categories, depending on level of equipment and technology involved.

Standard CA involves conservative atmosphere conditions used with minimum risk of gas-related injuries (table 4). Control of these atmospheres may be manual by daily reading and adjustment or via computer-controlled equipment. The margin of safety is large enough so that fluctuations in gas concentrations in manually adjusted storages should not cause fruit injury.

Table 4. Atmospheric and temperature requirements for standard CA storage of apples

Variety	CO_2	O_2	Temperature	Low-O_2*
	%	*%*	*°C*	
Braeburn	0.5	1.5-2	1	yes
Cortland	2-3 2-3 for 1 mo then 5	2-3 2-3	0 2	no
Delicious	2	0.7-2	0	yes
Empire	2-3†	2	2	yes
Fuji	0.5†	1.5-2	0-1	yes
Gala	2-3	1-2	0-1	yes
Golden Delicious	2-3	1-2	0-1	yes
Granny Smith	0.5	1.5-2	1	yes
Idared	2-3	2	1	yes
Jonagold	2-3	2-3	0	yes
Jonamac	2-3 2-3 for 1 mo then 5	2-3 2-3	0 2	no
Law Rome	2-3	2	0	yes
Macoun	5	2-3	2	no
Marshall McIntosh	2-3 for 1 mo then 5 2-3 for 1 mo then 5 2-3 for 1 mo then 5	4-4.5 3 2	2 2 3	no no

Table 4. Atmospheric and temperature requirements for standard CA storage of apples—*Continued*

Variety	CO_2	O_2	Temperature	Low-O_2*
	%	*%*	*°C*	
Mutsu	2-3	2	0	yes
Spartan	2-3	2-3	0	yes
Stayman	2-5	2-3	0	yes

Modified from Kupferman (1997).
* Storage potential at 1.5 to 1.8% O_2 (Eastern USA)
[†] CO_2 sensitive: keep CO_2 well below the O_2 level. If not treated with DPA, use 1.5% to 2% CO_2 during the first 30 days.

Low-O_2 CA storage requires that fruit be kept at O_2 below 2%, but above the concentration at which fermentation will occur. Nondescriptive terms such as "ultralow" are sometimes used but should be avoided in favor of describing specific O_2 percentages. The safe O_2 concentration varies by variety (table 4) and region. 'Delicious' apples from British Columbia, Canada, for example, can be stored safely at 0.7% (Lau 1997) allowing control of superficial scald without use of diphenylamine (DPA). Fruit of the same cultivar from other growing regions may show injury when stored at these low O_2 levels (Lau et al. 1998). Strains within a variety can also vary in sensitivity (Lau 1997). An extreme case is the Marshall strain of 'McIntosh,' where O_2 below 4 to 4.5% is not safe, whereas 2 to 3% O_2 is acceptable for other 'McIntosh' strains (Park et al. 1993). In general, it is necessary to increase storage temperature when low-O_2 CA storage is used. A number of guidelines have been developed for safe operation of long-term CA storage. Using the following techniques, it has also been possible to minimize risk of low-O_2 injury in the Northeastern United States:

1. Apply low-O_2 CA storage only to apples harvested early in their harvest window. Overmature fruit can be damaged by low-O_2 storage.
2. Avoid apples from orchard blocks that average fewer than five seeds per apple. Low seed count can be a problem with some varieties.
3. Reduce core temperatures to 1 to 2 °C within 2 days after harvest for 'McIntosh' and 'Empire.' (In Washington, cooling can take longer as it is done under CA, with the exceptions of 'Fuji' and 'Braeburn').
4. Decrease O_2 to under 5% within 7 days after harvest, except for 'Fuji' and 'Braeburn.'
5. Raise storage temperatures from 0 to 2 °C to reduce risk.
6. Obtain automatic gas analysis/control equipment to eliminate O_2 fluctuations that may lead to low-O_2 injury.
7. Avoid use of postharvest drench with DPA where possible; its application has been associated with low-O_2 injury, for example, for varieties with low-O_2 scald risk.

Low-ethylene CA storage is appropriate because apple fruit are climacteric, with autocatalytic ethylene production often beginning close to harvest. However, rates of ethylene production can vary greatly among apple varieties. An important physiological effect of CA storage is inhibition of either ethylene production or its action, due to lowered O_2 or increased CO_2.

Low-ethylene CA storage has been evaluated as a method for reducing superficial scald, as a safe substitute for low-O_2 CA storage, and for retarding flesh softening and other forms of senescence (Blanpied 1990). Low-ethylene CA storage (below 1 µL L^{-1}) was used successfully in New York for storage of the naturally low-ethylene-producing ‘Empire’ apple, but it has been replaced by low-O_2 storage. In general, low-ethylene CA storage has not proven successful for maintenance of fruit quality if levels of ethylene gas within the fruit cannot be controlled, and generally the return on investment in this technology has been poor.

Other methods used in conjunction with CA storage to maintain quality of apple fruit include treatments using short-term stress levels of low O_2 or high CO_2. In varieties including ‘Granny Smith,’ ‘Delicious,’ and ‘Law Rome,’ O_2 of 0.25 to 0.5% for up to 2 weeks has resulted in control of superficial scald (Little et al. 1982, Wang and Dilley 2000). High-CO_2 (15 to 20%) treatments before application of CA storage were used for maintenance of firmness of ‘Golden Delicious’ apples in northwestern North America but generally are no longer recommended because of fruit damage (Blanpied 1990).

Under commercial conditions, fruit from CA rooms should be sampled at monthly intervals to detect development of any storage problems and therefore reduce the chances of major fruit losses. Sampling should be carried out by placing representative samples of fruit near a sampling port in the door of the CA room. Samples should be kept in mesh bags rather than plastic bags to prevent false positive readings for scald.

CA and Apple Varieties

The selection of CA atmospheres and temperature must take into consideration the variety and, in some cases as mentioned above, the strain of a particular variety, in addition to where it was grown. Experience in Washington has shown that varieties can be divided into two types: those tolerant of high CO_2 and those that are not.

‘Gala’ and ‘Golden Delicious’ are CO_2-tolerant varieties that also benefit from rapid reduction of atmosphere. In Washington, fruit with moderate pulp temperatures can be placed into a low-O_2 environment without danger of CO_2 damage. Rapid CA is valuable because it helps retain fruit firmness and acidity better than slowly established CA on these varieties. Washington-grown ‘Gala’ and ‘Golden Delicious’ can be stored as low as 1.0% O_2 with CO_2 levels up to 2.5% at 1 °C (34 °F). If the temperature is lowered below this point, O_2 is raised. Regular storage is 0 °C (32 °F).

‘Fuji,’ ‘Braeburn,’ and ‘Granny Smith’ are in the CO_2-intolerant category. Their cells are densely packed, and air exchange within the fruit is therefore reduced. In Washington, these apples must have the flesh temperature close to the storage temperature *before* the O_2 is reduced. These varieties have a tendency to develop internal browning, a CO_2 damage symptom that is associated with a natural predisposition of the variety (and preharvest factors as well as storage regime). CO_2 should remain well below the O_2 level at all times, and temperatures should be slightly elevated. For example, fruit stored at 1.5% O_2 are stored with CO_2 below 0.5% at 1 °C (34 °F) if fruit are appropriately mature at harvest. It is not advisable to store waxed fruit in boxes with polyliners in CA, as this can hinder air exchange within fruit.

‘Red Delicious’ is somewhat CO_2-tolerant and is also tolerant of rapid CA. However, producers have not seen the dramatic positive effects of rapid CA on ‘Delicious’ that have been noted on ‘Golden Delicious’ or ‘Gala.’ ‘Delicious’ fruit soften more rapidly in a bin than on the tree, so CA should not be delayed after harvest. Typical regimes for CA of nonwatercored ‘Delicious’ are 1.5% O_2 and up to 2.0% CO_2 at 0 to 1 °C (32 to 34 °F).

State regulations on CA storage cover both the safe operation and the use of the legal definition of “controlled atmosphere” for stored apples. Regulations include the rate of establishment of CA conditions, the maximum level of O_2

permitted, and the length of time fruit are in CA. Since regulations vary from State to State, operators need to contact their State Department of Agriculture.

Many precautions must be taken to assure the safe operation of CA storage rooms. Operators must be aware of the risks of working with O_2 levels below those needed for survival. Additional precautions must be taken when working with CA generators to avoid implosion or explosion hazards. In short, workers must be thoroughly trained. Contact your local extension office for information about safety in CA.

1-Methylcyclopropene (1-MCP)

Softening, yellowing, respiration, loss of titratable acidity, and sometimes a reduction in SSC, as well as development of several physiological disorders, are delayed or inhibited by 1-MCP application (Watkins 2002, Watkins and Miller 2004). Responses of fruit to 1-MCP may be affected by cultivar and fruit maturity. Volatile production by apples also is inhibited by 1-MCP, being consistent with the view that volatile production is regulated by ethylene. Consumer studies on acceptability of 1-MCP treated fruit are required to ensure flavor is not unacceptably compromised.

Retail Outlet Display Considerations

Keeping apple fruit cold reduces metabolic rates and maintains fruit quality, but the trend in most new retail outlets is not to have refrigeration in display tables. Moreover, typical displays in U.S. supermarkets employ stacking of loose fruit with increased risk of bruising. There is some movement towards use of display cartons such as the 60×40 box, which reduces the need to handle fruit and ensures more rapid turnover of product.

Physiological Disorders

A wide variety of physiological disorders are found in apple fruit, but susceptibility varies by variety, preharvest factors, and postharvest conditions (Lidster et al. 1990, Smock 1977). Disorders can be considered in three categories:

Disorders That Develop Only on the Tree. The most important of these is watercore, in which intercellular air spaces in the core and cortical tissues become filled with liquid, predominantly sorbitol (Marlow and Loescher 1984). Usually the occurrence of watercore is associated with advancing fruit maturity and low night temperatures prior to harvest, but a variant of the disorder can occur as a result of heat stress. Presence of watercore in fruit at harvest creates problems in certain varieties such as ‘Delicious’ because fruit with moderate or severe watercore can develop breakdown during storage. By comparison, grade standards for ‘Fuji’ were modified so that watercore in ‘Fuji’ apples is not a grade defect in the United States or Canada, because watercore is a desirable feature for this cultivar due to the sweetness it imparts to the fruit. Mild or moderate watercore should not be a problem in storage of ‘Fuji’ if fruit are cooled prior to reduction of O_2. Severely watercored fruit should not be placed in CA since breakdown will develop over time.

Disorders That Develop on the Tree and During Storage. Bitter pit is a disorder characterized by development of discrete pitting of the cortical flesh, the pits being brown and becoming desiccated with time (Ferguson and Watkins 1989). The pits may occur predominantly near the surface or deep in the cortical tissue. An associated disorder, known as lenticel blotch, is also observed in some varieties. The incidence and severity of bitter pit are affected by variety, but within a variety, bitter pit is related to harvest date and climate. In susceptible varieties, harvest of less mature fruit can result in higher bitter pit incidence, as can excessive pruning or high temperatures and/or droughty conditions during the growing season. Effects of climatic conditions are at least partly related to low calcium concentrations in the fruit. Development of bitter pit during storage results in financial loss, and a number of strategies have been employed to prevent its occurrence (Ferguson and Watkins 1989). These include prediction of risk based on mineral (mainly low calcium) content at harvest or infusion of magnesium. Rapid cooling, CA storage, and application of postharvest calcium drenches may be able to reduce its occurrence. Recommended rates for application of calcium vary by variety and region; product labels should be followed in conjunction with advice of the local extension specialist. Preharvest applications of calcium may be far more effective than postharvest drenching as a means of increasing the concentration of fruit calcium and reducing bitter pit.

Disorders That Develop During Storage. These can be divided into senescent breakdown disorders, chilling disorders, and disorders associated with inappropriate atmospheres during storage. Senescent breakdown incidence is related to harvest of overmature fruit or fruit with low calcium content. It can be exacerbated by storing fruit at higher than optimal temperatures. Fruit of susceptible varieties are commonly drenched with calcium before storage, but incidence of senescent breakdown can also be reduced by harvesting fruit at a less mature stage, rapid cooling, and reducing storage duration. The most common disorders associated with temperature and atmospheres are superficial scald, soft scald, low-temperature breakdown, brown core, internal browning, low-O_2 injury, and high-CO_2 injury.

Specific Disorders

Superficial scald (storage scald) is a physiological disorder associated with long-term storage (Ingle and D'Souza 1989). It was the major cause of apple fruit loss until the advent of postharvest DPA treatments. Variety, climate, and harvest date affect susceptibility of fruit to the disorder, and decisions about treatment with DPA should be made after consultation with a local extension specialist. DPA is usually applied with a fungicide to reduce decay incidence, and calcium salts may also be included at the same time to reduce bitter pit or senescent breakdown. Application of label rates of clean DPA should prevent DPA-induced fruit damage and exceed residue tolerances. The risk of DPA damage to fruit increases if DPA is not discarded when soil accumulates in the solution. Both DPA use and DPA residues on fruit are prohibited in some countries. Another antioxidant, ethoxyquin, is no longer permitted for use on apples. Low levels of O_2 in CA storage reduce the risk of scald developing and also may permit use of lower DPA concentrations. Alternative ways of controlling superficial scald are being investigated, and storage operators are reducing use of DPA where possible. Low-O_2 and low-ethylene CA storage also reduce scald incidence. In British Columbia, Canada, 0.7% O_2 storage is used as a substitute for DPA treatment (Lau 1997). This technique cannot be used universally because fruit grown in other regions may be susceptible to low-O_2 injury or the risk of scald may be greater due to climate or variety.

Soft scald is characterized by irregular but sharply defined areas of soft, light-brown tissue that may extend into the cortex. Susceptibility of fruit to soft scald is variety- and climate-related, but effects of harvest maturity are inconclusive. Overmaturity is almost always a contributing factor in 'Golden Delicious.' Storing fruit at 3 °C rather than at lower temperatures can sometimes control the disorder, and DPA used for control of superficial scald may also reduce incidence of soft scald. Storage at a lower temperature following prompt cooling can reduce the incidence of soft scald on 'Golden Delicious.'

Chilling-related disorders include low-temperature breakdown, brown core, and internal browning. These disorders are affected by variety sensitivity to low temperatures and generally increase in incidence and severity as the length of storage is increased. Climate affects sensitivity of fruit to the disorders, with more problems occurring after colder, wetter growing seasons. Low-temperature breakdown is characterized by markedly brown vascular bundles, browning of flesh, and a clear halo of unaffected tissue underneath the skin. In contrast to senescent breakdown, the affected tissues are more likely to be firmer, moister, and darker in color. Brown core (coreflush) involves browning of the flesh, initially in the core area and later in the cortex, where it becomes difficult to distinguish from low-temperature breakdown. Internal browning does not involve breakdown of the flesh, but rather a graying of flesh that becomes apparent when apples are cut. Internal browning and coreflush are often associated with higher CO_2, since both can occur in CA when CO_2 is higher than O_2.

Low-O_2 injury affects fruit in a number of ways. The first indication of injury is loss of flavor, followed by fermentation-related odors. These odors may disappear if storage problems are identified soon enough and severe injury has not occurred. Injury symptoms range from purpling or browning of the skin in a red-colored variety, to development of brown soft patches resembling soft scald, to abnormal softening and splitting of fruit. As discussed earlier, varieties vary greatly in response to low O_2, and susceptibility to injury is influenced by a number of preharvest and postharvest factors.

CO_2 injury may be external or internal. The external form consists of wrinkled, depressed, colorless or colored areas restricted to the skin surface and usually on the greener side of the fruit. Internal forms are expressed as brown heart and/or cavities in the flesh. DPA can reduce incidence of both external and internal CO_2 injuries.

Postharvest Pathology

The main postharvest diseases of apples that develop in storage are blue mold caused by *Penicillium* species and gray mold caused by *Botrytis cinerea*. Blue mold is the most common and destructive of all the rots. Most blue mold decays are caused by *P. expansum*, but *P. solitum*, *P. commune*, and *P. crustosum* are also common postharvest pathogens of apples (Sanderson and Spotts 1995). *Penicillium* species enter fruit primarily through cuts, stem punctures, and bruises (Wright and Smith 1954). However, some cultivars of apples can also be invaded via the stem during long-term CA storage (Rosenberger 1999).

Numerous other pathogens can also appear in stored apples (Pierson et al. 1971, Snowdon 1990). Some postharvest pathogens infect fruit in the field but remain latent or quiescent until after apples are harvested and placed into storage. These include the *Colletotrichum* species that cause bitter rot; *Botryosphaeria* species that cause black rot and white rot; and *Pezicula malicortis*, the cause of bull's eye rot (Rosenberger 1990). Postharvest decays initiated in the field must be controlled using fungicides or other disease management strategies during the growing season.

Blue mold and gray mold have been controlled since the early 1970s by using postharvest applications of benzimidazole fungicides. Thiabendazole (TBZ), benomyl, and thiophanate-methyl were all registered for postharvest use on apples until the postharvest labels for benomyl and thiophanate-methyl were withdrawn in the early 1990s. TBZ is usually applied immediately after harvest in combination with the antioxidant DPA (Hardenburg and Spalding 1972). TBZ may be applied a second time as a line spray or in wax as apples are packed.

Benzimidazole-resistant strains of *P. expansum* and *B. cinerea* were discovered in apple storage during the mid to late 1970s. However, postharvest application of a benzimidazole plus DPA continued to control blue mold and gray mold because most benzimidazole-resistant strains of the pathogen were highly sensitive to DPA (Rosenberger and Meyer 1985, Sharom and Edgington 1985). During the mid 1990s, the incidence of blue mold began to increase in some apple packinghouses where the predominant strains of *P. expansum* had developed resistance to the benzimidazole-DPA combination. Gray mold is still controlled by the benzimidazole-DPA combination, presumably because it does not recycle on field bins as readily as does *P. expansum*, and it therefore has been subjected to less selection pressure for fungicide resistance.

Captan has a postharvest registration but has proven only moderately effective for controlling *P. expansum* and *B. cinerea*. Captan residues are not acceptable in some export markets. The fungicide fludioxonil is very effective for controlling *P. expansum* on apples (Rosenberger et al. 2000). Fludioxonil is not yet approved for use on apples in the United States, but it may receive an EPA registration in the near future.

Much effort has been devoted to development of biocontrols for postharvest diseases of apples (Roberts 1990, Mercier and Wilson 1994, Wisniewski et al. 1995, Filonow et al. 1996, Chand-Goyal and Spotts 1997, Janisiewicz 1998). The controlled postharvest environment theoretically should allow selection of biocontrol agents particularly suited to those environments. Many of the biocontrol agents selected and developed to date have proven very effective in controlled tests, but commercialization of biocontrols has been slow. Product developers view the market potential for postharvest treatments as relatively limited because the products are applied in a closed environment rather than being sprayed over thousands of acres, as are conventional fungicides used to protect crops in the field. Furthermore, liabilities involved in postharvest treatment of apples are considerable, both because of the value of the stored crop and because apples as a commodity have previously been spotlighted in debates relating to food safety issues. In addition, devising shelf-stable formulations of biocontrol agents has been difficult. Some currently registered products must be kept frozen until used. Activity of biocontrol organisms may be compromised by excessively high pathogen inoculum or by presence of other compounds in postharvest treatment mixtures.

Biocontrols generally cannot provide eradicant activity against established infections. Thus, infections by *P. expansum* that occur during harvest can be controlled with TBZ fungicide that is applied several hours later, whereas most biocontrol agents are ineffective if the pathogen is already established in the infection court when the biocontrol is applied. Using combinations of biocontrols and reduced rates of TBZ may be more effective than using either product alone (Chand-Goyal and Spotts 1997). When such combinations are used, the chemical fungicide may provide eradicant and short-term protectant activity necessary to prevent decay until the biocontrol agents become established in wounds or other infection courts. Biocontrols provide some protection against TBZ-resistant strains of the pathogens for which no other controls are currently available.

Regardless of the postharvest fungicide or biocontrol strategies that may evolve from current research, good sanitation will remain essential for reducing disease incidence. Inoculum for blue mold recycles from year to year on contaminated field bins and in packinghouses and cold storage rooms (Rosenberger 2001). Recycling of *P. expansum* on field bins results in repeated exposure of the same pathogen strains to postharvest fungicide treatments, thereby contributing to more rapid selection of fungicide-resistant strains. Badly contaminated bins should be cleaned and disinfested (steam-cleaned) before they are reused for a new crop. Plastic bins may carry less inoculum than wooden bins. Plastic bins also have the advantage of reducing bruising and abrasion where apples contact the sides of bins. Careful fruit handling, rapid cooling after harvest, and storage at recommended temperatures also help limit postharvest decays.

Quarantine Issues

These vary widely according to marketplace and country and guidance should be sought from the local Department of Agriculture.

Suitability as Fresh-Cut Product

As with other fruit, methods to reduce senescence and browning processes in cut apples are important, and commercial products are available (Lee and Smith 1995). However, potential for improvement is large.

Additional Information

Many States have workshops and materials available. Washington, Michigan, and New York offer regular CA workshops, and proceedings are available from Michigan State University and Cornell University. Contact your local extension office or horticulture society to obtain information for your State.

References

Anonymous. 1986. Apple Maturity Program Handbook, 57 pp., Apple Maturity Program, Wenatchee, WA.

Bartsch, J.A., and G.D. Blanpied. 1990. Refrigeration and Controlled Atmosphere Storage for Horticultural Crops. Northeast Regional Agricultural Engineering Service Bull. no. 22, 45 pp., (NRAES) PALS Publishing, Ithaca, NY.

Beaudry, R., P. Schwallier, and M. Lennington. 1993. Apple maturity prediction: an extension tool to aid fruit storage decisions. HortTechnology 3:233-239.

Blanpied, G.D. 1986. Empire harvest dates and storage strategies to meet the market demand for fruit quality and condition. Proc. NY State Hort. Soc. 131:150-166.

Blanpied, G.D. 1990. Controlled atmosphere storage of apples and pears. *In* M. Calderon and R. Barkai-Golan, eds., Food Preservation by Modified Atmospheres, pp. 265-299. CRC Press, Boca Raton, FL.

Blanpied, G.D., and K.J. Silsby. 1992. Predicting harvest date windows for apples. Cooperative Extension Information Bulletin 221, Cornell University, Ithaca, NY.

Chand-Goyal, T., and R.A. Spotts. 1997. Biological control of postharvest diseases of apple and pear under semi-commercial and commercial conditions using three saprophytic yeasts. Biol. Control 10:199-206.

Childers, N.F., J.R. Morris, and G.S. Sibbett. 1995. Modern Fruit Science - Orchard and Small Fruit Culture, pp. 145-170. Horticulture Publications, Gainesville, FL.

Ferguson, I.B., and C.B. Watkins. 1989. Bitter pit in apple fruit. Hort. Rev. 11:289-355.

Filonow, A.B., H.S. Vishniac, J.A. Anderson, and W.J. Janisiewicz. 1996. Biological control of *Botrytis cinerea* in apple by yeasts from various habitats and their putative mechanisms of antagonism. Biol. Contr. 7:212-220.

Hardenburg, R.E., and D.H. Spalding. 1972. Postharvest benomyl and thiabendazole treatments, alone and with scald inhibitors, to control blue and gray mold in wounded apples. J. Amer. Soc. Hort. Sci. 97:154-158.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66. U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Ingle, M., and M.C. d'Souza. 1989. Physiology and control of superficial scald of apples. A review. HortScience 24:28-31.

Janisiewicz, W.J. 1998. Biocontrol of postharvest diseases of temperate fruits: challenges and opportunities. *In* J. Boland and L. Kuykendall, eds., Plant-Microbe Interactions and Biological Control, pp. 171-198. Marcel Dekker, New York, NY.

Kader, A.A. Postharvest Technology of Horticultural Crops, DANR Pub. no. 3311, University of California, Davis, CA.

Kupferman, E. 1994. Report to the industry on fruit quality and packing practices for Washington grown apples. Tree Fruit Postharv. J. 5:3-26.

Kupferman, E. 1997. Controlled atmosphere storage of apples. *In* A.A. Kader, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 2, pp. 1-31. University of California, Davis, CA.

Lau, O.L. 1985. Harvest guide for B.C. apples. British Columbia Orchardist 7:1A-20A.

Lau, O.L. 1997. The effectiveness of 0.7% O_2 to attenuate scald symptoms in 'Delicious' apples is influenced by harvest maturity and cultivar strain. J. Amer. Soc. Hort. Sci. 122:691-697.

Lau, O.L., C.L. Barden, S.M. Blankenship, et al. 1998. A North American cooperative survey of 'Starkrimson Delicious' apple responses to 0.7% O_2 storage on superficial scald and other disorders. Postharvest Biol. Technol. 13:19-26.

Lee, C.Y., and N.L. Smith. 1995. Minimal processing of New York apples. New York's Food and Life Sciences Bull. 145, Cornell University, Ithaca, NY.

Lidster, P.D., G.D. Blanpied, and R.K. Prange. 1990. Controlled-atmosphere disorders of commercial fruits and vegetables. Publication 1847E, Agriculture Canada, Ottawa, Canada.

Little, C.R., J.D. Faragher, and H.S. Taylor. 1982. Effects of initial low-O_2 stress treatments in low oxygen modified atmosphere storage of 'Granny Smith' apples. J. Amer. Soc. Hort. Sci. 107:320-323.

Marlow, G.C., and W.H. Loescher. 1984. Watercore. Hort. Rev. 6:189-251.

Mercier, J., and C.L. Wilson. 1994. Colonization of apple wounds by naturally occurring microflora and introduced *Candida oleophila* and their effect on infection by *Botrytis cinerea* during storage. Biol. Contr. 4:138-144.

Park Y.M., G.D. Blanpied, Z. Jozwiak, and F.W. Liu. 1993. Postharvest studies of resistance to gas diffusion in McIntosh apples. Postharv. Biol. Technol. 2:329-339.

Pierson, C.F., M.J. Ceponis, and L.P. McColloch. 1971. Market Diseases of Apples, Pears and Quinces. Agriculture Handbook 376, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Roberts, R.G. 1990. Postharvest biological control of gray mold of apple by *Cryptococcus laurentii*. Phytopathology 80:526-530.

Rosenberger, D.A. 1990. Postharvest diseases. *In* A.L. Jones and H.S. Aldwinckle, eds., Compendium of Apple and Pear Diseases, pp. 53-54. APS Press, St. Paul, MN.

Rosenberger, D.A. 1999. Postharvest decays: research results and future directions. *In* CA Storage: Meeting the Market Requirements, pp. 49-62. NRAES Bull. 136, Northeast Regional Agricultural Engineering Service, Ithaca, NY.

Rosenberger, D.A. 2001. Postharvest decay control without fungicides. *In* Storage Workshop 2001: Apple Handling and Storage, pp. 21-23. NRAES Bull. 153, Northeast Regional Agricultural Engineering Service, Ithaca, NY.

Rosenberger, D.A., and F.W. Meyer. 1985. Negatively correlated cross-resistance to diphenylamine in benomyl-resistant *Penicillium expansum*. Phytopathology 75:74-79.

Rosenberger, D.A., C.A. Ahlers, and F.W. Meyer. 2000. Evaluation of Scholar for controlling blue mold of apples during storage, 1998-99. Fung. Nemat. Tests 55:24.

Sanderson, P.G., and R.A. Spotts. 1995. Postharvest decay of winter pear and apple fruit caused by species of *Penicillium*. Phytopathology 85:103-110.

Sharom, M.S., and L.V. Edgington. 1985. Temperature dependent negatively correlated cross-resistance between benomyl and diphenylamine for *Botrytis cinerea*, *Gerlachia nivalis*, and *Monilinia fructicola*. Can. J. Plant Path. 7:389-394.

Smock, R.M. 1977. Nomenclature for internal disorders of apples. HortScience 12:306-308.

Snowdon, A.L. 1990. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 1, General Introduction and Fruits. CRC Press, Boca Raton, FL.

Thompson, J.F., F.G. Mitchell, T.R. Rumsey, R.F. Kasmire, and C.C. Crisosto. 1998. Commercial cooling of fruits, vegetables, and flowers. DANR Pub. no. 21567, University of California, Davis, CA.

Tolle, W.E. 1962. Film Permeability Requirements for Storage of Apples. Technical Bull. 1257, U.S. Department of Agriculture, Washington, DC.

Wang, Z., and D.R. Dilley. 2000. Initial low oxygen stress controls superficial scald of apples. Postharv. Biol. Technol. 18:201-213.

Watkins, C.B. 1999. Maintaining firmness of apples: effects of packing, cooling, and transport. *In* CA Storage: Meeting the Market Requirements, pp. 65-71. NRAES Bull. 136, Northeast Regional Agricultural Engineering Service, Ithaca, NY.

Watkins, C.B. 2002. Ethylene synthesis, mode of action, consequences and control. *In* M. Knee, ed., Fruit Quality and Its Biological Basis, pp. 180-224. Sheffield Academic Press, Sheffield, U.K.

Watkins, C.B. 2003. Principles and practices of postharvest handling and stress. *In* D. Feree and I.J. Warrington, eds., Apples: Crop Physiology, Production and Uses, pp. 585-614. CAB Intl., Wallingford, U.K.

Watkins, C.B., and W.B. Miller. 2004. A summary of physiological processes or disorders in fruits, vegetables and ornamental products that are delayed or decreased, increased, or unaffected by application of 1-methylcyclopropane (1-MCP). *At* http://hort.cals.cornell.edu.

Wisniewski, M.W., S. Droby, E. Chalutz, and Y. Eilam. 1995. Effect of Ca^2+ and Mg^2+ on *Botrytis cinerea* and *Penicillium expansum* in vitro and on the biocontrol activity of *Candida oleophila*. Plant Pathol. 44:1016-1024.

Wright, T.R., and E. Smith. 1954. Relation of bruising and other factors to blue mold decay of Delicious apples. USDA Circular 935, U.S. Department of Agriculture, Washington, DC.

Apricot

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Scientific Name and Introduction

The apricot is native to central and western China. Apricots were brought to Italy about 100 BC, to England in the 13th century, and to North America by 1720. Most of the apricots in the United States are grown in California, with much smaller amounts grown in Washington and Utah.

Quality Characteristics and Criteria

Fruit size, shape, freedom from defects (including gel breakdown and pit burn), and freedom from decay are all important quality criteria. High consumer acceptance is attained for fruit with high (>10%) SSC and moderate TA (0.7 to 1.0%). Apricots with 2 to 3 lb-force (8.9 to 13.3 N) flesh firmness are ready to eat. Most cultivars soften very fast, making them susceptible to bruising and subsequent decay.

Horticultural Maturity Indices

In California, harvest date is determined by changes in skin ground color from green to yellow. The exact yellowish-green color depends on cultivar and shipping distance. Apricots should be picked when still firm because of their high bruising susceptibility when fully ripe and soft.

Grades, Sizes, and Packaging

Apricots are always harvested by hand, usually into picking bags or plastic totes. Apricots are generally handled in half bins or totes and hand-packed. In some cases, apricots are dry-dumped onto a padded packing line belt. Apricots are tray-packed in single and double layers or volume-filled (about 10 kg net). Apricots should be uniform in size, and not more than 5% in each container may vary more than 6 mm when measured at the widest part of the cross section.

Optimum Storage Conditions

Apricots are seldom stored in large quantities, though they keep for 1 to 2 weeks (or even 3 to 4 weeks, depending on the cultivar) at -0.5 to 0 ºC with RH of 90 to 95%. Susceptibility to freezing injury depends on SSC, which varies from 10 to 14%. The highest freezing point is -1.0 ºC.

Controlled Atmosphere (CA) Considerations

The major benefits of CA during storage and shipment are retaining fruit firmness and ground color. CA conditions of 2 to 3% O_2 + 2 to 3% CO_2 are suggested for moderate commercial benefits; the extent of benefits depends on cultivar. Exposure to less than 1% O_2 may result in development of off flavors, and higher than 5% CO_2 for more than 2 weeks can cause flesh browning and loss of flavor. The addition of 5 to 10% CO_2 as a fungistat during transport (less than 2 weeks) may improve the potential for benefit from CA. Prestorage treatment with 20% CO_2 for 2 days may reduce incidence of decay during subsequent transport and storage in CA or air.

Retail Outlet Display Considerations

Cold-table display is recommended because of apricots' fast ripening. Ripening before consumption should ideally be done at temperatures of 18 to 24 ºC.

Chilling Sensitivity

Chilling-sensitive cultivars develop and express chilling injury symptoms (gel breakdown, flesh browning, and loss of flavor) more rapidly at 5 °C than at 0 °C. Storage at 0 °C is necessary to minimize incidence and severity of chilling injury on susceptible cultivars.

Rates of Ethylene Production and Sensitivity

Ethylene production rate increases with ripening and storage temperature from under 0.1 μL kg^{-1} h^{-1} at 0 °C (32 °F) to 4 to 6 μL kg^{-1} h^{-1} at 20 °C (68 °F) for firm-ripe apricots and higher for soft-ripe apricots. Exposure to ethylene hastens ripening (as indicated by softening and color changes from green to yellow). Also, ethylene may encourage growth of decay-causing fungi.

Respiration Rate

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	4 to 8
10 °C	12 to 20
20 °C	30 to 50

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Gel Breakdown or Chilling Injury. Develops in cold storage, particularly at 2 to 7 °C (35 to 45 °F) when apricots are stored for a long time period. This physiological problem is characterized in early stages by the formation of water-soaked areas that subsequently turn brown. Breakdown of tissue is sometimes accompanied by sponginess and gel formation. Fruit stored at these temperatures have short market-life and lose flavor.

Pit Burn. Flesh tissue around the stone softens and turns brown when the apricots are exposed to temperatures above 38 °C (100 °F) before harvest. This heat injury increases with higher temperatures and longer durations of exposure.

Postharvest Pathology

Brown rot is caused by *Monilia fructicola* and is the most important postharvest disease of apricot. Infection begins during flowering. Fruit rots may occur before harvest, but often occur postharvest. Orchard sanitation to minimize infection sources, preharvest fungicide application, and prompt cooling after harvest are control strategies.

Rhizopus rot, caused by *Rhizopus stolonifer,* occurs frequently in ripe or near-ripe fruit held at 20 to 25 °C (68 to 77 °F). Cooling fruit and holding below 5 °C (41 °F) are very effective for controlling this fungus.

Quarantine Issues

Apricots are currently exported from California to Canada and Mexico and imported from Chile and New Zealand. California apricot shipments to Canada, except British Columbia, are not restricted. For export to British Columbia and Mexico, apricots must be free of oriental fruit moth *(Grapholita molesta/Cydia molesta)*. Apricot shipments require a phytosanitary certificate (PC) and a clear statement that the fruit were produced and inspected in accordance with the system approach guidelines agreed to by APHIS and the Canadian Food Inspection Agency.

For export to Mexico, a PC stating that the fruit are free of western fruit tree leaf roller *(Archips argyrospilus),* navel orangeworm *(Amyelois transitella),* oblique banded leaf roller *(Choristaneura rosaseana),* orange tortrix *(Argyrotaenia citrana),* carob moth *(Spectrobates ceratoniae),* omnivorous leaf roller *(Platynota stultana),* and peach twig borer *(Anarsia lineatella)* is needed. Additionally, a clear statement is required that the fruit were produced and inspected in accordance with the Mexico work plan. A copy of the work plan for the exportation of apricot fruit from the United States to Mexico can be obtained from the PPQ regional office in Sacramento, CA. The work plan is only valid for the current season.

Methyl bromide fumigation is required on apricots imported from Chile, but not from New Zealand. In some cases, apricots may be precleared. To do this, the shipments must be accompanied by a PPQ Form 203 signed by the APHIS inspector on site in Chile.

Suitability as Fresh-Cut Product

Fresh-cut apricot wedges should be kept at 0 °C (32 °F) and 90 to 95% RH to maintain quality for 2 to 5 days, depending on cultivar and ripeness.

Special Considerations

The greatest hazard in handling or shipping apricots is decay, mainly brown rot and rhizopus rot. Quick cooling of apricots to temperatures of 4 °C (39 °F) or lower and holding them as near to 0 °C (32 °F) as possible will retard ripening, softening, and decay.

Acknowledgments

Most of this information was extracted from the University of California, Davis, website on "Fresh Produce Facts" at http://postharvest.ucdavis.edu/produce_information.

References

Andrich, G., and R. Fiorentini. 1986. Effects of controlled atmosphere on the storage of new apricot cultivars. J. Sci. Food Agr. 37:1203-1208.

Brecht, J., A. Kader, C. Heintz, and R. Norona. 1982. Controlled atmosphere and ethylene effects on quality of California canning apricots and clingstone peaches. J. Food Sci. 47:432-436.

Chambroy, V., et al. 1991. Effects of different CO_2 treatments on postharvest changes of apricot fruit. Acta Hort. 293:675-684.

Claypool, L.L., and R.M. Pangborn. 1972. Influence of controlled atmosphere storage on quality of canned apricots. J. Amer. Soc. Hort. Sci. 97:636-638.

Folchi, A., G.C. Pratella, S.P. Tian, and P. Bertolini. 1995a. Effect of low oxygen stress in apricot at different temperatures. Ital. J. Food Sci. 7:245-254.

Guelfat-Reich, S., and R. Ben-Arie. 1967. Different factors affecting the keeping quality of "Canino" apricots in cold storage. *In* Proceedings of the 12th International Congress on Refrigeration, vol 3, pp. 447-457, Madrid, Spain.

Iwata, T., and M. Kinoshita. 1978. Studies on storage and chilling injury of Japanese apricot fruits. II. Chilling injury in relation to storage temperature, cultivar, maturity, and polyethylene packaging. J. Jpn. Soc. Hort. Sci. 47:97-104.

Trurter, A.B., J.C. Combrink, and L.J. von Mollendorff. 1994. Controlled-atmosphere storage of apricots and nectarines. Decid. Fruit Grower 44:421-427.

Wankier, B.N., D.K. Salunkhe, and W.F. Campbell. 1970. Effects of controlled atmosphere storage on biochemical changes in apricot and peach fruit. J. Amer. Soc. Hort. Sci. 95:604-609.

Witherspoon, J.M., and J.F. Jackson. 1996. Analysis of fresh and dried apricots. *In* H. Linskens and J. Jackson, eds., Modern Methods of Plant Analysis, pp. 111-131. Springer-Verlag, Berlin, Germany.

Arazá

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Scientific Name and Introduction

Eugenia stipitata Mac Vaugh, known as the arazá (Morton 1987, Arkcoll 1990), is a berry from a perennial tree of the *Myrtaceae* family. Two subspecies were described by McVaugh (1956): *stipitata* from Brazil and Peru (also known as araçá-boi in Brazil or as pichi in Peru, “the wild one”) and *sororia* from Peru (also called *rupina caspi*, “the domesticated one”). One landrace occurs in the western Amazon (Gentil and Clement 1997). Arazá is primarily grown in the western Amazon as well as in Costa Rica. There can be four flowering periods per year with 2-mo harvest periods followed by a 1-mo break (Swift and Prentice 1983). The main harvest season is February to May for subsp. *stipitata* in Belem, Brazil (Morton 1987). There are two main production seasons (March to May and October to December) in Colombia’s northern Amazon, whereas production is year-round in the southern Amazon.

Quality Characteristics and Criteria

High-quality arazá fruit are juicy with bright, canary-yellow flesh; bright yellow to orange rind; and no signs of shriveling, bruises, or skin scald. The edible portion is slightly fibrous with an exquisite fragrance but has an extremely sour taste (Arkcoll 1991). Arazá fruit are known for their high acidity (mostly malate, followed by succinate and, to a lesser extent, citrate), minerals, a high ascorbic acid content, and low concentrations of reducing sugars (Gentil and Clement 1997, Hernández et al. 2001, 2002a, 2002b). Quality defects include susceptibility to anthracnose, scab (*Sphaceloma* sp.), rust (*Uromyces* sp.), soft fruit texture, loss of aroma, skin scald at suboptimum temperatures, and high weight losses, particularly at low RH (Arkcoll 1991, Galvis and Hernández 1993b, Tai Chun 1995). The average number of seeds per fruit and seed length depends on the subspecies (Swift and Prentice 1983, Morton 1987, Rodriguez 1990, Ferreira 1992,). Thirty volatile compounds have been identified in ripe arazá fruit, with sesquiterpenes and particularly germacrene D as the most abundant compounds (Franco and Shibamoto 2000).

Horticultural Maturity Indices

Fruit are harvested green (Hue angle values above 100°) to avoid fruit softening (Arkcoll 1991, Galvis and Hernández 1993a,b). Harvest criteria are primarily size and color, and texture to a lesser extent. If arazá fruit mature on the tree, shelf-life is only about 3 days after harvest.

Grades, Sizes, and Packaging

Average fruit range from 100 to 200 g, and equatorial diameters range from 4 to 10 cm (Ferreira 1992). The domesticated round to oblate fruit from subspecies *sororia* reach 50 to 800 g, while the wild subspecies *stipitata* reaches 20 to 56 g (Morton 1987, Rodriguez 1990). In Colombia, markets pack fruit in baskets of small (smaller than 100 g), medium (150 to 200 g), and large (200 to 350 g) fruit.

Precooling Conditions

Arazá should be cooled to around 13 °C (55.4 ºF) within 24 h of harvest in a refrigerated chamber using air with 90 to 95% RH to maximize storability.

Optimum Storage Conditions

The recommended conditions are 12 to 13 °C (53.6 to 55.4 ºF) and 90 to 95% RH. Arazá fruit can be kept in good condition for 2 weeks at 12 °C (53.6 ºF), 7 days at 10 °C (50 ºF), and 5 days at 20 °C (68 ºF) (Hernández et al. 2001, 2002b).

Controlled Atmosphere (CA) Considerations

MA reduces weight loss, shriveling, development of skin scald, decay, softening, and the loss of TA (Hernández et al. 2001). Low-density polyethylene (LDPE) films have been used for MA. However, the effectiveness of MA storage depends on maturity, cultivar, temperature, and atmosphere. Storage under passive MA using PE film resulted in a steady state reached after 6 days at 10 °C (50 ºF) and gas composition of 5 to 6% CO_2 and 13% O_2, depending on the LDPE film used (Hernández et al. 2001). The use of active MA with 5% O_2 and 5% CO_2 with LDPE of 38 μm thickness results in maximum quality, but no recommendation can be made for MA storage. If O_2 decreases to below 2%, subsequent ripening in air may be irregular or inhibited.

Retail Outlet Display Considerations

Use of molded plastic trays, as well as individual seal packaging with high OTR films, is acceptable. Weight loss at RH under 90% and bruising are serious problems.

Chilling Sensitivity

Arazá fruit are sensitive to chilling below 13 °C (55 ºF). At 8 to 10 °C, fruit should be stored less than 5 days to avoid chilling injury.

Ethylene Production and Sensitivity

Ethylene production and sensitivity have not been determined. The fruit are climacteric.

Respiration Rates

Temperature	Preclimacteric	Climacteric
	-------*mg CO_2 kg^{-1} h^{-1}*-----------	
10 ºC	40 to 323	601
13 °C	60 to 337	861
20 °C	140 to 310	1,283

Data from Galvis and Hernández (1993a,b) and Hernández et al. (2002a).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

The main disorders are skin scald, browning partly due to bruises, abnormal ripening or uneven to ripe symptoms (blotchy green color, high flesh firmness), lack of flesh juiciness, increase in acidity, and green skin spots (Tai Chun 1995, Hernández et al. 2002a). $CaCl_2$ application, particularly at higher than 4% (w/v), can result in abnormal ripening. Green skin spots remain on the fruit and small brown spots develop that later expand into necrotic lesions that become sites for fungal infection.

Postharvest Pathology

The main rot in arazá is anthracnose *(Gloesporium album)* on wounds or chilling-injured (scalded) areas (Arkcoll 1991, Hernández et al. 2002a,b). *Cylindrocladium scoparium* rot is characterized initially by small, light-brown lesions, which evolve to severely damaged areas that can reach about 0.3 cm of pulp depth (Nuñes et al. 1995). The pathogenicity of *Curvularia* spp. isolated from rotted fruit is under study, though symptoms are fruit softness and pink spot areas in the pulp that lack juice and fermentative degradation. The incidence of rust (*Puccinia psidii* or *Uromyces* sp.) has been recorded in Manaus and Costa Rica (Moraes et al. 1994, Tai Chun 1995). Yeasts are a minor problem with fruit bruises and/or chemical-scalded areas caused by calcium dips of 4 to 8% (Hernández et al. 2003).

Quarantine Issues

Quarantine pests include *Anastrepha obliqua* and *A. striata* (Diptera:Tephritidae) (Saldanha and Silva 1999). The coleoptera *Conotrachelus eugeniae* and *Atractomerus immigrans* have been reported on arazá rinds. *Neosilba zadolicha* (Diptera: Lonchaeidae) larvae are seldom present on fruit blemishes caused by these insects (Couturier et al. 1996). Mediterranean fruit fly (*Ceratitis capitata* Wied) has been identified in Costa Rican orchards (Swift and Prentice 1983, Moraes et al. 1994, Tai Chun 1995).

Special Considerations

Fruit are highly susceptible to dehydration and shriveling. A warming treatment of 18 h at 20 °C (68 ºF) with 90% RH after 6 days at 10 °C (50 ºF) reduces skin scald and associated decay and extends shelf-life up to 2 weeks (Hernández et al. 1999, 2002b).

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References

Arkcoll, D. 1991. New crops from Brazil. *In* J. Janick and J.E. Simons, eds., Proceedings of the National Symposium on New Crops: Exploration, Research and Commercialization, pp. 367-371. John Wiley & Sons, Indianapolis, IN.

Couturier, G., E. Tanchiva, J. Gonzales, et al. 1996. Preliminary observations on the insect pests of araza (*Eugenia stipitata* Mc Vaugh, Myrtaceae), a new fruit crop in Amazonia. Fruits 51:229-239.

Ferreira, S.A. do N. 1992. Biometria de frutos de araçá-boi (*Eugenia stipitata* Mc. Vaugh) (biometry of the araza fruit). Acta Amazonica 22:295-302.

Franco, M.R.B., and T. Shibamoto. 2000. Volatile composition of some Brazilian fruits: umbu-caja *(Spondias citherea),* camu-camu *(Myrciaria dubia),* araca-boi *(Eugenia stipitata),* and cupuacu *(Theobroma grandiflorum).* J. Agric. Food Chem. 48:1263-1265.

Galvis, J.A., and M.S. Hernández. 1993a. Análisis del crecimiento del fruto y determinación del momento de cosecha del Arazá [Fruit development and harvest date in araza]. Colombia Amazónica 6:107-121.

Galvis, J.A., and M.S. Hernández. 1993b. Comportamiento fisiológico del arazá *(Eugenia stipitata)* bajo diferentes temperaturas de almacenamiento [Physiological behavior of araza *(Eugenia stipitata)* under different storage temperatures]. Colombia Amazónica 6:123-134.

Gentil, D.F.O., and C.R. Clement 1997. The arazá *(Eugenia stipitata):* results and research directions. Acta Horticulturae 452:9-17.

Hernández, M.S., H.E. Arjona, O. Martínez, and J.P. Fernández-Trujillo. 1999. Storage disorders of arazá fruit (*Eugenia stipitata* Mc Vaugh) related to postharvest treatments. HortScience 34:512.

Hernández, M.S., J.P. Fernández-Trujillo, O. Martínez, et al.. 2001. Modified atmosphere packaging of araza fruit (*Eugenia stipitata* McVaugh). *In* F. Artés, M.A. Conesa, and M.I. Gil, eds., Proceedings of the International Institute of Refrigeration Conference on Improving Postharvest Technologies of Fruits, Vegetables, and Ornamentals, Oct. 19-21, 2000, vol. 2, pp. 666-673. Murcia, Spain.

Hernández, M.S., J. Barrera, J.P. Fernández-Trujillo, et al. 2002a. Efecto de la temperatura de almacenamiento en la fisiología y calidad del fruto de arazá (*Eugenia stipitata* Mc Vaugh) [Effect of storage temperature on postharvest physiology and quality of araza fruit]. IV Iberian Congress. Spanish Soc. Hort. Sci., Cáceres, May 2001. Actas de Horticultura 37:1074-1081.

Hernández, M.S., H.E. Arjona, O. Martínez, and J.P. Fernández-Trujillo. 2002b. Influence of intermittent warming treatments on the postharvest quality of araza fruit (*Eugenia stipitata* McVaugh). *In* R. Dris and A. Sharma, eds., Food Technology and Quality Evaluation, vol. 43, pp. 261-265. Sci. Pub. Inc., Plymouth, U.K.

Hernández, M.S., J.P Fernández-Trujillo, and O. Martínez. 2003. Postharvest quality of araza fruit (*Eugenia stipitata* McVaugh) treated with calcium chloride solutions at two temperatures. Acta Hort. 628:53-660.

McVaugh, R. 1956. Tropical American Myrtaceae. Fieldiana. Botany 29:145-228.

Moraes, V.H. de F., C. Hans, A.G.C. de Souza, and I. Cohen. 1994. Native fruit species of economic potential from the Brazilian Amazon. Angewandte Botanik 68:47-52.

Morton, J.L. 1987. Fruits of Warm Climates. J.L. Morton Pub., Miami, FL.

Nuñes, A.M.L., R.L.B. Stein, and F.C. de Albuquerque. 1995. Araçá-boi *(Eugenia stipitata):* um novo hospedeiro de *Cylindrocladium scoparium* [Araza *(Eugenia stipitata):* a new host of *Cylindrocladium scoparium]*. Fitopatol. Bras. 20:488-490.

Rodriguez, S. 1990. Araza (*Eugenia stipitata*). Monografia 1, Corporación Colombiana para la Amazonia Araracuara COA, San Jose del Guaviare, Colombia.

Saldanha, L.A., and N.M. Silva. 1999. Semi-artificial bearing of the larvae of *Anastrepha obliqua* (Diptera:Tephritidae) in Manaus, Amazonas-Brazil. Florida Entomologist 82:82-87.

Swift, J.F., and W.E. Prentice. 1983. Native fruit species of the ecuadorian Amazon: production techniques and processing requirements. Proc. Amer. Soc. Hort. Sci. Trop. Reg. 27A:95-100.

Tai Chun, P.A. 1995. Pre- and post-harvest pests and diseases of Araza *(Eugenia stipitata)* in Costa Rica. Inter-American Institute for Cooperation on Agriculture, Costa Rica.

Artichoke

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Scientific Name and Introduction

Cynara scolymus L., the globe artichoke, is a perennial of the Asteraceae (Compositae) family. The edible portion includes the tender immature flower bud and fleshy central base that is protected by a cone of short, thick-stemmed bracts. The main types include Green Globe, Desert Globe Imperial Star, Emerald, and Big Heart. Artichokes are primarily grown in California and are available year round.

Quality Characteristics and Criteria

A high-quality artichoke will have tightly closed, turgid outer bracts without signs of black tip, blistering, or browning. It should be medium to dark glossy green in color, and some cultivars may have a magenta color at the base of each bract. The artichoke should not be soft when squeezed or feel heavy for its size. Both thorny and thornless cultivars are used commercially.

Horticultural Maturity Indices

The outer bracts of an artichoke ready for harvest should be tightly closed, firm, and turgid. They are harvested when immature and selected based on size and compactness.

Grades, Sizes, and Packaging

Grades include U.S. No. 1 and U.S. No. 2, based primarily on external appearance. Buds are classified by the number that fit into a standard carton of about 10 kg (23 lb.). For example, size 18 buds means 18 buds per carton (also referred to as "18s"). Standard grades include 18s (>13 cm diameter, 5.4 in), 24s (10 to 13 cm, 4.0 to 4.5 in), 36s (8.5 to 10 cm, 3.5 to 4.0 in), 48s (7.5 to 8.5 cm, 3.0 to 3.5 in) or 60s (6.5 to 7.5 cm, 2.75 to 3 in) buds per box. Smaller buds (2.5 to 6.5 cm, 1.0 to 2.75 in) are often "jumble packed" at an average of 100 to 175 buds per box. The fresh-produce market prefers 24s and 36s, but some retailers prefer 36s and 48s, since artichokes are generally priced by bud, not by weight.

A new grade was adopted for U.S. No. 1 long stem globe artichokes in 2006. The stems must be smoothly cut to a minimum of at least 20 cm (8 in) unless otherwise specified to a longer length in connection with a grade.

Precooling Conditions

In order to maintain quality and storage life, artichoke buds should be precooled to below 5 °C (41 °F) within 24 h of harvest (Lipton and Stewart 1963). Hydrocooling, forced-air cooling, and package-icing are common methods of postharvest cooling of artichokes and will generally retard deterioration such as discoloration, weight loss, and decay.

Optimum Storage Conditions

The recommended conditions for storage of artichokes are 0 °C (32 °F) and >95% RH. Artichoke buds can be kept in good condition for 2 weeks at 0 °C (32 °F), 10 days at 5 °C (41 °F), and 5 days at 10 °C (50 °F) (Ryall and Lipton 1979, Saltveit 1991).

Controlled Atmosphere (CA) Considerations

A reduction in browning of the outer bracts is the major benefit from CA storage when artichokes are stored at temperatures higher than 0 °C (32 °F). However, the effectiveness of CA storage depends on bud maturity, cultivar, temperature, and the particular atmosphere used (Rappaport and Watada 1958, Andre et al. 1980, Ryder et al. 1983). Optimal CA conditions vary widely among cultivars, ranging between 1 to 6% O_2 and 2 to 7% CO_2 (Ryall and Lipton 1979, Saltveit 1997, Andre et al. 1980, Escriche et al. 1982). Little or no beneficial effect on quality retention can be obtained by CA storage when artichoke buds are stored at 0 °C (32 °F) (Miccolis and Saltveit 1988). Therefore, no general recommendation can be made for CA storage. O_2 below 2% may result in internal blackening (Suslow and Cantwell 1998).

Retail Outlet Display Considerations

Use of both top ice and water sprinklers are acceptable.

Chilling Sensitivity

Artichokes are not sensitive to chilling and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Artichokes produce only very low amounts of ethylene and are not particularly sensitive to ethylene exposure.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	16 to 44
5 °C	26 to 60
10 °C	44 to 98
15 °C	76 to 144
20 °C	134 to 252

Data from Suslow and Cantwell (1998).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Splitting of the bract tip is a common problem caused by rough handling during and after harvest. The surfaces of bracts are also easily bruised and scratched, so careful handling is important. The abraded areas usually turn brown or black, which greatly detracts from appearance and quality and provides a route through which microorganisms can enter. Also, violet discoloration of inner bracts occurs, the severity of which was low when artichokes were stored at temperatures below 10 °C (50 °F) or above 25 °C (77 °F) (Bianco 1979) and may have been due to low ethylene production (Ryder et al. 1983).

Postharvest Pathology

The most common decay found in artichokes is gray mold *(Botrytis cinerea)* (Moline and Lipton 1987). The lesions most frequently begin on wounds and spread to other areas of the bud. Since storage at low temperatures slows the rate of spread of the disease, fungal growth near freezing temperature is minimal. Bacterial soft rot *(Erwinia carotovora)* may be a problem in storage and distribution if optimum temperature is not maintained. Therefore, low temperatures must be maintained throughout the cold chain to minimize pathological disorders and prolong shelf-life.

Quarantine Issues

There are no quarantine issues.

Suitability as Fresh-Cut Product

No current potential.

Special Considerations

Artichokes must be handled with care to avoid mechanical damage and therefore limit discoloration and pathological problems. During winter, artichokes may have a white or bronze, blistered appearance due to being frosted in the field. The artichokes are said to have been “frost-kissed.” This is purely an appearance issue and does not affect eating quality. In fact, this condition may enhance the nutty flavor. Avoid wilted, moldy, significantly discolored, or woody (overmature) artichokes.

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Some of the information included was from the Produce Marketing Association’s “Fresh Produce Manual” and the University of California, Davis, website on “Fresh Produce Facts” at http://postharvest.ucdavis.edu/produce_information.

References

Andre, P., R. Blanc, M. Buret, et al. 1980. Trails of preservation of artichokes by combined utilization of vacuum precooling, controlled atmospheres, and cold. Revue Hort. 211:33-40.

Bianco, V.V. 1979. Influence of temperature on the coloration of interior bracts and the inflorescence complex of stored artichokes. *In* 3rd International Congress on Artichoke Studies Abstracts, pp. 166. Bari, Italy.

Escriche, A., F. Artes, and J.C. Marin. 1982. Conservation d’artichauts en atmosphere controlée. *In* Progress in the Design and Operation of Refrigerating Equipment in the Storage of Fruits and Vegetables by Refrigeration, pp. 336-341. Inst. Intl. du Froid, Paris, France.

Lipton, W.J., and J.K. Stewart. 1963. Effects of Precooling on Market Quality of Globe Artichokes. Marketing Research Report 633, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Miccolis, V., and M.E. Saltveit. 1988. Influence of temperature and controlled atmosphere on storage of ‘Green Globe’ artichoke buds. HortScience 23:736-741.

Moline, H.E., and W.J. Lipton. 1987. Market Diseases of Beets, Chicory, Endive, Escarole, Globe Artichokes, Lettuce, Rhubarb, Spinach, and Sweet Potatoes. Agriculture Handbook 155, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Rappaport, L., and A.E. Watada. 1958. Effect of temperature on artichoke quality. *In* Proceedings of the Conference on Transport of Perishables, pp. 142-146. University of California, Davis, CA.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation and Storage of Fruits and Vegetables, vol. 1, Vegetables and Melons. AVI, Westport, CT.

Ryder, E.L., N.E. DeVos, and M.A. Bari. 1983. The globe artichoke (*Cynara scolymus* L). HortScience 18:646-653.

Saltveit, M.E. 1991. Artichokes. *In* P. Lidster, G. Blanpied, and R. Prange, eds., Controlled-Atmosphere Disorders of Commercial Fruits and Vegetables, pp. 23-24. Pub. no. 1847/E, Agriculture Canada, Ottawa, Ontario, Canada.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California, Davis, CA.

Suslow, T., and M. Cantwell. 1998. Globe artichoke in “Fresh Produce Facts.” *At* http://postharvest.ucdavis.edu/produce_information.

Asian Pear

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Scientific Name and Introduction

The cultivated varieties of Chinese and Japanese pears were developed from *Pyrus ussuriensis* Maximowicz, *P. serotina* Rehder (*P. pyrifolia* [Burman] Nakai) and possibly other native species, according to Kikuchi (1948). Hu (1937) included the Chinese varieties 'Tsu Li' and 'Ya Li' under the binomial *P. bretschneideri* Rehder. Catlin and Olsson (1966) reported that the Japanese pears 'Kikusui,' 'Nijisseiki' ('20th Century'), 'Seigyoku,' 'Shinseiki,' 'Chojuro,' 'Doitsu,' 'Imamura Aki,' and 'Ishiiwase' were varieties of *P. serotina*, and they were unable to distinguish 'Tsu Li' and 'Ya Li' from the Japanese varieties.

Asian pears remain firm and are crisp and juicy when eaten ripe, whereas 'Bartlett' and other *Pyrus communis* Linnaeus varieties become soft and melting when ripe. Asian pears are also called Oriental pears, Chinese pears, Japanese pears, nashi, sand apples, and salad pears. In fresh-fruit market reports, they are usually called "apple pears," an unfortunate and misleading term. Though most Japanese pear varieties are roundish, their texture and flavor are entirely different from those of apples. The main Chinese pear varieties are pyriform. Sometimes market reports refer to Asian pears as "apple (shalea) pears." The name "shalea" probably is derived from the words "sha li," which means "sand pear" in Chinese. 'Sha Li' is the name of one of three main groups of pears grown in China, as well as the name of an old variety in the group (Hu 1937).

Quality Characteristics and Criteria

Freedom from mechanical injury is desired. ('Nijisseiki' pears are very sensitive to impact and compression bruising; 'Tsu Li' and 'Ya Li' pears increase in susceptibility to bruising after storage; and 'Chojuro' pears are firmer and more resistant to mechanical damage). Flesh firmness (penetration force using an 8-mm tip) of 7 to 10 lb-force, depending on cultivar, is optimum for eating. Only small changes in firmness occur during storage at 0 °C (32 °F). Asian pears should be juicy, not mealy, and sweet with 11 to 14% SSC, depending on the cultivar.

Horticultural Maturity Indices

Change in skin color can occur from green to yellowish green ('Nijisseiki,' 'Shinseiki,' 'Tsu Li,' and 'Ya Li') or to golden brown ('Hosui,' 'Kosui,' 'Niitaka,' and 'Shinko'). Delayed harvest (which does not always mean higher SSC) results in increased incidence and severity of physiological disorders and greater susceptibility to physical injury.

Grades, Sizes, and Packaging

Fruit should be held lightly in the palm of the hand and an upward twisting motion used to remove the fruit from the spur. A natural abscission layer forms at the spur end of the stalk and separation at this zone becomes easier as fruit mature. A pulling motion can result in damage as the stalk can be removed from the fruit.

The skin of Asian pears is very susceptible to abrasion and friction marks. Smooth-surfaced containers such as polystyrene trays, shallow plastic buckets, or plastic trays with foam pads should be used for collecting fruit.

Fruit should be placed into trays or buckets with the stem end up, preferably in single layers and packed firmly to avoid movement. Care must be taken to avoid stem punctures if fruit are packed in two or more layers. Bulk handling of fruit should be confined to the use of single trays stacked together in a large bin rather than volumes of fruit packed into large trays or bins. Once the fruit are harvested, they should be placed in the shade and not left in direct sunlight.

Optimum Storage Conditions

Asian pears should be stored at 0 ºC (32 ºF) in trays complete with packet pack and polyliners. It is necessary to maintain RH above 90% in the storage atmosphere because fruit are susceptible to water loss. When water loss has been greater than 5 to 7%, fruit become dehydrated and have a shriveled appearance, especially in ‘Kosui’ and ‘Hosui.’ Eating quality is also affected and fruit lack a crisp and juicy texture.

The continued presence of ethylene in the storage environment may increase the development of skin browning and fruit senescence. Therefore, ethylene levels in the coolstore should be kept as low as possible. Asian pears should not be stored for long periods with fruit that produce high levels of ethylene. Damaged or decayed fruit or fruit with disorders produce higher levels of ethylene than sound fruit and should not be stored alongside sound fruit.

Forced-air cooling is not recommended for Asian pears. Results from experiments conducted with Asian pears grown in New Zealand indicate that there is no benefit to fruit quality (fruit firmness and SSC) from rapid precooling. Furthermore, fruit are likely to have a higher incidence of flesh spot decay during storage if they have been rapidly cooled within 24 h of harvest. Therefore, it is recommended that fruit be room-cooled after harvest.

Optimum Temperature

Optimum storage conditions are 0±1 °C (32±2 °F) with RH of 90 to 95%. The freezing point is -1.5 °C (29 °F); it will vary depending on SSC.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	2 to 8
20 ºC	20 to 30

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Controlled Atmosphere (CA) Considerations

Based on limited studies, it appears that the magnitude of CA benefits for Asian pears is cultivar specific and is generally less than that for European pears and apples. CA may extend storage duration of some Asian cultivars by about 25% relative to storage in air. O_2 levels of 1 to 3% for some cultivars (such as ‘Nijisseiki’) or 3 to 5% for others (such as ‘Ya Li’) help retain firmness and delay changes in skin color. Asian pears are sensitive to CO_2 injury (above 2% CO_2 for most cultivars) when stored longer than 1 mo.

Retail Outlet Display Considerations

Display shelf should be kept as cold as possible without freezing or ice.

Rates of Ethylene Production and Sensitivity

Some cultivars (such as ‘Nijisseiki,’ ‘Kosui,’ and ‘Niitaka’) produce very little ethylene, less than 0.1 μL kg^{-1} h^{-1}, and have a nonclimacteric respiratory pattern (no rise in CO_2 production during ripening). Other cultivars, such as ‘Tsu Li,’ ‘Ya Li,’ ‘Chojuro,’ ‘Shinsui,’ ‘Kikusui,’ and ‘Hosui,’ have a climacteric respiratory pattern and produce ethylene up to 9 to 14 μL kg^{-1} h^{-1} (‘Tsu Li’ and ‘Ya Li’) or 1 to 3 μL kg^{-1} h^{-1} (other cultivars) at 0 °C (32 °F).

Exposure of climacteric cultivars to <1 µL L^{-1} ethylene accelerates loss of green color and slightly increases softening at 20 °C (68 °F). The effects at 0 °C (32 °F) are minimal.

Physiological Disorders

Internal breakdown and chilling injury can be a problem with Chinese pear cultivars such as 'Ya Li,' 'Daisui Li,' 'Seuri,' 'Tse Li,' 'Shin Li,' and Korean pears such as 'Shingo,' 'Okysankichi,' and 'Dan Be.' Internal browning or core breakdown is the main worldwide consumer complaint. Development of brown to dark-brown water-soaked areas in the core and/or flesh occurs during storage, with no visible external indication of internal browning.

Fruit grown under the hot conditions of California's San Joaquin Valley and picked later than 180 days after full bloom are likely to develop *browning* during storage. In order to apply this information to other locations or years, fruit should be picked no later than 3,000 degree-days as calculated by averaging the daily maximum and minimum temperatures, subtracting 4 and summing the resulting values (Johnson and Lakso 1985). The fruit should be picked when most of the pears on the tree are still green, though it is all right if a few at the top have begun to develop some light-yellow spots. Fruit picked when the skin is completely yellow will develop internal browning within 1 mo after harvest. In China, reduction of 'Ya Li' internal breakdown has been accomplished using a temperature program that decreases storage temperature gradually.

Flesh spot decay (FSD) can be a problem with Japanese pear cultivars. FSD is more frequent on large (<300 g) and overmature fruit. FSD limits opportunities to grow and market Japanese pears. Symptoms include partial browning of spots and development of cavities in the flesh. It appears along and around the vascular bundles when the symptoms are severe, but there is no external indication of the disorder. Generally, FSD is more pronounced above the equator of the fruit (towards the stem end), but it can also be observed all the way down to the calyx. Cavities are usually dry and surrounded by apparently healthy tissue. This disorder can occur in fruit while still on the tree. It is more obvious, however, after 2 to 6 weeks in cold storage. The cause of FSD is still unknown. However, climatic factors, such as a fluctuating hot and cool summer or high rainfall right before harvest, may enhance the incidence of this disorder. There is no effective way to control FSD since definite causes have not been identified. The problem is the inability to predict FSD without cutting the fruit. Further research needs to be done to determine the causes, variety of susceptibility in local climates, and other control methods, either preharvest or postharvest, that will reduce FSD symptoms to a commercially acceptable level. Meanwhile, whenever possible, avoid the following conditions that might induce FSD: low crop load (large fruit), later picking (advanced maturity), extreme temperature changes during the maturation season, sunburn, erratic irrigation or precipitation (frequency, amount, and timing), harvesting fruit under warm temperatures, and cooling the fruit rapidly.

Low-O_2 injury manifests itself as discolored surface depressions from exposing 'Nijisseiki' pears to ≤1% O_2 for 4 mo at 0 °C (32 ºF) and from exposing 'Ya Li' and 'Tsu Li' pears to ≤1% O_2 for 2 mo, ≤2% O_2 for 4 mo, or ≤3% O_2 for 6 mo at 0 °C (32 ºF).

High-CO_2 injury is manifested as core or medial flesh browning, with cavities developing in severe cases as a result of desiccation of dead tissue. 'Ya Li' pears can exhibit CO_2 injury after exposure to ≥5% CO_2 for 6 weeks at 0 ºC (32 ºF).

Watercore symptoms (glassy, diffuse water-soaked areas in flesh; affected areas may taste sweet and turn slightly brown) occur in some cultivars (for example, 'Nijisseiki,' 'Shinseiki,' and 'Hosui') under conditions favoring vigorous tree growth. Avoid harvesting overmature fruit to reduce watercore incidence and severity.

Superficial scald or skin browning can occur after long-term (>16 weeks) storage of 'Shinsiki' and 'Nijisseiki' fruit. Long-term storage can lead to the development of a skin disorder that is characterized by the appearance of scaldlike browning symptoms. Initially, the affected areas of the skin are light brown in color, but as the disorder progresses the skin becomes dark brown and develops a bronze, scaldlike appearance. The disorder is confined to the skin and is similar to superficial scald in apples. Scald appears to be a problem associated with packaging in that most of the scald appears at the calyx end or that portion of the fruit that is tightly confined within the pocket of the pocket pack. However, the whole fruit surface is susceptible to the disorder, which is rapidly induced if Asian pears are stored together with apples. To avoid the disorder, adequate ventilation during storage and storage of fruit in a relatively ethylene-free atmosphere are recommended.

Postharvest Pathology

Asian pear fruit are susceptible to many pathogens, such as *Botrytis, Alternaria,* and *Phomopsis* species. These pathogens invade fruit through wounds caused by mishandling of fruit after harvest. The rots develop slowly in fruit during storage and eventually the whole fruit becomes affected. Affected flesh areas become soft and discolored. Damage to fruit surfaces by birds while fruit are on the tree can provide entry points for pathogens.

Quarantine Issues

Limited import (Chile) and export (Canada) activity is occurring. If imported from Chile, Asian pear shipments must be accompanied by a PPQ (Plant Pest Quarantine Form 203) signed by the USDA, Animal Plant Health Inspection Service (APHIS) inspector on site in Chile. If shipments were not precleared at origin, sampling at arrival time is necessary. APHIS issues rules regarding import requirements and provides information to assist exporters in targeting markets and defining what entry requirements a particular country has. In cooperation with the State plant boards, APHIS developed a database called "Excerpt" to track phytosanitary requirements for each country. APHIS also provides phytosanitary inspections and certifications that declare fruit are free of pests to facilitate compliance with foreign regulatory requirements. Issues associated with exotic pest quarantines, addressing both imported and exported fruit, can change rapidly.

Suitability as Fresh-Cut Product

Preliminary research conducted in the laboratory of Dr. Adel Kader at the University of California, Davis, CA in 2000 showed that Asian pear slices have a very short shelf-life, even at 0 to 2 °C (32 to 36 °F), due to tissue browning. Dipping slices in 1% ascorbate + 1% $CaCl_2$ for 2 min soon after slicing delayed browning, but shelf-life was less than 5 days at 2 °C (36 °F).

Special Considerations

The five varieties 'Shinsui,' 'Shinseiki,' 'Kosui,' 'Hosui,' and 'Nijisseiki' all have an adequate storage life. If fruit are harvested at the recommended maturity, a storage life of 12 to 20 weeks and a subsequent shelf-life of 10 to 15 days can be expected, depending on the variety. The major limitation to the storage life of Asian pears is development or enhancement of maturity-related disorders.

Acknowledgments

Most of this information was taken from the University of California, Davis, website "Fresh Produce Facts" at http://postharvest.ucdavis.edu/produce_information.

References

Beutel, J. 1990. Asian pears. *In* J. Janick and J.E. Simon, eds., Advances in New Crops, pp. 304-308. Timber Press, Portland, OR.

Crisosto, C.H., K.R. Day, S. Sibbett, et al. 1994. Late harvest and delayed cooling induce internal browning of ‘Ya Li’ and ‘Seuri’ Chinese pears. HortScience 29:667-670.

Crisosto, C.H., D. Garner, G.M. Crisosto, et al. 1994. Early harvest prevents internal browning in Asian pears. Calif. Agric. 48:17-19.

Davis, L.D., and W.P. Tufts. 1941. Pear growing in California. Circular no. 122, California Agricultural Extension Service, 87 pp., University of California, Davis, CA.

Griggs, W., and B. Iwakiri. 1997. Asian Pear Varieties in California. DANR Pub. no. 4068, University of California, Oakland, CA.

Hu, C.C. 1937. The variety and distribution of pears in China. Nanking J. 7:103-193.

Johnson, R.S., and A.N. Lakso. 1985. Relationship between stem length, leaf area, stem weight, and accumulated growing degree-days in apple shoots. J. Amer. Soc. Hort. Sci. 110:586-590.

Lallu, N. 1990. Fruit growth, handling and storage. *In* A.G. White, ed., Nashi, Asian Pear in New Zealand, pp. 53-74. DSIR Publishing, Wellington, New Zealand.

Lidster, P.D., G.D. Blanpied, and R.K. Prange, eds. 1990. Controlled-Atmosphere Disorders of Commercial Fruits and Vegetables. Agric. Canada Pub. no. 1847/E, Agriculture Canada, Ottawa, Ontario, Canada.

Porritt, S.W., M. Meheriuk, and P.D. Lindster. 1982. Postharvest Disorders of Apples and Pears. Agr. Canada Pub. no. 1737/E, Agriculture Canada, Ottawa, Ontario, Canada.

Tian, M.S., C.C. Sheng, and Y. Li. 1987. Relationship between ethylene release, membrane permeability and activity of polyphenol oxidase changes of Duck pears (*Pyrus bretschneideri* Rehder) during low-temperature storage. Acta Bot. Sinica 29:614-619.

Asparagus

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Scientific Name and Introduction

Asparagus (*Asparagus officinalis* L.) is a perennial of the Liliaceae family. The edible portion of asparagus is a rapidly growing stem (shoot) with scale leaves that arise at nodes. There are two forms of marketed asparagus, namely white (blanched) and green. White asparagus is more common in Europe and Asia (Lipton 1990); green asparagus is popular in the United States and is produced predominantly in California and Washington. Asparagus has a high metabolic rate after harvest and is among the most perishable crops.

Quality Characteristics and Criteria

High-quality asparagus spears are dark green and firm with tightly closed and compact tips (Suslow 1998a,b). Spears are straight, tender, and glossy in appearance. Spears with green butts are preferred over the spears with white butts, as the latter are associated with increased toughness. However, a small amount of white tissue at the butt will delay decay development under typical commercial distribution conditions (Lipton 1990, Suslow 2001).

Horticultural Maturity Indices

Asparagus spears are harvested as they emerge through the soil from the underground crowns. Typically, spears are cut when they reach 10 to 25 cm (8 to 10 in) in length, with spear tips still tightly closed. Tender, immature (that is, shorter) asparagus may be harvested for special markets.

Grades, Sizes, and Packaging

Harvested spears are prepared for market by grading, sizing, and bunching. Grades are based on freshness, length and diameter of the stalks, color of spears, tightness of the spear tips, and the extent of bruising. Sizing is based on spear diameter with U.S. No. 1 having a diameter >1 cm (>0.5 in) and U.S. No 2 having a diameter >0.8 cm (>5/16 in). Spears of larger diameter are considered to be superior in quality with less fiber (Peirce 1987). Spears are tied in bunches weighing 0.45 to 1.1 kg (1 to 2.5 lb) and trimmed to a standard length of 18 to 25 cm (7 to 10 in). Color is also important, with U.S. No. 1 spears being green for more than 2/3 their length, while U.S. No. 2 are green for more than half their length. After trimming the butt-end, the bunches are packed upright in trapezoidal-shaped crates to minimize geotropic bending (curving away from gravity) in transit. The container should include a wet pad in contact with the butt end to maintain turgidity. Headspace is provided in the carton to prevent tip curvature or breakage during spear elongation.

Precooling conditions

Asparagus is highly perishable and must be cooled immediately to 0 to 2 °C (32 to 36 °F). A 4-h delay in cooling resulted in an average 40% increase in shear force due to tissue toughening (Hernandez-Rivera et al. 1992). Asparagus is typically partially cooled during the washing, selection, and packing operation, and then hydrocooled to near 0 °C (32 °F) after packing.

Optimum Storage Conditions

The recommended conditions for commercial storage of asparagus are 0 to 2 °C (32 to 36 °F) with 95 to 99% RH, yielding 14 to 21 days of storage life. Maintaining a low storage temperature is critical to delay senescence, tissue toughening, and flavor loss (King et al. 1993). High RH is essential to prevent desiccation and to maintain freshness. Typically, asparagus is packed and shipped with water-saturated pads in the bottom of the containers to maintain high RH and to replenish water lost by the spear or water used during spear elongation; this practice maintains spear turgidity. Excessive free water at elevated storage or shipping temperatures may lead to increased decay.

Controlled Atmosphere (CA) Considerations

Elevated CO_2 at 5 to 10% is beneficial in preventing decay and slowing toughening of the spears. Short exposure to higher CO_2 concentration is safe and beneficial only if the temperature is maintained at 0 to 1 °C (32 to 34 °F). The combination of intermediate O_2 (2 to 10% O_2) may or may not provide benefit compared with air enriched with CO_2 alone (Lipton 1990, Kleiber and Wills 1992, Lill and Corrigan 1996, Saltveit 1997). At O_2 levels below 2%, off odors and discoloration may develop. Signs of CO_2 injury are small to elongated pits, generally first observed just below the tips. Severe CO_2 injury results in ribbiness. Asparagus tolerated a 100% nitrogen atmosphere for 6 h at 2.5 °C (37 °F) or 20 °C (68 °F) without affecting sensory quality (Torres-Penaranda and Saltveit 1994). High CO_2 (40 to 60%) can be applied at 5 °C (41 °F) for up to 4 days without affecting sensory quality, and may be used as an insect disinfestation treatment (Corrigan and Carpenter 1993).

Retail Outlet Display Considerations

Asparagus is often displayed upright in shallow trays containing chilled water. It will also tolerate icing on retail displays. The preferred method to maintain freshness at retail display is refrigerated display with light misting.

Chilling Sensitivity

Asparagus is subject to chilling injury after about 10 days at 0 °C (32 °F). Symptoms include loss of sheen and glossiness and graying of tips. A limp, wilted appearance may be observed. Severe chilling injury may result in darkened spots or streaks near the tips.

Ethylene Production and Sensitivity

Ethylene production is low to intermediate, increases with time after harvest, and varies with where the spears are cut relative to the soil surface (Lipton 1990). For spears cut at the soil surface and held at 20 °C (68 °F) for 45 and 90 min, ethylene production changes from 2.1 and 3.1 $\mu L\ kg^{-1}\ h^{-1}$ (Haard et al. 1974). Exposure to ethylene accelerated the lignification (toughening) of asparagus spears (Hennion et al. 1992). Prompt cooling and maintaining optimal shipping temperatures minimizes ethylene-induced toughening.

Respiration Rates

Respiration rates depend on storage temperature, time after harvest, and the spear portion on which determinations are made (Lipton 1990). Freshly harvested asparagus is among the highest respiring fresh produce items. However, rates decline rapidly after harvest (King et al. 1990, Lipton 1990). Respiration rates of the apical tips are much higher than those of the basal portions of the stems (Saltveit and Kasmire 1985, Lill et al. 1990). Listed below are respiration rates of asparagus spears held at 20 °C for various times:

Temperature	Time after harvest (days)		
	0.25	1.0	3.0
	mg CO_2 kg^{-1} h^{-1}		
0 ºC	80	60	40
5 ºC	145	105	65
10 ºC	305	215	120
15 ºC	325	235	160
20 ºC	500	270	185

Data from Lipton (1957).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Elongation and Tip Bending. Asparagus continues to grow and elongate after harvest if not immediately cooled and stored at temperatures below 5 °C (41 °F). Holding the butt in contact with water (the moist pad) promotes spear growth and elongation. Tip bending occurs as the result of upward growth of the tips when the spears are horizontal. If spears are held in an upright position, tip bending may still occur if the tips reach the top of the package and are physically deflected. Postharvest treatment of asparagus spears in heated water at 45 to 50 °C (113 to 122 °F) for 2 to 5 min reduces tip bending (Paull and Chen 1999).

Spear Toughening. Tissue lignification and fiber development, which progresses from butt to tip, cause spear toughening. It develops at >10 °C (50 °F), rapidly above 15 °C (59 °F), and is accelerated by ethylene.

Feathering. Feathering is the appearance of bracts of spear tips, which have opened due to outgrowth of the underlying buds. Tip feathering is a sign of senescence, often observed following extended storage at higher than optimal temperature or harvesting of overmature spears.

Freezing Injury. Water-soaked appearance and tissue softening occur at temperatures below -0.5 °C (31 °F).

Postharvest Pathology

The most prominent postharvest disease on asparagus is bacteria soft rot, caused by *Pectobacterium carotovora* or *Pseudomonas* spp. Decay may occur anywhere on the spears in the form of "soft rot pits," most frequently found on the tips or the butts (Snowdon 1992, Suslow 2001). Spears with green butts are more susceptible to this decay than spears with white butts. Storing asparagus at <5 °C (41 °F) controls this disease. In some production areas, the fungi such as *Fusarium*, *Penicillium*, and *Phytophthora* are associated with postharvest decay or spoilage of asparagus (Snowdon 1992).

Quarantine Issues

Asparagus may be fumigated during international distribution and marketing if live common insects (hitchhikers) are found.

Suitability as Fresh-Cut Product

The tender portion can be prepared as a food service product. There is limited minimal processing of asparagus, but consumer-oriented packing of tips is increasing.

References

Corrigan, V.K., and A. Carpenter. 1993. Effects of treatment with elevated carbon dioxide levels on the sensory quality of asparagus. N.Z. J. Crop Hort. Sci. 21:49-357.

Everson, H.P., K.W. Waldron, J.D. Geeson, and K.M. Browne. 1992. Effects of modified atmospheres on textural and cell wall changes of asparagus during shelf-life. Intl. J. Food Sci. Tech. 27:187-199.

Haard, N.F., S.C. Sharma, R. Wolfe, and C. Frenkel. 1974. Ethylene induced isoperoxidase changes during fiber formation in postharvest asparagus. J. Food Sci. 39:452-456.

Hennion, S., C.H.A. Little, and C. Hartmann. 1992. Activities of enzymes involved in lignification during the postharvest storage of etiolated asparagus spears. Physiol. Plant. 86:74-478.

Hernandez-Rivera, L., R. Mullen, and M. Cantwell. 1992. Textural changes of asparagus in relation to delays in cooling and storage conditions. HortTech. 2:378-381.

King, G.A., D.C. Woollard, D.E. Irving, and W.M. Borst. 1990. Physiological changes in asparagus spear tips after harvest. Physiol. Plant. 80:93-400.

King, G.A., P.L. Hurst, D.E. Irving, and R.E. Lill. 1993. Recent advances in the postharvest physiology, storage and handling of green asparagus. Postharv. News Info. 4(3):5N-89N.

Klieber, A., and R.B.H. Wills. 1992. Optimization of storage conditions for 'UC 157' asparagus. Australian J. Expr. Agric. 32:529-534.

Lill, R.E., and V.K. Corrigan. 1996. Asparagus responds to controlled atmospheres in warm conditions. Intl. J. Food Sci. Tech. 31:117-121.

Lill, R.E., G.A. King, and E.M. O'Donoghue. 1990. Physiological changes in asparagus spears immediately after harvest. Scientia Hort. 44:191-199.

Lipton, W.J. 1990. Postharvest biology of fresh asparagus. Hort. Reviews. 12:69-155.

Lipton, W.J. 1957. Physiological changes in harvested asparagus *(Asparagus officinalis)* as related to temperature of holding. Ph.D. Dissertation, University of California, Davis, CA.

Paull, R.E., and N.J. Chen. 1999. Heat treatment prevents postharvest geotropic curvature of asparagus spears (*Asparagus officinalis* C.). Postharv. Biol. Technol. 16:37-41.

Peirce, L.C. 1987. Vegetables—Characteristics, Production, and Marketing. John Wiley & Sons, New York, NY.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California, Davis, CA.

Saltveit, M.E., and R.F. Kasmire. 1985. Changes in respiration and composition of different length asparagus spears during storage. HortScience 20:1114-1116.

Snowdon, A.L. 1992. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, CRC Press, Boca Raton, FL.

Suslow, T.V. 1998a. Asparagus Producers and Shippers Quality Assurance Guidance to Minimizing Microbial Food Risks. University of California Vegetable Research and Information Center, Davis, CA, and the California Asparagus Commission, El Centro, CA.

Suslow, T.V. 1998b. Asparagus produce facts. Recommendations for Maintaining Postharvest Quality. *At* http://postharvest.ucdavis.edu/produce_information.

Suslow, T. 2001. Progress note on asparagus handling and display. University of California Perishables Handling Quarterly, no. 106. *At* http://postharvest.ucdavis.edu.

Torres-Penaranda, A.V., and M.E. Saltveit. 1994. Effects of brief anaerobic exposures on carbon dioxide production and quality of harvested asparagus. J. Amer. Soc. Hort. Sci. 119:51-555.

Atemoya

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Scientific Name and Introduction

Atemoya is a hybrid between *Annona squamosa* L. (sweetsop) and *A. cherimola* Mill. (cherimoya). The fruit can vary in external appearance, reflecting the different parents (Nakasone and Paull 1998). Favorable characteristics from the cherimoya include being heart shaped, having few seeds, and having smooth skin that does not break apart during ripening. There are about six varieties, with 'African Pride' and 'Gefner' being the most common. Atemoya are grown in Florida and Hawaii.

Quality Characteristics and Criteria

Atemoya fruit should be heart shaped, preferably with a smooth, cherimoyalike skin instead of the bumpy skin of the sweetsop. Besides shape, size, and skin texture, the fruit should be free of blemishes and mechanical injury, which can lead to skin blackening.

Horticultural Maturity Indices

Fruit skin color changes from darker to lighter green and can be greenish yellow. During ripening, skin splitting occurs and the skin darkens (Paull 1996).

Grades, Sizes, and Packaging

Atemoya fruit are sold in single-layer 4.5 kg (10 lbs) or 9 kg (20 lbs) fiberboard boxes with foam sleeves or paper wrapping. Fruit weighing 250 to 500 g (9 to 18 oz) are used.

Precooling Conditions

Room or forced-air cooling to 10 to 13 °C (50 to 55 ºF).

Optimum Storage Conditions

Store at 10 to 13 ºC (50 to 55 ºF) with 90 to 95% RH.

Controlled Atmosphere (CA) Consideration

There is no published information on this subject. The fruit may have similar potential as cherimoya.

Retail Outlet Display Considerations

Ripe fruit can be held at 2 to 5 ºC (36 to 41 ºF). If unripe, display at room temperature. Ripe fruit, if split, can be overwrapped.

Chilling Sensitivity

Atemoya fruit are very chilling sensitive, suffering skin darkening and loss of aroma and flavor.

Ethylene Production and Sensitivity

Climacteric fruit production rates of ethylene are high, up to 100 to 300 µL kg^{-1} h^{-1} at 20 ºC (68 ºF) (Brown et al. 1988). Ripening is accelerated by exposure to 100 µL L^{-1} for 24 h.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
10 ºC	48 to 190
15 ºC	54 to 281
20 ºC	40 to 460

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and

1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

The fruit are very susceptible to bruising. Preharvest russeting can be a problem.

Postharvest Pathology

As with cherimoya, anthracnose, *Phomopsis* rot, and *Rhizopus* have been recorded (Sanewski 1988).

Quarantine Issues

Atemoya fruit are a fruit fly host. Irradiation and heat are potential treatments.

Suitability as Fresh-Cut Product

Atemoya can be sold in pieces but only before becoming too soft.

References

Brown, B.I., L.S. Wong, A.P. George, and R.J. Nissen. 1988. Comparative studies on the postharvest physiology of fruit from different species of *Annona* (custard apple). J. Hort. Sci. 63:521-528.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K.

Paull, R.E. 1996. Postharvest atemoya splitting during ripening. Postharv. Biol. Technol. 8:329-334.

Sanewski, G.M. 1988. Growing Custard Apples. Information Series QI 87014, Queensland Department of Primary Industries, Brisbane, Queensland, Australia.

Avocado

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Scientific Name and Introduction

The avocado originated in Central America and southern Mexico. The Aztecs considered the avocado an aphrodisiac and called it “huacatl.” In Chile, Peru, and Ecuador, it is called “palta,” an Incan name. Spanish-speaking people also call it “aguacate,” “cura,” or “cupandra.” The avocado is known as “abogado” in Spain. Historically, the avocado has also been referred to as “alligator pear,” “vegetable butter,” “butter pear,” and “midshipman’s butter.”

The avocado is botanically classified into three races: (1) West Indian (WI), *Persea americana* Mill. var. *americana* (*P. gratissima* Gaertn.), tropical with large variably shaped fruit and lower oil content; (2) Mexican (MX), *P. americana* Mill. var. *drymifolia* Blake (*P. drymifolia* Schlecht. & Cham.), semitropical with smaller elongated, thin-skinned fruit and higher oil content; and (3) Guatemalan (G), *P. nubigena* var. *guatemalensis* L. Wms., subtropical with mostly round, thick-skinned fruit and intermediate oil content (Bergh and Lahav 1996). Many of the commercial cultivars are hybrids of these three races. There is great variability in fruit traits not only between races but between cultivars within a race. One of the most distinct differences between cultivars is the peel color when ripe. The peel of some cultivars changes from green to black or purple with increasing maturity or ripening.

Avocados are available year-round in the United States and are supplied by two major producing areas: California (90%) and Florida (10%). Fruit (mainly ‘Hass’) are also imported from (in approximate order by volume) Chile, Mexico, the Dominican Republic, New Zealand, Bahamas, and Jamaica.

There are many cultivars of avocados grown commercially in the United States, and they come in assorted sizes and shapes. The primary California cultivar is Hass, a G-MX hybrid that accounts for approximately 95% of the planted acreage. Other cultivars include ‘Bacon,’ ‘Fuerte,’ ‘Gwen,’ ‘Lamb Hass,’ ‘Pinkerton,’ ‘Reed,’ and ‘Zutano.’ With the exception of ‘Reed,’ which is believed to be entirely of the G race, the other cultivars are considered to be primarily G-MX hybrids. ‘Hass’ accounts for 80% of avocado consumption in the United States and is the main focus of research and development. The main Florida cultivars (West Indian and Guatemalan races and hybrids) are ‘Simmonds,’ ‘Nadir,’ ‘Booth 8,’ ‘Choquette,’ and ‘Lula.’

Quality Characteristics and Criteria

For avocado, the major quality criteria used during grading are size and skin color, as well as freedom from wounds, blemishes, insect damage (particularly from caterpillar and thrip scarring), spray residues (most commonly copper), and other contaminants on the skin. When ripe, the key issues are absence of disease (body rot and stem end rots), physiological disorders (flesh graying), and physical damage (bruising). Many of these quality factors depend on the cultivar, and consumer preference for size, shape, and color can vary from region to region.

While avocados from both Florida and California are high-quality fruit, there are significant differences in size, texture, and flavor. Florida avocados are usually at least twice as large as those from California and often sell at a lower price. The smaller California avocados have a desirable nutlike flavor and a richer, creamier texture than the less oily Florida fruit, which are sometimes marketed as "lite avocados." These differences are mainly due to the fact that different horticultural races of the avocado are produced in California and Florida.

Avocados are one of the few fruit that contain significant quantities of oil; sometimes more than 30% of fresh weight, depending on cultivar and maturity. Oil content is a key part of the sensory quality. Oil quality is very similar to that of olive oil, with approximately 75% monounsaturated, 15% saturated, and 10% polyunsaturated fatty acids (omega-6). However, there is variation with race, cultivar, growing region, and season. The high-monounsaturated, high-polyunsaturated, and low-saturated fatty acid content makes this a "healthy" oil in terms of effect on heart disease. In addition, avocado oil contains a range of other health-promoting compounds such as chlorophyll, carotenoids, α-tocopherol, and β-sitosterol. These health factors, along with the absence of cholesterol, should be emphasized with consumers since avocados are perceived by some as an unhealthy or "fat" fruit. Extraction of oil from reject avocados is carried out in some countries for use in cosmetic products and for culinary purposes.

Traditionally, fruit produced in the United States have been "clip" harvested (peduncle cut to leave a "button" at the top of the fruit). However other producing countries (Australia, Israel, Spain, and South Africa) are now "snap"-harvesting 'Hass' fruit. The ultimate success of snap harvesting depends on fruit maturity, growing conditions (rain), and cultivar (Arpaia and Hofshi 1998).

Horticultural Maturity Indices

The percentage of dry matter in avocado fruit is highly correlated to oil content and is the key maturity index used in California and worldwide (Lee et al. 1983). Minimum dry matter percentage ranges from 17 to 25%, depending on cultivar. In California, the minimum percentage of dry matter at harvest for the major cultivars are 'Bacon' (17.7%), 'Fuerte' (19.0%), 'Gwen' (24.2%), 'Hass' (20.8%), 'Pinkerton' (21.6%), 'Reed' (18.7%), and 'Zutano' (18.7%). In California, fruit are also released into the market at predetermined dates based on dry matter and size for each cultivar. For example, the size and release dates for 'Hass' are size 40 and greater on November 28; Size 48, December 12; Size 60, January 2; and Size 70 or smaller, January 16. Florida avocados have lower oil content (3 to 15%) and are generally harvested at a specific date and weight or size.

Avocados can be held on the tree for many months after they are physiologically mature because they do not ripen until they are harvested. However, time to ripen does decrease with increasing time on the tree. Freshly harvested avocados tend to have "green" skins, though 'Hass' fruit that are harvested late in the season may have some skin darkening at harvest. The peel of ripe 'Hass' and 'Lamb Hass' avocados should have a dark, purple-black or black skin, while green-skinned cultivars remain green when ripe. Avocados are ripe when the fruit yields slightly to light finger pressure. Pulp color, texture, and flavor when ripe are cultivar specific.

Grades, Sizes, and Packaging

California avocados are packed in single-layer 12.5 lb (5.67 kg) flats or trays, 2-layer 25 lb (11.34 kg) lugs, and 25 lb (11.34 kg) volume-fill boxes. RPCs (returnable plastic containers) are used increasingly. There is also increased usage of prepacked units such as polyethylene containers ("clam shells") or mesh bags. For Florida avocados, the common packages used are single-layer, 13 lb (6.12 kg) flats; two-layer, 27 lb (12.47 kg) lugs; 35 lb (15.88 kg) cartons; and 10 lb (4.54 kg) natural packs.

California avocados are graded as No. 1 or No. 2. Florida avocados are graded as U.S. No. 1, U.S. No. 2, and U.S. Combination. However, only some Florida varieties are graded, while the others are marketed as unclassified. In California, fruit are weight-sized into the following categories: 20 (18.75 to 22.0 oz, 532 to 624 g), 24 (15.75 to 18.75 oz, 447 to 532 g), 28 (13.75 to 15.75 oz, 390 to 447 g), 32 (11.75 to 14.0 oz, 333 to 397 g), 36 (10.5 to 12.5 oz, 298 to 354 g), 40 (9.50 to 11.50 oz, 269 to 326 g), 48 (7.50 to 9.50 oz, 213 to 269 g), 60 (6.25 to 7.50 oz, 177 to 213 g), 70 (4.75 to 6.25 oz, 135 to 177 g), and 84 (3.75 to 4.75 oz, 106 to 135 g) count for 25 lb packs, and half these values for flats (or single-layer trays). Florida fruit are packed by count. Regulations specify that the pack shall be at least fairly tight and that the weight of the smallest fruit in any container shall not be less than 75% that of the largest fruit in the same container. Commonly used sizes for Florida packages are 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, and 24 count.

Precooling Conditions

Ripening and associated softening of avocados can be delayed by cooling soon after harvest. This is critical where long storage periods are required or where field temperatures are above 25 °C (77 °F). Forced or passive air-cooling is generally carried out as rapidly after harvest as possible; within 24 to 48 h or sooner is recommended. Hydrocooling of 'Hass' is also used commercially. Recommendations as to the target temperature (prior to packing) vary between 5 and 15 °C (41 and 59 °F) and may be influenced by the emphasis on whether fruit should be graded with condensation or not.

Optimum Storage Conditions

Optimum storage conditions vary by cultivar, growing conditions, time in the season (maturity), and length of storage required. However, in general, unripe avocados should be stored at 5 to 12 ºC (41 to 54 ºF) with RH of 85 to 95%. Optimum storage temperatures for 'Hass' are 5 to 7 °C (41 to 45 °F) for early-season fruit and 4 to 5.5 °C (40 to 42 °F) for late-season fruit. After 3 to 4 weeks storage, 'Hass' fruit quality is reduced, and storing fruit for longer than 6 weeks remains a challenge.

Increased physiological disorders—for example, chilling disorders and uneven ripening—and rots result from suboptimal storage temperatures. Therefore, it is important to maintain the appropriate temperature for unripe fruit and stack containers to allow for proper air circulation and temperature control.

Controlled Atmosphere (CA) Considerations

CA storage is commonly used for transporting fruit to distant markets in refrigerated shipping containers. The atmosphere used and technology for controlling the atmosphere vary between shipping companies. Generally, O_2 levels of 2 to 5% (or possibly as high as 10%) + 3 to 10% CO_2 are used. The primary benefit of low O_2 is that of delayed softening and reduction of respiration and ethylene production from standard storage temperatures. Elevated CO_2 may delay softening and reduce sensitivity to external chilling injury and allow lower storage temperatures (Faubion et al. 1992). Low-O_2 injury may appear as irregular brown to dark brown patches on the skin and may additionally cause diffuse browning of flesh beneath affected skin. CO_2 atmospheres above 10% can be detrimental by leading to discoloration of the skin and development of off flavor, particularly when the O_2 concentration is less than 1%. Reducing ethylene levels to below 1 $\mu L\ L^{-1}$ using ethylene scrubbers during CA storage may provide added benefits for retarding ripening and decrease development of chilling injury (Faubion et al. 1992).

Alternative Technologies for Long-Term Storage

1-MCP Treatments. Use of 1-MCP (1-methylcyclopropene) is in the experimental stage and should be used with caution. Application of 1-MCP to avocados delays ripening and thus reduces internal chilling injury (flesh graying, vascular browning), which is associated with ripening during storage if storage times are long or temperature management is poor (Pesis et al. 2002). The optimum treatment conditions are likely to be in the area of 50 to 100 $nL\ L^{-1}$

(ppb) at about 6 °C (43 °F) for 18 to 24 h. For 'Hass,' 1-MCP treatments will have benefit if fruit are stored for longer than 4 weeks. However, for other cultivars that exhibit higher levels of internal chilling injury at even short storage times, 1-MCP may be of more benefit. Care should be taken because applying higher concentrations may result in excessive delays to softening and ripening, which in turn are likely to increase disease incidence. 1-MCP does not reduce external chilling injury (skin blackening) of 'Hass' avocados.

Step-Down Temperatures. The other key technology for maintaining fruit quality (particularly preventing internal chilling injury), proven over many years by the South African industry, is the use of "step-down" temperatures (Vorster et al. 1987). Temperatures are typically decreased 1 to 2 °C each week during shipping, with the final temperature not to drop below 3.5 °C (38 °F), and with progressively lower initial temperatures as fruit maturity increases. These temperature regimes have been developed and refined over many years and have resulted in a protocol for each cultivar for differing times in the season and growing region.

Retail Outlet Display Considerations

Avocados are best ripened at 15 to 20 ºC (59 to 68 ºF) (Hopkirk et al. 1994). The ripening rate at temperatures below 15 ºC (59 ºF) is relatively slow, and ripening at temperatures above 25 ºC (77 ºF) may result in increased decay, uneven ripening of the flesh, and off flavors. As for bananas, ethylene treatment can be used to "precondition" or "preripen" fruit. Avocados are very susceptible to bruising during softening (Arpaia et al. 1987) and thus should be handled carefully during transport and display. Any means of minimizing "squeezing" by customers will also improve quality. Since quality can decrease rapidly during softening, it is best to check avocado ripeness every day and to display or use the ripest fruit first. If possible, ripe or near-ripe fruit should be held at lower temperatures (1 to 6 °C, 34 to 43 °F) (Young and Kosiyachinda 1976) to reduce the proportion of fruit that become overripe, with concomitant increase in rots and other disorders. Avocados should not receive a water sprinkle or top ice.

Chilling Sensitivity

Avocados exhibit two forms of chilling injury, internal and external, which are generally induced by quite different storage conditions. Internal chilling injury manifests as a grayish-brown discoloration of the flesh, particularly at the base of the fruit around the seed. This can be associated with vascular browning, which starts at the base of the fruit (rather than at the stem end, which is often associated with stem end rots). In 'Hass,' internal chilling injury tends to occur after about 4 or more weeks in storage at about 6 °C (43 °F), but will be influenced by maturity and growing conditions. Cultivars differ in their susceptibility to this disorder, with some being very sensitive. Calcium levels are a possible explanation for differences in internal chilling injury (Chaplin and Scott 1980). Another low-temperature disorder, "pulp spot," may be observed in 'Fuerte' fruit in which small dark spots can be observed in the flesh. Internal chilling injury is generally associated with softening of fruit during storage and thus is increased by the presence of ethylene (Chaplin et al. 1983). Internal chilling injury is the key limiting factor for long-term storage of avocados.

External chilling injury occurs as irregular patches of blackening on the skin (similar to apple scald) that can be observed during storage but that generally increase slightly in intensity after removal from cold storage. The damage is first seen in inner cell layers of the exocarp and then the outer layers of the skin (Woolf 1997). In cultivars that naturally darken during ripening, such as 'Hass,' the damage will be less apparent after ripening but may be distinguished as brown, corky skin tissue in ripe fruit. External chilling injury is generally induced by temperatures below 3 °C (38 °F). However, fruit become less sensitive with increasing maturity, and ripe fruit are less affected. Fruit exposed to low temperatures may be of poor internal quality when ripe, with a high incidence of rots and softening disorders (Woolf et al. 1995), but will have lower incidence of internal chilling injury (graying). For 'Hass' fruit stored for long periods at standard storage temperatures (for example, 6 to 7 weeks at about 6 °C [43 °F]), a form of external chilling injury is expressed that is of a very similar appearance to that observed at low temperatures. This form of external chilling injury will tend to be seen in fruit that are quite soft (nearly ripe) at the point of removal from storage.

Ethylene Production and Sensitivity

Rates of ethylene production are generally low for unripe avocados, less than 0.1 µL kg^{-1} h^{-1} at 20 ºC (68 ºF), but increase rapidly after harvest up to levels greater than 100 µL kg^{-1} h^{-1} at 20 ºC (68 ºF) when fully ripe. Therefore, ripe avocados should not be stored with fruits and vegetables that are sensitive to ethylene damage. Unripe avocados are very sensitive to ethylene. They should not be stored near ripe fruit or other fresh produce that produces more than trace ethylene. Ethylene exposure during storage accelerates ripening and softening and can increase incidence and severity of internal chilling injury and decay.

Ethylene Treatment ("Preconditioning" or "Preripening")

There is an increasing move at the retail level toward "ripe for tonight" programs that generally result in significant increases in sales. This is achieved by treating avocados with 10 to 100 µL L^{-1} ethylene at 17 to 20 ºC (63 to 68 ºF) for approximately 48 to 72 h (early season), 24 to 48 h (mid season), or 12 to 24 h (late season). This significantly reduces both the time to ripen (to 3 to 6 days, depending on cultivar and maturity) and fruit-to-fruit variability in ripening. If fruit are stored prior to ethylene treatment, the duration of treatment required to achieve maximum rate of ripening is reduced. For 'Hass,' after 3 to 4 weeks of storage, there may be relatively little benefit to ethylene treatment (particularly for later-season fruit), since the time to ripen decreases during storage. Because heat production of avocados is much greater than that of many other fruit crops, careful attention should be paid to air flow and temperature management during ethylene treatment and subsequent ripening. Palletized fruit may reach temperatures of more than 30 °C (86 °F), with negative effects on ripe fruit quality. For this reason, ethylene treatment of palletized fruit should be carried out under forced-air conditions. During ethylene treatment, CO_2 levels should be maintained at less than 1 to 2% by either continual venting of the atmosphere or full venting and ethylene reinjection if "shot" systems are used. Following ripening, fruit should be precooled to 5 °C (41 °F).

Respiration Rates

Respiration rate of avocados is relatively high compared with many other fruit crops.

Temperature	mg CO_2 kg^{-1} h^{-1}
5 ºC	20 to 50
10 ºC	50 to 160
20 ºC	80 to 300

Data from Kader and Arpaia (2001).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

There is a range of physiological disorders of avocados (Arpaia et al. 2009), and most of these occur following long storage periods. The key disorders are flesh graying, vascular browning, and pulp spot, which are all symptoms of internal chilling injury (see *Chilling Sensitivity*). If fruit are stored for excessively long periods, the flesh may also fail to ripen evenly and become increasingly susceptible to pathogens. The timing of expression of internal chilling injury and its severity depend on temperature management, initial ripeness, cultivar, production area, and fruit maturity. External chilling injury may occur if fruit are stored at low temperatures (0 to 3 °C [32 to 38 °F]) or for long periods (more than 6 weeks) at standard storage temperatures.

Postharvest Pathology

Rots of avocados are divided into two categories on the basis of their location (Snowdon 1990). Stem end rots enter the fruit at the stem, or peduncle end of the fruit, and move down the fruit resulting in discolored flesh, often with associated browning of the vascular strands (Johnson and Kotze 1994). Body rots invade through the skin and are generally manifested as circular brown to black spots that may be covered with spore masses in the later stages of infection. Decay penetrates through to the flesh resulting in discrete areas of discolored flesh. In cultivars that darken when ripe (‘Hass’), rots may be less obvious externally. Rots are rarely observed at harvest or during storage but can increase rapidly with fruit softening. Where infection pressure is high and physical damage to the skin occurs prior to storage, small, soft-black circles of infection (“measles”) can occur during storage. These generally spread rapidly outwards after removal from storage.

The causal organisms can vary with growing environment and country. The following pathogens (in order of frequency) have been isolated from decayed California avocados: *Colletotrichum, Dothiorella, Alternaria,* and *Phomopsis* spp. (Smilanick and Margosan 2001). Differences in the pathogens responsible for decay exist among countries; for example, New Zealand versus Australia (Everett 1996, Arpaia et al. 2009).

Preharvest control methods for postharvest fungal decay include good orchard sanitation (removal of mummified fruit and dead wood) and effective preharvest fungicide application, such as copper, which is widely used in some countries (including the United States, in Florida) where humid growing conditions prevail. Harvesting should not be carried out in the rain or when fruit are wet, and careful handling to minimize skin damage helps reduce rots. Snap picking of fruit can reduce stem end rot incidence in dry periods, but it can result in increased rots in humid growing environments or when fruit are harvested in wet conditions.

Perhaps the most important area for reducing rots is that of maintaining good ripe-fruit quality by optimizing temperatures during handling, storage, transport, and ripening. It is also critical not to store fruit for long periods. Ripening fruit at lower temperatures—for example, 15 to 20 °C (59 to 68 °F)—can lead to significant reduction in rots compared with higher temperatures (Hopkirk et al. 1994). Storing ‘Hass’ fruit for 1 to 3 weeks can also reduce rot incidence (as compared with nonstored fruit), as can ethylene treatments, which both synchronize and hasten ripening. Postharvest fungicides (prochloraz, benlate [benomyl], and thiabendazole) are used in some countries, but these are not registered for use in the United States (Darvas et al. 1990). Research on biological control agents is being carried out in South Africa, New Zealand, and Australia.

Quarantine Issues

Issues relating to quarantine will vary according to the marketplace and country of origin, and guidance should be sought from the Department of Agriculture. If avocados are grown in fruit-fly-infested areas, significant quarantine issues will arise. Methyl bromide treatment is an APHIS-approved treatment for Mediterranean fruit fly, but it results in a significant reduction in fruit quality. Because avocados do not tolerate standard high-temperature disinfestation treatments, (for example, fruit core temperatures of 47 °C [117 °F] for 20 min), low-temperature disinfestation is the most viable approach. Tolerance to temperatures that can be used for low-temperature disinfestation can be imparted by pretreatments at 38 °C (100 °F) (Sanxter et al. 1994, Woolf et al. 1995), for example, or by low-temperature conditioning (Woolf et al. 2003). However, the only commercial disinfestation treatment in use is for Queensland fruit fly in ‘Hass’ avocados: 6 to 8 °C (43 to 47 °F) for 3 to 5 days followed by 16 days at temperatures <1 °C (34 °F) (Hofman et al.

2003). However, this low-temperature disinfesting treatment may not be effective for all fruit fly species, since cold tolerance varies.

Suitability as a Fresh-Cut Product

Avocados are not currently marketed as fresh-cut products, but they are marketed as chunks, paste, and guacamole dips.

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References

Arpaia, M.L., and R. Hofshi. 1998. Preliminary report on the feasibility of "snap" harvesting 'Hass' avocados. Subtrop. Fruit News 6(2):7-9.

Arpaia, M.L., F.G. Mitchell, P.M. Katz, and G. Mayer. 1987. Susceptibility of avocado fruit to mechanical damage as influenced by variety, maturity, and stage of ripeness. Proceedings of World Avocado Congress, May 1987, Pretoria, Republic of South Africa. South African Avocado Growers' Association Yearbook 10:149-151.

Bergh, B.O., and E. Lahav. 1996. Avocados. *In* J. Janick and J.N. Moore, eds., Fruit Breeding, vol. I, Tree and Tropical Fruits, pp. 113-166. John Wiley & Sons, New York, NY.

Chaplin, G.R., and K.J. Scott. 1980. Association of calcium in chilling injury susceptibility in stored avocados. HortScience 15:514-515.

Chaplin, G.R., R.B.H. Wills, and D. Graham. 1983. Induction of chilling injury in stored avocados with exogenous ethylene. HortScience 18:952-953.

Darvas, J.M., J.M. Kotze, and F.C. Wehner. 1990. Effect of treatment after picking on the incidence of postharvest diseases of avocado. Phytophylactica 22:93-96.

Everett, K.R. 1996. Postharvest diseases of avocados. *At* http://www.hortnet.co.nz/publications/science/everavo1.htm.

Faubion, D.F., F.G. Mitchell, G. Mayer, and M.L. Arpaia. 1992. Response of 'Hass' avocado fruit to postharvest storage in controlled atmosphere conditions. *In* C.J. Lovatt, and P. Holthe, eds., Proceedings of 2nd World Avocado Congress, Orange, CA, April 1991, pp. 467-472. University of California, Riverside, CA.

Hofman, P.J., B.A. Stubbings, M.F. Adkins, et al. 2003. Low temperature conditioning treatments before cold disinfestation improve 'Hass' avocado fruit quality. Postharv. Biol. Technol. 28:123-133.

Hopkirk, G., A. White, D.J. Beever, and S.K. Forbes. 1994. Influence of postharvest temperatures and the rate of fruit ripening on internal postharvest rots and disorders of New Zealand 'Hass' avocado fruit. New Zealand J. Crop Hortic. Sci. 22:305-311.

Johnson, G.L., and J.M. Kotze. 1994. Stem-end rot. *In* R.C. Ploetz et al., eds., Compendium of Tropical Fruit Diseases, pp. 81-83. APS Press, St Paul, MN.

Kader, A.A., and M.L. Arpaia. 2001. Avocado. Recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

Kosiyachinda, S., and R.E. Young. 1976. Chilling sensitivity of avocado fruit at different stages of the respiratory climacteric. J. Amer. Soc. Hort. Sci. 101:665.

Lee, S.K., R.E. Young, P.M. Schiffman, and C.W. Coggins. 1983. Maturity studies of avocado fruit based on picking dates and dry weight. J. Amer. Soc. Hort. Sci. 108:390-394.

Pesis, E., M. Ackerman, R. Ben-Arie, et al. 2002. Ethylene involvement in chilling injury symptoms of avocado during cold storage. Postharv. Biol. Technol. 24:171-181.

Sanxter, S.S., K.A. Nishijima, and H. Chan. 1994. Heat-treating ‘Sharwil’ avocado for cold tolerance in cold treatments. HortScience 29:1166-1168.

Smilanick, J.L., and D.A. Margosan. 2001. Management of postharvest decay of avocado fruit. *In* California Avocado Research Symposium, Oct. 2001, pp. 115-119. *At* http://www.avocadosource.com/arac/symposium_2001/smilan.pdf.

Snowdon, A.L. 1990. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 1, General Introduction and Fruits. CRC Press, Boca Raton, FL.

Vorster, L.L., J.C. Toerien, and J.J. Bezuidenhout. 1987. A storage temperature regime for South African export avocados. South African Avocado Growers’ Association Yearbook 10:146-148.

Wang, C.Y. 1993. Approaches to reduce chilling injury of fruits and vegetables. Hort. Rev. 15:63-95.

M.L. Arpaia, P. Hofman, A. White, and A. Woolf. 2009. The International Avocado Quality Manual, 70 pp., University of California, Davis, CA.

Woolf, A.B. 1997. Reduction of chilling injury in stored ‘Hass’ avocado fruit by 38 °C water treatments. HortScience. 32:1247-1251.

Woolf, A.B., C.B. Watkins, J.H. Bowen, et al. 1995. Reducing external chilling injury in stored ‘Hass’ avocados with dry heat treatments. J. Amer. Soc. Hort. Sci. 120:1050-1056.

Woolf, A.B., K.A. Cox, A. White, and I.B. Ferguson. 2003. Low temperature conditioning treatments reduce external chilling injury of ‘Hass’ avocados. Postharv. Biol. Technol. 13:113-122.

Young, R.E., and S. Kosiyachinda. 1976. Low temperature storage of ripe avocado fruit. *In* California Avocado Society Yearbook, pp. 73-76. Temecula, CA.

Banana and Plantain

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Scientific Name and Introduction

Most cultivars of edible bananas and plantains are derived from two members of the family Musaceae: *Musa acuminate* and *Musa balbisiana* (Simmonds and Shepherd 1955). Before the 1940s, the cultivar 'Gros Michel' dominated the international banana trade until it succumbed to *Fusarium* wilt (Panama disease). Since the 1940s, the trade has adopted cultivars of the Cavendish subgroup. Bananas are eaten mainly raw as a dessert fruit because they are sweet when ripe. Plantains, also referred to as "cooking bananas," are much starchier and can be eaten either ripe or unripe. The edible cultivars of bananas and plantains are seedless. The two obvious tissues that constitute the fruit are the pulp and the peel. The peel is the ovary wall. The pulp originates from cell division of the innermost layers of the pericarp. The growth of the peel begins to slow down as the fruit matures but the growth of the pulp continues. Consequently, peel splitting often occurs in very mature green fruit (Turner 1997).

Quality Characteristics and Criteria

A premium quality banana is very clean (free from defects such as scars, physical damage, insect injury, and latex staining), free from decay, has an adequate finger length and diameter, does not have excess curvature, and, upon ripening, has the desired uniform bright-yellow color and sensory attributes in flavor (sweetness and acidity) and aroma. Attributes are defined by consumer preference.

Horticultural Maturity Indices

Commercially, bananas and plantains must be harvested while mature green and transported to destination markets where they are ripened under controlled conditions (bananas) and controlled or natural conditions (plantains). Fruits ripened on the plant often split and have poor texture. Harvest time represents a compromise between leaving the fruit on the plant long enough to maximize yield and harvesting it soon enough so that sufficient green life remains to market fruit with acceptable quality. The stage of maturity for harvesting the fruit depends on the market for which it is intended and is determined in terms of the marketable life required. Plantains tend to mature more prematurely than bananas when harvested at the same age. One very useful criterion for harvesting fruit that is used commercially is age of the bunch after emergence from the pseudostem. (Emergence can be defined as the day on which the first complete hand of fruit is visible.) Because bananas are growing rapidly when harvested, fruit size (finger length and diameter) and finger fullness (angularity) are suitable measures of harvest maturity. At a given age, the maturity of hands in a stem varies, those hands at the proximal end of the stem being more mature than those at the distal end. An estimate of maturity of the entire stem is then assessed using the second hand from the proximal end. It is usual to measure length and diameter (caliper grade or calibration) of the middle finger on outer whorls of the second hand on the stem before running fruit through the packing plant processes.

Grades, Sizes, and Packaging

Minimum acceptable size (length and diameter) grade standards for export markets vary depending on banana and plantain cultivar and market specifications. Hands, clusters, or single fingers not meeting these fresh market grades are used for processing products or discarded. Bananas are packed in corrugated fiberboard boxes as whole hands, clusters, or individual fingers holding an average weight for premium fruit between 13 and 18 kg (28 to 40 lb), depending on market preference. Plantains are packed as individual fingers in 18 kg boxes. Most exporters use polyethylene film liners and paper pads to reduce moisture loss and protect fruit from physical damage during handling and transport.

Precooling Conditions

Precooling of bananas or plantains is not generally done. Adequate cooling is not initiated until fruit are loaded into containers or cargo holds aboard ships.

Optimum Storage Conditions

Optimum temperatures for storage and holding of green bananas are 13 to 14 ºC (56 to 58 ºF) (Thompson and Burden 1995). Because marketing quality standards are more relaxed for plantains, and plantains are more prone to premature ripening during transit and storage, it is recommended that green plantains be held between 9 and 12 ºC (48 to 53 ºF). Plantains grown during the warmer months tend to attain physiological maturity faster than fruit grown during the winter months; thus green-life potential varies during the year. Optimum RH for holding and transporting fruit is 90 to 95%. Holding of ripe fruit should be kept to a minimum.

Controlled Atmosphere (CA) Considerations

Bananas and plantains respond well to CA. CA is used commercially during ocean transport of green bananas. Modified atmosphere packaging using polyethylene bags (banavac) is used for both bananas and plantains, but plantain are physiologically more active than bananas and have higher respiration rates and so could exhaust O_2 more rapidly than bananas. Optimum gas levels for most cultivars range between 2 to 5% O_2 and 2 to 5% CO_2 (Bishop 1990, Kader 1992, Kader 1994, Kader 1997). Main benefits of controlled atmosphere include delaying of ripening, reduction of crown rot incidence, and a much fresher condition (latex flowing through the vascular tissues) on arrival at destination. Shelf-life can potentially be extended twofold to threefold by optimum CA. O_2 levels below 1 to 1.5% may cause grayish or brown peel discoloration, failure to ripen properly, and off flavor (Kader 1992, 1994, 1997). CO_2 levels above 6 to 8% may cause pulp to soften while the peel is still green and may confer undesirable texture and flavor (Wei and Thompson 1993, Kader 1994, Kader 1997). Ripe fruit can tolerate higher levels of CO_2.

The beneficial and detrimental effects of reduced O_2 and/or elevated CO_2 depend on temperature and time of exposure. Removal of ethylene gas can have an additional benefit on extending green-life of bananas and plantains under both ambient and modified atmosphere conditions (Scott et al. 1970, Liu 1976, Scott 1977, Turner 1997). CO_2 inhibits the effect of ethylene on ripening, and higher levels of O_2 than those under CA are necessary for adequate ripening. Thus, bananas held under CA should be ventilated with fresh air for at least 18 to 24 h before ripening (gassing with ethylene) is initiated. An underpeel discoloration resembling chilling injury has been observed on green bananas when transported long distances under CA conditions at temperatures below 14 ºC (58 ºF). This disorder has also been associated with high temperatures of 33 to 35 ºC (91 to 95 ºF) in the field (Stover and Simmonds 1987).

Retail Outlet Display Considerations

Fruit should be displayed at retail in nonrefrigerated areas in the produce section. Existing refrigerated shelf space in supermarkets normally is below the minimum safe temperature for bananas and plantains and chilling injury can still occur in ripe fruit. Displaying surfaces should be cushioned to avoid physical damage to the fruit.

Chilling Sensitivity

Chilling injury is an important disorder of bananas and plantains. Both green and ripe fruit are susceptible, with green fruit being slightly more sensitive than ripe fruit. Chilling injury results from exposing fruit to temperatures below about 13 ºC (56 ºF) for a few hours to a few days, depending on cultivar, maturity, condition of the fruit, temperature, and duration of exposure (Stover 1972, John and Marchal 1995, Turner 1997). Chilling injury is mainly a peel disorder. Symptoms include subepidermal discoloration visible as brown or black streaks in a longitudinal cut, a dull or grayish (smokey) cast on ripe fruit, and failure to ripen. In severe cases, the peel turns dark brown or black, and even the flesh can turn brown and develop an off taste (John and Marchal 1995, Turner 1997). Chilled fruit are more sensitive to mechanical injury. Ripe fruit, if chilled, turn dull brown when later exposed to higher temperatures and are very susceptible to handling marks: The slightest pressure can cause discoloration. Inflicted chill in green or ripe fruit may not become apparent until 18 to 24 h after actual damage has occurred.

Ethylene Production and Sensitivity

Bananas and plantains are sensitive to physiological levels of ethylene as low as 0.3 to 0.5 µL L^{-1} if the O_2 and CO_2 levels are similar to those found in outside fresh air (Peacock 1972). The three main factors affecting response to external ethylene are fruit maturity, time from harvest when ethylene exposure began, and length of exposure to ethylene.

Ethylene production rates:

Temperature	µL C_2H_4 kg^{-1} h^{-1}
13 ºC	0.04 to 2.0
15 ºC	0.15 to 5.0
18 ºC	0.20 to 8.0
20 ºC	0.30 to 10.0

Lower values in the range are for mature-green fruit, and higher values are for ripening fruit. Data modified from Kader (1998).

Controlled ripening. Mature bananas left to ripen naturally will eventually soften, but the change in color will not be uniform and the peel will be dull, pale yellow, and unattractive. In order for the fruit to attain a bright yellow peel color, a firm pulp texture, and good flavor, bananas are ripened by releasing ethylene into a sealed chamber or room and at controlled temperature and RH. Plantains are being ripened by this controlled method in most markets, but some markets still rely on natural ripening. Immediately after harvest, bananas do not respond to ethylene treatment or, in the best scenario, will initiate ripening but will never attain the characteristic bright yellow color. One main reason for controlled ripening is to provide retailers and wholesalers with fruit at a stage of ripeness desired by consumers.

Generally, very low concentrations of ethylene are sufficient to ripen the fruit—10 to 50 µL L^{-1} (Thompson and Seymour 1982). In commercial practice, however, 1,000 µL L^{-1} is commonly used to ensure uniform ripening. This is partly because many ripening rooms are not fully gas-tight and the concentration may be rapidly reduced through leakage. Most commercial cultivars of bananas and plantains require exposure to ethylene for 24 to 48 h at 14 to 18 ºC (58 to 64 ºF) (Thompson and Burden 1995, Robinson 1996). However, temperatures of up to 20 ºC (68 ºF) are sometimes necessary (Thompson and Burden 1995). Optimum RH levels during ripening are 90 to 95%. (After coloring is underway, RH should be reduced to 85% to prevent peel splitting.) High RH requirements for proper ripening can be attained when the fruit is being packed in partially sealed polyethylene liners. Exposure of ripe bananas or plantains to temperatures higher than those in the ripening range can hasten softening and decay, weaken the neck, and cause splitting of the peel and poor color development.

The color of the peel is used as an indicator of ripening. A scale of 1 to 7 is convenient: 1 is dark green, 2 is light green, 3 is more green than yellow, 4 is more yellow than green, 5 is yellow with green tips, 6 is fully yellow, and 7 is flecking (Kader 1992). Room ventilation after gassing with ethylene is essential to keep CO_2 below

1% and avoid its effects on delaying ethylene action. Use of a forced-air system (pressurized) in ripening rooms assures more uniform cooling or warming of the fruit as needed and more uniform ethylene concentrations throughout the ripening. When ripening is done in nonpressurized conventional rooms, open stacking of boxes is essential to allow adequate air circulation for uniform ripening. Many stacking patterns are used and the best pattern to be used depends on pallet sizes and ripening facilities. Because heat rises, the amount of box-op area exposed is most important for preventing heat buildup in the stack and controlling pulp temperature during ripening. Bananas are usually ripened to color stage 3 to 4 before delivery to distribution centers, retailers, or wholesalers.

Within certain limits, the period required for ripening bananas can be shortened or extended to meet trade requirements by adjusting the temperature. Under average conditions, depending on initial temperatures chosen and condition of the fruit, the ripening cycle can be as short as 4 days (above 18 ºC) or may be extended to 8 to 10 days (at 14 ºC). If initial ripening temperatures are too high (above 25 ºC), the pulp will soften but the peel will remain green (a condition described as "cooked" or "boiled" fruit) (Robinson 1996, Turner 1997). Uneven ripening can be caused by low temperatures and insufficient ethylene. Ripening rates and characteristics of the fruit vary to some extent between lots depending on cultivar, country of origin, weather conditions during the growing of the fruit, temperatures during handling and transit, and maturity of the fruit. Hard-green fruit (less full) will take longer to ripen than more advanced and full fruit.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
13 ºC	20 to 80
15 ºC	26 to 140
18 ºC	32 to 200
20 ºC	40 to 280

Data modified from Kader (1998).

The lower value of the range is for mature-green fruit, and the higher value is for ripening fruit. To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

A condition known as "maturity bronzing" or "maturity stain" has been observed in Australia and Central America at certain times during the year, 20 to 30 days before harvest (Stover and Simmonds 1987). The fruit is unacceptable for market, although eating quality is unaffected. This disorder has been associated with water deficits at bunch emergence during rapid fruit growth under very humid and hot conditions (Daniells et al. 1987, Williams et al. 1989, 1990). If bananas and plantains are exposed to temperatures above 30 to 35 ºC, ripening can be irreversibly inhibited (high-temperature injury).

Postharvest Pathology

The main postharvest diseases of bananas and plantains are crown rot—a disease complex caused by several fungi (*Colletotrichum musae, Fusarium semitectum, Fusarium pallidoroseum, Lasiodiplodia theobromae, Botryodiplodia theobroame, Ceratocystis paradoxa, Verticillium* sp., *Acremonium* sp., and *Curvularia* sp.)—and anthracnose *(Colletotrichum musae)* (Stover 1972, Wardlaw 1972, Stover and Simmonds 1987, Snowdon 1990, Jeger et al. 1995). Anthracnose is a latent infection that occurs in the plantation. Though it can appear on green fruit, it is more apparent in ripening fruit as numerous small, dark, circular spots. Crown-rot organisms normally enter after harvest, usually as a result of mechanical injury to the fruit.

Other diseases that from time to time become important locally include stem-end rot (*Lasiodiplodia theobromae / Thielaviopsis paradoxa*), in which the invaded flesh becomes brown, soft, and water-soaked, and cigar-end rot (*Verticillium theobromae / Trachysphaera fructigena*), in which the rotted tip of the finger is dry and appears similar to the ash of a cigar (Stover 1972, Wardlaw 1972, Stover and Simmonds 1987, Snowdon 1990, Jeger et al. 1995). Sigatoka disease of bananas is caused by *Mycosphaerella* sp. and has been reported in most banana/plantain-producing countries (Snowdon 1990). The potential of this fungal disease is such that a flourishing banana industry can be destroyed within a few years. Fruit symptoms include premature ripening, buff-colored pulp, and increased susceptibility to chilling injury. Preventive and control measures to reduce decay incidence begin with strict sanitation in plantation and packing plant, postharvest treatment with systemic fungicides, minimizing mechanical damage during handling, prompt cooling of fruit to lowest safe temperature, and expediting transport to final destination.

Quarantine Issues

There are no quarantine issues.

Suitability as Fresh-Cut Product

Bananas and plantains are not good candidates for fresh-cut processing because of their very high oxidation and browning potential (John and Marchal 1995).

Special Considerations

Mechanical damage in bananas and plantains takes several forms that vary in importance depending on the perceptions of consumers. Banana peel is very sensitive to mechanical damage. Export markets for bananas require a blemish-free fruit, though requirements are a bit more relaxed for plantains. Great care during handling is needed at all times. Bruising of the pulp is undesirable and cannot always be detected from damage to the peel (Akkaravessapong 1986). RH levels below 85 to 90% accentuate symptoms of mechanical damage.

Acknowledgments

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References

Akkaravessapong, P. 1986. The ripening of bananas increases their susceptibility to mechanical damage. M.Sc. (Agric) Prelim. Report, University of Western Australia, Perth, Australia. Unpublished report.

Bishop, D. 1990. Controlled atmosphere storage. *In* C.J.V. Dellino, ed., Cold and Chilled Storage Technology, pp. 66-98. Blackie, London, U.K.

Daniells, J.W., B.J. Watson, P.J. Farrell, and J.C. Mulder. 1987. Soil water stress at bunch emergence increases maturity bronzing of banana fruit. Queen. J. Agric. An. Sci. 44:97-100.

Jeger, M.J., S. Eden-Green, J.M. Thresh, et al. 1995. Banana diseases. *In* S. Gowen, ed., Bananas and Plantains, pp. 317-381. Chapman and Hall, London, U.K.

John, P., and J. Marchal. 1995. Ripening and biochemistry of the fruit. *In* S. Gowen, ed., Bananas and Plantains, pp. 434-467. Chapman and Hall, London, U.K.

Kader, A.A., ed. 1992. Postharvest Technology of Horticultural Crops. Pub. no. 3311, University of California, Division of Agriculture and Natural Resources, Davis, CA.

Kader, A.A. 1994. Modified and controlled atmosphere storage of tropical fruits. *In* B.R. Champ, E. Highley, and G.I. Johnson, eds., Postharvest Handling of Tropical Fruits. International Conference on Postharvest Handling of Tropical Fruits, Chiang Mai, Thailand, July 1993, pp. 239-249. ACIAR Proceedings no. 50, ACIAR, Canberra, Australia.

Kader, A.A. 1997. A summary of CA recommendations for fruits other than apples and pears. *In* A.A. Kader, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, CA, July 13-18, 1997, vol. 32, pp. 1-34. University of California, Davis, CA.

Kader, A.A. 1998. Bananas. *In* Fresh Produce Facts. *At* http://postharvest.ucdavis.edu/produce_information.

Liu, F.W. 1976. Banana response to low concentrations of ethylene. J. Amer. Soc. Hort. Sci. 101:222-224.

Peacock, B.C. 1972. Role of ethylene in the initiation of fruit ripening. Queensland J. Agric. Animal Sci. 29:137-145.

Robinson, J.C. 1996. Bananas and Plantains. CAB Intl., Wallingford, U.K.

Scott, K.J., W.B. McGlasson, and E.A. Roberts. 1970. Potassium permanganate as an ethylene absorbent in polyethylene bags to delay ripening of bananas during storage. Austr. J. Exp. Agric. Animal Husb. 10:237-240.

Scott, K.J. 1977. Some Australian contributions on postharvest physiology and pathology of the banana fruit. Tech. Bull. 38, ASPAC Food and Fertilizer Technology Center,Taipei, Taiwan.

Simmonds, N.W., and K. Shepherd. 1955. The taxonomy and origins of the cultivated bananas. J. Linnean Soc. (Botany) 55:302-312.

Snowdon, A.L. 1990. Postharvest Disease and Disorders of Fruits and Vegetables, vol. 1, General Introduction and Fruits. CRC Press, Boca Raton, FL.

Sommer, N.F., and M.L. Arpaia. 1992. Postharvest handling systems: tropical fruits. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, 2nd ed., pp. 241-245. DANR Pub no. 3311, University of California, Davis, CA.

Stover, R.H. 1972. Banana, Plantain, and Abaca Diseases. Commonwealth Agricultural Bureaux, Slough, U.K.

Stover, R.H., and N.W. Simmonds. 1987. Bananas. Longman Scientific and Technical, Essex, U.K.

Thompson, A.K., and G.B. Seymour. 1982. Comparative effects of acethylene and ethylene gas on initiation of banana ripening. Ann. Appl. Biol. 101:407-410.

Thompson, A.K., and O.J. Burden. 1995. Harvesting and fruit care. *In* S. Gowen, ed., Bananas and Plantains, pp. 403-433. Chapman and Hall, London, U.K.

Turner, D.W. 1997. Bananas and plantains. *In* S.K. Mitra, ed., Postharvest Physiology and Storage of Tropical and Subtropical Fruits, pp. 47-83. CAB Intl., Wallingford, U.K.

Wardlaw, C.W. 1972. Banana Diseases Including Plantain and Abaca. Longman, London, U.K.

Wei, Y., and A.K. Thompson. 1993. Modified atmosphere packaging of diploid bananas (*Musa* AA). *In* J. de Baerdemaeker, B. McKenna, M. Janssens, A. Thompson, F. Artes Calero, E. Hohn, and Z. Somogyi, eds., Proceedings of the COST-94 Workshop on Postharvest Treatment of Fruit and Vegetables: Systems and Operations for Postharvest Quality, September 14-15, 1993, Leuven, Belgium, pp. 235-246. Commission of the European Communities, Leuven, Belgium.

Williams, M.H., M. Vesk, and M.G. Mullins. 1989. Characteristics of the surface of banana peel in cultivars susceptible and resistant to maturity bronzing. Can. J. Bot. 67:2154-2160.

Williams, M.H., M. Vesk, and M.G. Mullins. 1990. Development of the banana fruit and occurrence of the maturity bronzing disorder. Ann. Bot. 65:9-19.

Bean

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Scientific Name and Introduction

Fresh snap or common beans (string beans, yellow wax beans, green beans) (*Phaseolus vulgaris* L.), runner or flat beans (*P. coccineus* L.), and long beans *(Vigna sesquipedalis)* are members of the Fabaceae (Leguminosae) family. Both the fleshy pod and seeds are consumed. Fresh pod beans are available from many production areas in the United States, but in the winter months they are produced mainly in Florida and Mexico.

Quality Characteristics and Criteria

Beans should be well-formed and straight, bright in color with a fresh appearance free of defects, and tender (not tough or stringy) but firm. The diameter of the pod, rather than length, is a good indicator of quality. Buyers prefer pods with no or only slight bulges indicating tender, young seeds. As the name implies, snap beans should break easily when the pod is bent, giving off a distinct audible snap. Poor quality is most often associated with overmaturity, broken beans, water loss, chilling damage, and decay.

Horticultural Maturity Indices

Snap beans (yellow, green, and purple types) are harvested when they are rapidly growing, about 8 to 10 days after flowering for typical mature snap beans. All pod beans should be harvested when the pod is a bright color and fleshy, and the seeds are small and green. After that period, excessive seed development reduces quality and the pod becomes pithy and tough and loses its bright color.

Grades, Sizes, and Packaging

U.S. grades for snap beans are U.S. Fancy, U.S. No. 1, and U.S. No. 2, based primarily on external appearance. Though not sized for market, a reasonable size is expected according to the characteristics of each variety. Beans are packed in 11.4 to 13.6 kg (25 to 30 lb) crates and 6.8 or 9.1 kg (15 or 20 lb) cartons; presnipped beans for foodservice are available in 4.5 kg (10 lb) bags.

Cooling

Snaps beans can be hydrocooled. This is especially beneficial in dry climates where dehydration is a concern and in situations where evaporation of surface moisture occurs rapidly after cooling (for example, beans packed in wire-bound crates). Hydrocooling is very rapid, but significant postharvest decay can occur if the product remains wet after cooling. Forced-air cooling is the method of choice if beans have been packed. Efficient cooling is achieved without leaving free moisture on beans, but high relative humidity must be maintained to reduce excessive water loss (Boyette et al. 1994, Sargent 1995).

Optimum Storage Conditions

Snap beans should be stored at 5 to 7.5 °C (41 to 46 °F) with 95 to 100% RH. At 5 to 7.5 °C (41 to 46 °F), a storage life of 8 to 12 days is expected. Good quality can be maintained for a few days at temperatures below 5 °C (41 °F), but chilling injury will be induced (see *Chilling Sensitivity*). Some chilling may occur even at the recommended storage temperature of 5 °C (41 °F) after 7 to 8 days, depending on cultivar. Quality rapidly decreases above 7.5 °C (46 °F) due to yellowing, seed development, and water loss. Waxed cartons and plastic film liners reduce water loss. The perishability and rates of water loss of immature beans are higher than for mature beans. Long beans have postharvest requirements similar to those of snap beans with similar responses to chilling (Zong et al. 1992).

Controlled Atmosphere (CA) Considerations

At recommended temperatures, 2 to 5% O_2 reduces respiration (Saltveit 1997). Snap beans benefit from CO_2 levels between 3 and 10% with retention of color, reduced discoloration, and reduced decay on damaged beans (Cano et al. 1997, Hardenburg et al. 1986, Trail et al. 1992). Higher CO_2 levels (20 to 30%) are used for short periods (for example, 24 h) but can cause off flavors (Costa et al. 1992).

Retail Outlet Display Considerations

Snap beans should not come in contact with ice or water, both of which can produce translucent, water-soaked areas on the pods. For the same reason, misting is not generally recommended unless the beans are seriously dehydrated.

Chilling Sensitivity

Snap and pod beans are chilling sensitive, and visual symptoms depend on the storage temperature. Below 5 °C (41 °F), chilling injury produces a general opaque discoloration of the entire bean. A less common symptom is pitting on the surface and increased water loss. Discrete rusty brown spots appear at 5 to 7.5 °C (41 to 46 °F). These lesions are very susceptible to attack by common fungal pathogens. Beans can be held about 2 days at 1 °C (34 °F), 4 days at 2.5 °C (37 °F), and 6 to 10 days at 5 °C (41 °F) before chilling symptoms appear (Cantwell and Suslow 2008). No discoloration occurs on beans stored at 10 °C (50 °F), but undesirable seed development, water loss, and yellowing will occur. Different varieties differ substantially in susceptibility to chilling injury (Watada and Morris 1966b, Cantwell and Suslow 2008).

Freezing Injury

Freeze damage occurs at -0.7 °C (30.7 °F) or below and appears as water-soaked areas that subsequently deteriorate and decay.

Ethylene Production and Sensitivity

Beans produce only very low amounts of ethylene (less than 0.05 µL kg^{-1} h^{-1} at 5 °C or 41 °F). Ethylene exposure greater than 0.1 µL L^{-1} promotes chlorophyll loss, increases browning, and reduces green bean storage life by 30 to 50% at 5 °C (41 °F) (Wills and Kim 1996).

Respiration Rates

Beans are rapidly growing when harvested and have high respiration rates.

Temperature	Snap beans	Long beans
	------mg CO_2 kg^{-1} h^{-1}------	
0 °C	40	80
5 °C	66	90
10 °C	110	175
15 °C	170	374
20 °C	234	396

Snap bean data from Watada and Morris (1966a); long bean data from Zong et al. (1992).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

See *Chilling Sensitivity.*

Postharvest Pathology

Various decay organisms may attack fresh pod beans as a result of chilling injury, surface moisture, or mechanical damage. Common decay-causing fungi are those causing “nesting decays” (cottony leak caused by *Pythium* spp. and *Rhizopus* spp), gray mold *(Botrytis cinerea)*, and watery soft rot (*Sclerotinia* spp.). Water-soaked spots may be due to lesions caused by bacterial infections (*Pseudomonas* spp. and *Xanthomonas* spp.) (Snowdon 1992).

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Beans are snipped to remove stems and tails for food service. Browning of the cut ends can be a problem, and high-CO_2 atmospheres retard discoloration.

Special Considerations

Extra careful and expedited postharvest handling are required for highly perishable, very fine French beans (haricot verts) to avoid physical damage and dehydration.

References

Boyette, M.D., J.R. Schultheis, E.A. Estes, and W.C. Hurst. 1994. Postharvest cooling and handling of green beans and field peas. Bull. AG-413-8, North Carolina Cooperative Extension Service, Raleigh, NC.

Cano, M.P., M. Monreal, B. de Ancos, and R. Alique. 1997. Controlled atmosphere effects on chlorophylls and carotenoids changes in green beans (*Phaseolus vulgaris* L., cv. Perona). *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 46-52. University of California, Davis, CA.

Cantwell, M., and T. Suslow. 1998. Snap bean produce facts. Recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

Costa, M.A.C., J.K. Brecht, S.A. Sargent, and D.J. Huber. 1994. Tolerance of snap beans to elevated CO_2 levels. Proceedings of the Annual Meeting of the Florida State Horticultural Society 107:271-273.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California, Davis, CA.

Sargent, S.A. 1995. Optimizing packing and cooling methods for maintaining high quality snap beans. *In* G.J. Hochmuth and D.N. Maynard, eds., FACTS Proceedings, p. 8. University of Florida, Gainesville, FL.

Snowdon, A.L. 1992. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables. CRC Press, Boca Raton, FL.

Trail, M.A., I.A. Wahem, and J.N. Bizri. 1992. Snap bean quality changed minimally when stored in low density polyolefin film package. J. Food Sci. 57:977-979.

Watada, A.E., and L.L. Morris. 1966a. Growth and respiration patterns of snap bean fruits. Plant Physiol. 42:757-761.

Watada, A.E., and L.L. Morris. 1966b. Effect of chilling and nonchilling temperatures on snap bean fruits. Proc. Amer. Soc. Hort. Sci. 89:368-374.

Wills, R.B.H., and G.H. Kim. 1996. Effect of ethylene on postharvest quality of green beans. Aust. J. Exp. Agric. 36:335-337.

Zong, R.J., M. Cantwell, L. Morris, and V. Rubatzky. 1992. Postharvest studies on four fruit-type Chinese vegetables. Acta Hort. 318:345-354.

Beet

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Scientific Name and Introduction

Beta vulgaris L. Crassa group—table beet, or red beet—is a biennial of the Chenopodiaceae family. In the first year, it forms a fleshy storage root (enlarged hypocotyl) that is edible. In the early stages of plant development, the whole plant may be consumed. Beets are grown worldwide, the top producers being Germany, Poland, the Russian Federation, and the United States.

Quality Characteristics and Criteria

Quality criteria include root shape, root size (diameter), color, firmness (turgidity), smoothness, cleanness, trimming of rootlets, and freedom from defects. Intensive and uniform color with minimum zoning is the most important quality criterion.

Horticultural Maturity Indices

Fresh-market bunched beets (with tops) are harvested as early as 50 to 70 days after planting; whereas roots (without tops) are usually harvested later but before they reach full maturity, especially when they are intended for long-term storage.

Grades, Sizes, and Packaging

Grades U.S. No. 1 and U.S. No. 2 are based primarily on external appearance. Unless otherwise specified, the diameter of each beet shall not be less than 2.5 to 3.8 cm (1 to 1.5 in). Standard bunches shall be fairly uniform in size, and each bunch of beets shall not weigh less than 0.5 kg (1.1 lb) and must contain at least 3 beets. Fresh-market bunches are packed in small crates of 10 to 15 kg (22 to 33 lb) capacity, whereas beets intended for storage are packed in 20 kg (44 lb) polyethylene-lined crates or bins of 500 to 600 kg (1,100 to 1,320 lb) capacity.

Precooling Conditions

Bunched beets should be precooled to below 4 °C (39 °F) within 4 to 6 h of harvest. Hydrocooling, forced-air cooling, and package icing are common cooling methods. Proper precooling and packaging retard subsequent discoloration of the leaves, weight loss, and decay. Mature harvested beets should be precooled within 24 h after harvest to below 5 °C (41 °F) with forced-air cooling.

Optimum Storage Conditions

Bunched beets can be kept for about 10 to 14 days at 0 °C (32 °F) and above 98% RH. Topped beets should be stored at 1 to 2 °C (33 to 36 °F) and 98% RH. During storage at 0 to 1 °C (32 to 34 °F), more black spot and rot occur than at higher temperatures (Schouten and Schaik 1980). Red beets can be in air-ventilated storage for 4 to 6 mo and in mechanical refrigerated storage for as long as 8 to 10 mo. Before storage, beets should be topped and sorted to remove all diseased or mechanically damaged roots. Large roots keep much better than small ones because they lose water and shrivel more slowly.

Red beets can be stored in pits and trenches, especially where winter temperatures are low for prolonged periods. Insulation of pits (clamps) and trenches is needed to avoid injurious temperature fluctuations. The temperature in pits (clamps) and cellars should not drop below -0.5 °C (31 °F) or exceed 5 °C (41 °F) to minimize losses caused by freezing, sprouting, and rotting.

Controlled Atmosphere (CA) Considerations

There is little or no benefit from CA or MA storage of beet roots. Elevated levels of CO_2 (over 5%) in the atmosphere may promote decay (Shipway 1968).

Retail Outlet Display Considerations

Bunched beets should be placed on refrigerated shelves at 3 to 5 °C (37 to 41 °F), and beet roots should be held below 10 °C (50 °F).

Chilling Sensitivity

Beet roots are not sensitive to chilling and should be stored in temperatures as low as possible without freezing.

Ethylene Production and Sensitivity

Beet roots produce very low amounts of ethylene, (<0.1 µL kg^{-1} h^{-1}) and are not particularly sensitive to ethylene exposure.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	4 to 6
5 °C	10 to 12
10 °C	16 to 20
15 °C	24 to 38
20 °C	50 to 70

Data from Uddin (1998).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Death of shoots and breakdown of the top part of roots are common problems during long-term storage at 0 ºC (32 °F). Physiological disorders can appear quickly during subsequent shelf-life at 20 ºC (68 °F) after storage (Adamicki and Badełek 1997).

Postharvest Pathology

The most common decay during storage is gray mold (*Botrytis cinerea* Pers.) (Robak and Wiech 1998). Beet roots are also affected by black rot caused by *Phoma betae* Frank. Water-soaked and brown lesions become black and affect mostly the tip of the root. Good air circulation and optimal storage conditions retard development of black rot.

Quarantine Issues

None.

Suitability as Fresh-Cut Product

No current potential.

References

Adamicki, F., and E. Badelek. 1997. The effect of temperature and size of roots on storage and shelf-life of red beet. Research Report of the Research Institute of Vegetable Crops, pp. 10. The Ministry of Agriculture and Rural Development, Warsaw, Poland.

Elkner, K., E. Badełek, and F. Adamicki. 1997. The effect of cultivar and storage conditions on quality of red beet. Biuletyn Warzywniczy 46:65-78.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Robak, J., and K. Wiech. 1998. Diseases and Pests of Vegetable Crops, pp. 352. Plantpress Sp. z.o.o., Krakow, Poland.

Ryall, A.L., and W.J. Lipton.1983. Handling, Transportation and Storage of Fruits and Vegetables, vol. 1, 2nd ed. AVI Publishing Co., Westport, CT.

Schouten, S.P., and A.C.R. Schaik. 1980. Storage of red beets. Acta Hort. 116:25-29.

Shipway, M.R. 1968. Refrigerated Storage of Fruit and Vegetables. Ministry of Agriculture, Fisheries and Food, London, U.K.

Thompson, A.K. 1998. Controlled Atmosphere Storage of Fruits and Vegetables. CAB Intl., Wallingford, U.K.

Uddin, N. 1998. Fruit and vegetable storage and transport database. *At* http://www.postharvest.com.au/beetroot.pdf.

Zwart-Roodzant, M.H., P.S. Hak, C.F.G. Kramer, et al. 1990. Long term bulk storage of red beets in forced ventilated clamps in comparison with long term storage in mechanical cooling. Acta. Hort. 267:163-168.

Blackberry

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Scientific Name and Introduction

Blackberry (*Rubus* sp.) is a member of the Rosaceae family and is grown as a perennial crop. Soft and juicy, blackberries are compound fruits made up of many drupelets and attached to a receptacle. The fruit detaches from the pedicel and the receptacle remains fleshy and firmly attached to the drupelets. The commercially important cultivars are ‘Chester Thornless,’ ‘Triple Crown,’ ‘Kotata,’ ‘Shawnee,’ ‘Navaho,’ ‘Kiowa,’ ‘Brazos,’ ‘Thornless Evergreen,’ and ‘Arapaho.’ Blackberries are widely grown in the South Central and Northwestern United States and are found as three plant types. Trailing blackberries and dewberries are thorny and must be trellised. Semierect blackberries are generally thornless and have long, trailing lateral branches. Erect blackberries can be found as thorny or thornless cultivars and have upright growth with lateral branches that remain upright. Blackberry-raspberry hybrids include tayberry, loganberry, youngberry, and boysenberry (Jennings 1988).

Quality Characteristics and Criteria

High-quality blackberries are free of injury, decay, calyxes (caps), and sunscald. They are fully black in color, appear and feel turgid, and are of regular shape. To meet U.S. No. 1 grade standards, no more than 1% of the lot can be affected by mold or decay and no more than 5% can have other serious damage.

Horticultural Maturity Indices

For the fresh market, blackberry maturity can be determined by fruit color, gloss, and ease of detachment. Fully black berries should pull easily from the pedicel yet be firm, not mushy. Blackberries lose acidity with ripening and are quite astringent if harvested partially colored. Some varieties (for example, ‘Chester Thornless’) must be harvested only when fruit are dull black; otherwise they are too acid to eat.

Grades, Sizes, and Packaging

Generally, containers of 1 to 2 pints are used, but 1-quart containers occasionally are used. The most common packaging is vented plastic “clamshell” boxes packed in units of 12 per carton.

Precooling Conditions

Forced-air cooling to 5 ºC within 4 h is recommended for best shelf-life. Blackberries should be shipped with refrigeration at temperatures under 5 ºC. A similar protocol is used for fruit destined for processing and fruit processed within 24 h of harvest.

Optimum Storage Conditions

Blackberries can be held 2 to 14 days, depending on cultivar, at -0.5 to 0 ºC (31 to 32 ºF), with higher than 90% RH.

Controlled Atmosphere (CA) Considerations

Blackberries benefit from 10 to 20% CO_2 + 5 to 10% O_2 to reduce decay and softening (Kader 1997).

Retail Outlet Display Conditions

Blackberries should be stored and displayed at the coldest refrigeration temperature possible and with no mist. As little as 1 day at room temperature can stimulate growth of gray mold.

Chilling Sensitivity

Blackberries are not known to be chilling sensitive.

Ethylene Production and Sensitivity

Stimulation of *Botrytis cinerea* (gray mold) growth can occur on blackberries in the presence of ethylene. Ethylene production by blackberries is widely variable by cultivar and can be as little as 0.1 µL kg^{-1} h^{-1} or as high as 2 µL kg^{-1} h^{-1} (Burdon and Sexton 1993).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 ºC	18 to 20
4 to 5 ºC	31 to 41
10 ºC	62
15 to 16 ºC	75
20 ºC	100 to 130

Data from Perkins-Veazie et al. (1996) for 'Navaho,' 'Shawnee,' and 'Choctaw' at 20 ºC (68 °F) and from Robinson et al. (1975) for 'Bedford Giant' at other temperatures.

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

The major disorders are red drupelet disorder (areas of red drupelets on fully ripe berry), weight loss (shrivel), and leakers (berries with leakage of juice) (Perkins-Veazie et al. 1996, Mitcham et al. 1998).

Postharvest Pathology

The most common postharvest diseases are gray mold *(Botrytis cinerea)* and rhizopus rot *(Rhizopus stolonifer)* (Jennings 1988, Ellis et al. 1991).

Quarantine Issues

No known issues.

Suitability as Fresh-Cut Product

Blackberries are incorporated into fruit cups and fruit plates.

Special Considerations

Blackberries are easily damaged. They can develop red areas after storage, which may be due to loss of pigment from water contact or from cultivar-dependent red drupelet disorder.

References

Burdon, J.N., and R. Sexton. 1993. Fruit abscission and ethylene production of four blackberry cultivars (*Rubus* spp.). Ann. Appl. Biol. 123:121-123.

Ellis, M.A., R.H. Converse, R.N. Williams, and B. Williamson, eds. 1991. Compendium of Raspberry and Blackberry Diseases and Insects. APS Press, St. Paul, MN.

Jennings, D.L. 1988. Raspberries and Blackberries: Their Breeding, Diseases, and Growth. Academic Press, New York, NY.

Kader, A.A. 1997. A summary of CA requirements and recommendations for fruits other than apples and pears. *In* A.A. Kader, ed., 7th International

Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 3, pp. 1-34. University of California, Davis, CA.

Mitcham, E.J., C.H. Crisosto, and A.A. Kader. 1998. Bushberries in fresh produce facts. *At* http://postharvest.ucdavis.edu/produce_information.

Perkins-Veazie, P.M., J.K. Collins, and J.R. Clark. 1996. Cultivar and maturity affect postharvest quality of fruit from erect blackberries. HortScience 31:258-261.

Robinson, J.E., K.M. Browne, and W.G. Burton. 1975. Storage characteristics of some vegetables and soft fruits. Ann. Appl. Biol. 81:399-408.

Blueberry

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Scientific Name and Introduction

Blueberries (*Vaccinium* sp.) are a member of the heath family (Ericaceae) grown as a perennial crop. Blueberries have a blue to blue-black epidermis or skin that is covered by a waxy bloom, giving the fruit a light-blue appearance. The flesh is juicy and creamy white to green in color. Blueberries of commercial importance include the lowbush (*V. angustifolium* Ait.), northern (*V. corymbosum* L.)**,** southern highbush (hybrids of *V. corymbosum*, *V. ashei*, and *V. darrowi* Camp.), and rabbiteye (*V. ashei* Reade). Lowbush blueberries are much smaller (less than 1 g) than highbush types and are prized for their use in processed products such as pie and pastry fillings, pancakes, muffins, jams, and sauces. Northern highbush berries are grown primarily in the northern tier of the United States and require 600 to 1,000 h of chilling below 7 °C (45 °F) (Pritts 1992). Southern highbush berries require fewer chill hours and can lose fruit to frost damage if grown in areas where spring temperatures drop below 0 °C (32 °F) during bloom and early fruit set. Rabbiteye blueberries are hardy only in the Southern United States or where winter temperatures remain above 10 °C (50 °F). These berries often have a gritty mouth feel from seeds and stone cells and lack a well-developed calyx but have a longer shelf-life and more pigment than highbush berries.

Quality Characteristics and Criteria

High-quality blueberries are free of injury, decay, and sunscald. They are are fully blue in color, with little or no red at the stem end, and appear and feel turgid.

Horticultural Maturity Indices

For fresh market, fruit should be fully blue and firm.

Grades, Sizes, and Packaging

Highbush blueberries are graded as U.S. No. 1 or are unclassified. Size can be used in connection with grade: extra large is fewer than 90 berries per cup (250 mL), large is 90 to 129 berries per cup, medium is 130 to 189 berries per cup, and small is 190 to 250 berries per cup (AMS 1966). Blueberries are packaged as 1- or 2-pint units, usually in polyethylene or polystyrene-ventilated clamshells, and sold as 12-unit trays.

Precooling Conditions

Blueberries for fresh market should be forced-air cooled to under 10 ºC (50 °F), graded, then maintained under refrigeration at 0 to 3 °C (32 to 37 °F) within an hour after harvest to remove field heat and extend storage life. Precooling to 5 ºC (41 °F) can cause condensation problems in lowbush blueberries when packed at ambient temperatures but should be incorporated when delays between picking and packing exceed 21 h (Jackson et al. 1999).

Optimum Storage Conditions

Blueberries should be held at -0.5 to 0 ºC (31 to 32 ºF) and at above 90% RH for up to 2 weeks for lowbush, northern highbush, and southern highbush (Perkins-Veazie et al. 1995, Jackson et al. 1999) and up to 4 weeks for rabbiteye (Miller et al. 1988).

Controlled Atmosphere (CA) Considerations

Rabbiteye, highbush, and lowbush blueberries benefit from 10 to 15% CO_2 + 1 to 10% O_2 when held at or below 5 ºC (41 °F) (Smittle and Miller 1988, Prange et al. 1995). Firmness and total acidity were maintained and decay decreased with a shelf-life up to 6 weeks.

Retail Outlet Display Considerations

Blueberries should be stored and displayed under refrigeration with temperatures as close to 0 °C (32 °F) as possible.

Chilling Sensitivity

Blueberries are not known to be chilling sensitive.

Ethylene Production and Sensitivity

Botrytis cinerea (gray mold) growth can be stimulated on blueberries in the presence of ethylene. Ethylene production ranges from 0.5 to 2 µL kg^{-1} h^{-1} for northern highbush, varying with year and cultivar (Suzuki et al. 1997), to 10 µL kg^{-1} h^{-1} for rabbiteye blueberry (El-Agamy et al. 1982)

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 ºC	2 to 10
4 to 5 ºC	9 to 12
10 ºC	23 to 35
15 to 16 ºC	34 to 62
20 to 21 ºC	52 to 87
25 to 27 ºC	78 to 124

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

The major disorders are shrivel (water loss), sunscald, and fruit cracking.

Postharvest Pathology

Blueberries are susceptible to *Botrytis cinerea* (gray mold) and anthracnose (ripe rot, *Colletotrichum gloesosporiodes*) (Milholland 1995). At temperatures above 10 ºC (50 °F), *Rhizopus stolonifer* can grow readily in fruit packs.

Quarantine Issues

Blueberry maggot (*Rhagoletis mendax* Curran) is the primary postharvest pest limiting shipments of unfumigated blueberries to Canada and States west of the Rockies. Methyl bromide is currently the only USDA-approved method of postharvest control. Plum cucurlico (*Conotrachelus nenuphar* [Herbst]) and blueberry maggot are quarantine pests for shipments to Japan (Guy Hallman, 2000, personal communication).

Suitability as Fresh-Cut Product

Fruit can be incorporated into fruit cups and prepared fruit trays.

Special Considerations

Bruising caused by improper handling or mechanical harvesting reduces the storage life of fresh fruit. Mechanical harvesting can reduce fruit storage life by half compared with hand harvesting.

Acknowledgments

Some of the information in this chapter was from the Produce Marketing Association's "Fresh Produce Manual" and the University of California,

Davis, website “Fresh Produce Facts” at http://postharvest.ucdavis.edu/produce_information.

References

AMS [USDA Agricultural Marketing Service]. 1966. United States Standards for Grades of Blueberries. U.S. Government Printing Office, Washington, DC.

El-Agamy, S.Z.A., M.M. Aly, and R.H. Biggs. 1982. Fruit maturity as related to ethylene in ‘Delite’ blueberry. Proceedings of the Annual Meeting of the Florida State Horticultural Society 95:245-246.

Jackson, E.D., K.A. Sanford, R.A. Lawrence, et al. 1999. Lowbush blueberry quality changes in response to prepacking delays and holding temperatures. Postharv. Biol. Technol. 15:117-126.

Kaufman, D. 1992. Harvesting and handling blueberries. *In* M. Pritts and J. Hancock, eds., Highbush Blueberry Production Guide. NRAES-55, Cooperative Extension Service, Ithaca, NY.

Miller, W.R., R.E. McDonald, and T.E. Crocker. 1988. Fruit quality of rabbiteye blueberries as influenced by weekly harvests, cultivars, and storage duration. HortScience 23:182-184.

Milholland, R.D. 1995. Anthracnose fruit rot (ripe rot). *In* F. Caruso and D. Ramsdell, eds., Compendium of Blueberry and Cranberry Diseases, pp. 17. American Phytopathological Society, St. Paul, MN.

Perkins-Veazie, P., J.R. Clark, J.K. Collins, and J. Magee. 1995. Southern highbush blueberry clones differ in postharvest fruit quality. Fruit Var. J. 49:46-52.

Prange, R.K., S.K. Asiedu, J.R. DeEll, and A.R. Westgarth. 1995. Quality of Fundy and Blomidon lowbush blueberries: effects of storage atmosphere, duration and fungal inoculation. Can. J. Plant Sci. 75:479-483.

Pritts, M.P. 1992. Site selection and preparation. *In* M. Pritts and J. Hancock, eds., Highbush Blueberry Production Guide. NRAES-55, Cooperative Extension Service, Ithaca, NY.

Smittle, D.A., and W.R. Miller. 1988. Rabbiteye blueberry storage-life and fruit quality in controlled atmospheres and air storage. J. Amer. Soc. Hort. Sci. 113:723-728.

Suzuki, A., T. Kikuchi, and K. Aoba. 1997. Changes of ethylene evolution, ACC content, ethylene forming enzyme activity and respiration in fruits of highbush blueberry. J. Japan. Soc. Hort. Sci. 66:23-27.

Bok Choy

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Scientific Name and Introduction

Bok choy *(Brassica campestris* L. ssp. *chinensis)* is also known as Chinese chard, boy-toyo, pak-choy, and pak-tsoi (King 1989). Bok choy is a nonheading type of Chinese cabbage (Li 1981). It is an annual in the Cruciferae family. The edible portions are the shiny, dark green leaves and the thick, chalk-white stalks (Peirce 1987). Most U.S. bok choy is produced in California.

Quality Characteristics and Maturity Indices

High-quality bok choy has thick, fleshy, firm stalks and glossy, dark-green leaves. Bok choy with bruised or slimy spots and wilted leaves should be avoided.

Grades, Sizes, and Packaging

Bok choy is mainly supplied to ethnic markets in the United States, but many large supermarkets are carrying it in their "ethnic" fresh produce departments. There are no standard U.S. grades.

Precooling Conditions

Prompt precooling to near 0 °C (32 °F) is important to maintain freshness and for extended storage.

Optimum Storage Conditions

The recommended storage conditions for bok choy are 0 to 5 °C (32 to 41 °F) with higher than 95% RH.

Controlled Atmosphere (CA) Considerations

Low-O_2 atmospheres of 0.5 to 1.5% retard leaf yellowing caused by chlorophyll degradation (O'Hare et al. 1995). A combination of 5% CO_2 + 3% O_2 delays leaf yellowing and senescence during storage (Wang and Herner 1989).

Retail Outlet Display Considerations

Bok choy is displayed loosely on refrigerated shelves. Misting should be done to minimize moisture loss and wilting.

Chilling Sensitivity

Bok choy is not chilling sensitive and should be stored as cold as possible without freezing. It freezes at -0.5 °C (31 °F).

Ethylene Production and Sensitivity

Bok choy produces very small amounts of ethylene, 0.1 to 0.2 µL kg^{-1} h^{-1}, and is not overly sensitive to ethylene.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	5 to 6
5 °C	10 to 12
10 °C	19 to 21
15 °C	34 to 44
20 °C	48 to 63

Data from Luo and Zheng (2001).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders and Postharvest Pathology

Leaf yellowing indicates that senescence has occurred during extended storage or storage at higher than optimal storage temperatures. Storing bok choy at 0 to 5 °C (32 to 41 °F) will mitigate this problem.

Quarantine Issues

None.

Suitability as Fresh-Cut Product

No current potential.

References

King, J. 1989. Consumers learning new names: bok choy to jicama. Farmline, vol. 10, pp. 11-13.

Li, C.W. 1981. The origin, evolution, taxonomy and hybridization of Chinese cabbage. *In* N.S. Talekar and T.D. Griggs, eds., Chinese Cabbage, pp. 1-10. Hong Wen Printing Works, Tainan, People’s Republic of China.

Luo, Y., and Y. Zheng. 2001. Respiration rate and ethylene production of bok choy at different temperature regime. Unpublished data.

O’Hare, T.J, L.G. Smith, L.S. Wong, and G.F. Meiburg. 1995. Low-oxygen storage of whole and minimally processed pak choi. Australasian Postharvest Horticulture Conference, pp. 459-462.

Peirce, L.C. 1987. Vegetables: Characteristics, Production, and Marketing. John Wiley & Sons, New York, NY.

Wang, H., and R.C. Herner. 1989. Effect of CA storage on the ultrastructure of chloroplasts and chlorophyll content of Chinese mustard. *In* E. Kupferman, and M. Patterson, eds., Proceedings of the 5th International Controlled Atmosphere Research Conference, vol. 2, pp. 9-17. Wenatchee, WA.

Breadfruit

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Scientific Name and Introduction

The tropical breadfruit (*Artocarpus altilis* [Parkins] Fosb.) develops from the whole inflorescence and is normally round, sometimes cylindrical, 15 to 30 cm (6 to 12 in) in diameter, and weighs from 0.5 to 3 kg (1.1 to 6.6 lb) (Nakasone and Paull 1998). The fruit receptacle (core) is surrounded by a pale yellow-white, edible pulp that is covered by a yellowish green, thin, reticulated skin. Most varieties are seedless (Ragone 1991). Seeded varieties have from 10 to 150, 2.5-cm-long (1-in-long) brown seeds (Bennett and Nozzolillo 1987). The tropical breadfruit is widely grown in tropical areas.

Quality Characteristics and Criteria

Fruit must be physiologically mature, have green skin and firm flesh with uniform shape, and be free from decay, sunscald, cracks, bruises, and mechanical damage.

Horticultural Maturity Indices

Fruit at different growth stages are harvested for different uses. Mature green fruit are harvested as a starch vegetable, while some people prefer to eat the ripe sweet fruit. Harvested green fruit produce copious latex, especially from the cut peduncle and injuries on the fruit. Maturity is indicated by larger size, a slight change in the skin color to a yellowish green, small drops of latex on the rind, firm flesh texture, and the segments appearing more rounded and smoother than less mature fruit. As the fruit starts to ripen, the skin changes to a yellowish green. Latex should be allowed to drain from the fruit after harvest before washing in water to avoid latex stain.

Grades, Sizes, and Packaging

There are no U.S. or international grade standards. Fruit are graded according to size and various counts per fiberboard carton containing 9 to 18 kg (20 to 40 lb). Fruit are sold on a weight basis. Telescoping two-piece fiberboard cartons are generally used for packaging. One-piece cartons having dividers to minimize fruit movement and rubbing also are used.

Precooling Conditions

Cool and ship fruit as soon as possible after harvest. Room cooling to 12 ºC (54 ºF) is generally used. Do not use hydrocooling as it leads to skin browning.

Optimum Storage Conditions

Store at 12 to 14 ºC (54 to 57 ºF) and 90 to 95% RH for a maximum of about 20 days.

Controlled Atmosphere (CA) Considerations

Film-wrapping delays softening and skin discoloration of breadfruit stored at 13 ºC (55 ºF) (Thompson et al. 1974). The O_2 levels in film-wrapped fruit were less than 5% (Worrell and Carrington 1997), while CO_2 rose to 10 to 30% (Worrell and Carrington 1997). CA studies indicated that at 12 ºC (54 ºF), the best storage atmosphere is 2 to 5% O_2 and 5% CO_2 for up to 3 weeks (Ramlochan 1991).

Retail Outlet Display Considerations

Display at 12 to 14 ºC (54 to 57 ºF). Do not mist.

Chilling Sensitivity

Long-term storage is not possible. At 12 ºC (54 ºF), chilling injury symptoms begin to develop within 7 days (Marriott et al. 1979). Symptoms are a brown, scaldlike discoloration of the skin, failure to fully soften, poor flavor development, and an increase in decay.

Ethylene Production and Sensitivity

Early-maturing fruit have a production rate of 1.0 to 1.5 µL kg^{-1} h^{-1} and late-maturing fruit, 0.7 to 1.2 µL kg^{-1} h^{-1} (Worrell and Carrington 1997). Breadfruit are sensitive to ethylene exposure, which leads to rapid ripening.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
13 ºC	94 to 564
25 ºC	362 to 597

Data from Worrell and Carrington (1997) and Worrell et al. (1998).

To get mL kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day..

Physiological Disorders

Mechanical injury leads to rapid deterioration, possibly due to wound ethylene inducing premature and more rapid ripening. No other disorders have been reported (Worrell and Carrington 1997).

Postharvest Pathology

Fruit rot due to *Phytophthora palmivora* and pink disease *(Botryobasidium salmonicola)* have been reported (Salunke and Desai 1984). Purseglove (1968) reported a fruit rot caused by *Rhizopus artocarpi* in India.

Quarantine Issues

Breadfruit is a fruit fly host and has been successfully treated by vapor heat treatment and irradiation.

Suitability as Fresh-Cut Product

Possibly, but no products have yet been developed.

Special Considerations

Fruit can be boiled, dried, used in breadmaking, or fermented. Slices can be fried or stored in brine (Whitney 1988, Bates et al. 1991). The sweet ripe fruit is eaten as a dessert. The cooked seeds are also eaten.

References

Bates, R.P., H.D. Graham, R.F. Matthews, and L.R. Clos. 1991. Breadfruit chips: preparation, stability, and acceptability. J. Food Sci. 56:1608-1610.

Bennett, F.D., and C. Nozzolillo. 1987. How many seeds in a seeded breadfruit. Econ. Bot. 41:370-374.

Marriot, J., C. Perkins, and B.D. Been. 1979. Some factors affecting the storage of fresh breadfruit. Sci. Hort. 10:177-181.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K.

Purseglove, J.W. 1968. Tropical Crops. Dicotyledons. Longman, London, U.K.

Ragone, D. 1991. Ethnobotany of breadfruit in Polynesia. *In* P.A. Cox and S.A. Banack, eds., Islands, Plants, and Polynesians—An Introduction to Polynesian Ethnobotany, pp. 203-220. Dioscorides Press, Portland, OR.

Ramlochan, R. 1991. Transient Cooling and Storage of Breadfruit in Refrigerated and Controlled Atmosphere Environment. Thesis, University of the West Indies, St. Augustine, Trinidad.

Salunke, D.K., and B.B. Desai. 1984. Postharvest Biotechnology of Fruits. Vol 2. CRC Press, Boca Raton, FL.

Thompson, A.K., B.O. Been, and C. Perkins. 1974. Storage of fresh breadfruit. Trop. Agric. 51:407-415.

Whitney, P.J. 1988. The microbiology of breadfruit and cassava preservation by pit fermentation. Trop. Sci. 28:43-50.

Worrell, D.B., and C.M. Carrington. 1997. Breadfruit. *In* S.K. Mitra, ed., Postharvest Physiology and Storage of Tropical and Subtropical Fruits, pp. 347-363. CAB Intl., Wallingford, U.K.

Worrell, D.B., C.M. Carrington, and D.J. Huber. 1998. Growth, maturation and ripening of breadfruit, *Artocarpus altilis* (Park.) Fosb. Sci. Hort. 76:17-28.

Broccoli

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Scientific Name and Introduction

Brassica oleracea L., Italica group, also known as broccoli, calabrese, or sprouting broccoli, is a native of southern Europe and a member of the Brassicaceae (Cruciferae) family. The crop is annual and grows to maturity in about 75 to 95 days, depending on cultivar, season, and planting date. The whole immature influorescence (head) is the edible portion, with the floret tissue most often preferred by consumers. It grows best in cool climates and is available year-round from many areas of North America, though a large portion is grown in California.

Quality Characteristics and Criteria

High-quality broccoli is either a dark or bright green with closed flower buds (termed "beads"). The head should be firm to hand pressure and compact, and the stalk cleanly cut to the appropriate length for a particular grade standard or for "crowns" (dissected portions of the whole influorescence).

Horticultural Maturity Indices

Ideal maturity is based on head diameter, compactness, and tightly closed flowers (beads). Overmature heads are characterized by open flower buds or enlarged buds on the verge of opening, resulting in a loose head.

Grades, Sizes, and Packaging

There are three grades: U.S. Fancy, U.S. No. 1, and U.S. No. 2. They are based on external appearance, level of damage, trimming, and stalk diameter (AMS 1943). Two or three heads are normally bunched together for the fresh market. Such bunches are packed 14 to 18 units in waxed cardboard boxes and weigh approximately 10 kg (21 lb) (Boyette et al. 1996). Larger heads may have the stem trimmed to produce "crowns," and these are packed loose in 9 kg (20 lb) boxes. Individual florets are also cut and packed in 2.5 to 5 kg (5.5 and 11 lb) film bags for hotel, restaurant, and institutional use.

Precooling Conditions

Field-packed broccoli is commonly cooled by injecting liquid ice into waxed cartons (Cantwell and Suslow 1999). Ice maintains the proper temperature and RH for transport and distribution. Hydrocooling and forced-air cooling are also options, but good temperature management is required during transport (Cantwell and Suslow 1999).

Optimum Storage Conditions

Broccoli can be kept in excellent condition for 2 to 3 weeks at 0 ºC (32 ºF) with 98 to 100% RH. Package icing is required if storage or transport conditions cannot maintain the recommended temperature or RH (Shewfelt et al. 1983). Use of ice is not necessary if temperature can be maintained (Kleiber et al. 1993). Perforated plastic film packaging is recommended to minimize wilting (Toivonen 1997). Loss of quality during prolonged storage is caused by wilting, yellowing of buds and leaves, loosening or opening of buds, and decay.

Controlled Atmosphere (CA) Considerations

The recommended CA for broccoli is 1 to 2% O_2 and 5 to 10% CO_2 at 0 to 5 °C (32 to 41 °F) (Makhlouf et al. 1989, Cantwell and Suslow 1999). Optimal CA conditions can double storage life, especially when broccoli is held above optimum temperatures. However, if O_2 drops to below 1% in storage, there is a risk of off odors caused by the generation of sulfur-containing volatiles (Forney et al. 1991). High rates of air exchange are recommended in shipping containers to avoid accumulation of off odors. Modified atmosphere packaging systems generally maintain both O_2 and CO_2 at 10% to prevent accumulation of off odors.

Retail Outlet Display Considerations

Bottom-icing of the refrigerated display will prolong shelf-life (Perrin and Gaye 1986). Misting of the refrigerated display will also prolong shelf-life and preserve quality (Barth et al. 1992).

Chilling Sensitivity

Broccoli is not sensitive to chilling and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Broccoli produces very little ethylene, <0.1 µL kg^{-1} h^{-1} at 20 ºC (68 ºF), but it is extremely sensitive to ethylene, with floret yellowing being the most prevalent symptom. Exposure to ethylene at 2 µL L^{-1} at 10 ºC (50 °F) halves shelf-life (Cantwell and Suslow 1999).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	20 to 22
5 °C	32 to 36
10 °C	76 to 86
15 °C	160 to 180
20 °C	280 to 320

Data from Cantwell and Suslow (1999).

Respiration rates for cut florets are slightly higher (Izumi et al. 1996).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Bead (bud) yellowing may occur in overmature broccoli when stored at higher-than-optimal temperatures or in response to exposure to ethylene. Presence of yellow beads ends the commercial marketability of broccoli. There is sometimes confusion between senescence-associated yellow bead and yellow-to-light-green marginal areas of floret that occur due to shading by adjacent floret tissue. This is normal for tissue that is not exposed to light during head growth (Cantwell and Suslow 1999). A disorder called black speck on stems occurs in stored broccoli, and certain cultivars are more sensitive than others (DeEll and Toivonen 1998).

Postharvest Pathology

Grey mold rot (*Botrytis cinerea* Pers.:Fr.) is the most commonly reported mold in shipped broccoli (Ceponis et al. 1987). *Erwinia carotovora* (Jones) Bergey et al. and *Pseudomonas* spp. bacterial head rots are found on shipped and stored broccoli. Injury to the bead tissue during handling may enhance development of these rots (Liao and Wells 1987). While *Erwinia carotovora* decay seldom develops below 5 °C (41 °F), decay caused by *Pseudomonas* spp. can be severe (Liao and Wells 1987) since it grows relatively well even at low storage temperatures (Brocklehurst and Lund 1981). A few cultivars of broccoli have been identified with some resistance to *Pseudomonas* spp. (Canaday et al. 1991).

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Broccoli is commonly converted to fresh-cut floret products. Stems are also shredded into a packaged coleslaw-type product.

Special Considerations

Some cultivars have greater storage life potential than others (Cantwell and Suslow 1999). If long-distance shipping or storage is integral to a marketing strategy, then consideration should be made for appropriate cultivar selection, especially if controlled atmospheres are not being used. Freezing injury may occur during liquid-ice cooling if excessive salt is used in the slurry mixture or if the broccoli is stored below -1 ºC (30 ºF). Thawed buds will be very dark and translucent and can later turn brown or may serve as sites for development of bacterial decay. Rough handling during harvest and packing can damage floret tissue and lead to increased levels of decay. Hot-water dips prolong shelf-life (Forney 1995).

References

AMS [USDA Agricultural Marketing Service]. 1943. United States Standards for Grades of Bunched Italian Sprouting Broccoli. *At* http://www.ams.usda.gov/AMSv1.0/standards.

Barth, M.M., A.K. Perry, S.J. Schmidt, and B.P. Klein. 1992. Misting affects market quality and enzyme activity of broccoli during retail storage. J. Food Sci. 57:954-957.

Boyette, M.D., D.C. Sanders, and G.A. Rutledge. 1996. Packaging requirements for fresh fruits and vegetables. *At* http://www.bae.ncsu.edu/programs/extension/publicat/postharv/ag-414-8/index.html.

Brocklehurst, T.F., and B.M. Lund. 1981. Properties of pseudomonads causing spoilage of vegetables stored at low temperature. J. Appl. Bacteriol. 50:259-266.

Canaday, C.H., J.E. Wyatt, and J.A. Mullins. 1991. Resistance in broccoli to bacterial soft rot caused by *Pseudomonas marginalis* and fluorescent *Pseudomonas* species. Plant Dis. 75:715-720.

Cantwell, M., and T. Suslow. 1999. Broccoli: recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

Ceponis, M.J., R.A. Cappellini, and G.W. Lightner. 1987. Disorders in cabbage, bunched broccoli, and cauliflower shipments to the New York market, 1972-1985. Plant Dis. 71:1151-1154.

DeEll, J., and P. Toivonen. 1998. Characterization and control of black speck in broccoli. Agriculture and Agri-Food Canada, Horticulture Research and Development Centre Research Summary 1997/98, p. 9. Agriculture and Agri-Food Canada, Quebec, Canada.

Forney, C.F. 1995. Hot-water dips extend the shelf-life of fresh broccoli. HortScience 30:1054-1057.

Forney, C.F., J.P. Mattheis, and R.K. Austin. 1991. Volatile compounds produced by broccoli under anaerobic conditions. J. Agric. Food Chem. 39:2257-2259.

Gillies, S.L., and P.M.A. Toivonen. 1995. Cooling method influences the postharvest quality of broccoli. HortScience 30:313-315.

Izumi, H., A.E. Watada, and W. Douglas. 1996. Optimum O_2 or CO_2 atmosphere for storing broccoli florets at various temperatures. J. Amer. Soc. Hort. Sci. 121:127-131.

Kleiber, A., L. Jewell, and N. Simbeya. 1993. Ice or and ice-replacement agent does not improve refrigerated broccoli storage at 1 ºC. HortTechnology 3:317-318.

Liao, C.H., and J.M. Wells. 1987. Diversity of pectolytic, fluorescent pseudomonads causing soft rots of fresh vegetables at produce markets. Phytopathology 77:673-677.

Makhlouf, J., F. Castaigne, J. Arul, et al. 1989. Long-term storage of broccoli under controlled atmosphere. HortScience 24:637-639.

Perrin, P.W., and M.M. Gaye. 1986. Effect of simulated retail display and overnight storage treatments on quality maintenance in fresh broccoli. J. Food Sci. 51:146- 149.

Shewfelt, R.L., K.M. Batal, and E.K. Heaton. 1983. Broccoli storage: effect of N6-benzyladenine, packaging, and icing on color of fresh broccoli. J. Food Sci. 48:1594-1597.

Toivonen, P.M.A. 1997. The effects of storage temperature, storage duration, hydro-cooling, and micro-perforated wrap on shelf-life of broccoli (*Brassica oleracea* L., Italica Group). Postharv. Biol. Technol. 10:59-65.

Brussels Sprouts

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Scientific Name and Introduction

Brassica oleracea L., Gemmifera group, also known as brussels sprouts, is a tall-stemmed cabbage in which the axillary buds in the axis of each leaf form tiny heads or “sprouts.” It has a common origin from the wild cabbage of southern Europe with other cole crops including cabbage, broccoli, and cauliflower (all members of the Brassicaceae [Cruciferae] family). Brussels sprouts prefer a cool growing environment. Most sprouts grown in the United States are from the central coast of California.

Quality Characteristics and Criteria

High-quality brussels sprouts are about 2.5 cm (1 in) in diameter, firm with green outer leaves, and a white cut end. The inner leaves are light yellow, fairly tightly arranged, and without large air pockets between them.

Horticultural Maturity Indices

Harvest maturity is based on sprout size and compactness. Sprouts should be 2.5 cm (1 in) or more in diameter but not more than 7 cm (2.75 in) in length. Stem elongation, resulting in space between older leaves, is a sign of overmaturity.

Grades, Sizes, and Packaging

There are two grades: U.S. No. 1 and U.S. No. 2. They are based on size, external appearance, decay, and damage (AMS 1954). To meet these grades, sprouts should be larger than 2.5 cm (1 in) in diameter and shorter than 7 cm (2.75 in). Brussels sprouts are packaged loose in 11-kg (25-lb) cartons or in 3.6- to 4.6-kg (8- to 10-lb) flats or cartons containing 12 plastic containers of sprouts (Boyette et al. 1996). Plastic liners are often used in cartons with loose sprouts to reduce moisture loss. In addition, polyethylene bags are sometimes used in place of the plastic containers for consumer units.

Precooling Conditions

Effective cooling methods include vacuum cooling, hydrocooling, icing, and forced-air cooling. Vacuum cooling is most effective when sprouts are premoistened to reduce wilting and can be an effective method of cooling even when sprouts are packaged, as long as the packaging material is ventilated (Stenvers 1971). Hydrocooling is also an efficient method to rapidly cool sprouts from 20 to 2 °C (68 to 36°F) in about 15 min (Stewart and Barger 1963). Package or top-icing can also be used, especially if storage or transport conditions cannot maintain recommended temperature or RH. Forced-air cooling effectively cools sprouts if packaging is properly vented to allow good air movement about the product.

Optimum Storage Conditions

Quality can be maintained for 3 to 5 weeks at 0 °C (32 °F) and 95 to 100% RH. Storage life is half as long at 5 °C (41 °F) and only 10 days at 10 °C (50 °F).

Controlled Atmosphere (CA) Considerations

Atmosphere modification inhibits yellowing and decay and prevents discoloration of the cut end when sprouts are held above optimum temperatures. At 7.5 °C (46 °F), an atmosphere of 2.5% O_2 and 10% CO_2 can maintain quality for

4 weeks. CO_2 ranging from 5 to 10% and O_2 of 1 to 2% are beneficial (Lyons and Rappaport 1962, Isenburg 1969, Lipton and Mackey 1987). CO_2 above 10% and O_2 below 0.5% can be injurious. CO_2 above 20% causes internal browning and pitting of outer leaves (Lyons and Rappaport 1962), while O_2 at 0.5% or less can induce a reddish-tan discoloration of the heart leaves and bitter flavor (Lipton and Mackey 1987). Brussels sprouts do not produce severe off odors when held in low O_2 as do other *Brassica* vegetables such as broccoli (Forney and Jordan 1999).

Retail Outlet Display Considerations

Bottom-icing of the refrigerated display will enhance shelf-life of brussels sprouts. Plastic overwraps or misting of bulk displays minimize wilting.

Chilling Sensitivity

Brussels sprouts are not sensitive to chilling and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Brussels sprouts produce <0.25 µL kg^{-1} h^{-1} ethylene at 7.5 °C (46 °F), though rates increase 10-fold with prolonged storage (Lipton and Mackey 1987). Brussels sprouts are extremely sensitive to ethylene, with leaf yellowing and abscission being the most prevalent symptoms.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	20 to 60
5 °C	44 to 96
10 °C	126 to 168
15 °C	128 to 272
20 °C	172 to 380

Data from Lyons and Rappaport (1959).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Internal browning, or “tipburn,” is the margins of inner leaves in buds turning brown and is caused by inadequate transport of calcium to young expanding leaves. Growing conditions that favor rapid growth promote internal browning (Maynard and Barker 1972).

Postharvest Pathology

Diseases of importance during storage are bacterial soft rots (*Erwinia* sp. and *Pseudomonas* sp.), bacterial leaf spot (*Pseudomonas syringae* pv. *maculicola* [McCulloch]), black or gray leaf spot (*Alternaria* sp.), and grey mold (*Botrytis cinerea* Pers.) (Snowdon 1991).

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Some trimming of the stem-end could be done to convert the sprouts to a ready-to-cook form.

Special Considerations

Brussels sprouts can be stored attached to their stem to prolong storage life. Packaging in vented poly-bags or overwrapped cups reduces wilting. Sprout freeze at -0.8 °C (30.6 °F) (Cantwell 2001).

References

AMS [USDA Agricultural Marketing Service]. 1954. United States Standards for Grades of Brussels Sprouts. *At* http://www.ams.usda.gov/AMSv1.0/standards.

Boyette, M.D., D.C. Sanders, and G.A. Rutledge. 1996. Packaging requirements for fresh fruits and vegetables. *At* http://www.bae.ncsu.edu/programs/extension/publicat/postharv/ag-414-8/index.html.

Cantwell, M. 1997. Properties and recommended conditions for storage of fresh fruits and vegetables. *At* http://postharvest.ucdavis.edu.

Forney, C.F., and M.A. Jordan. 1999. Anaerobic production of methanethiol and other compounds by *Brassica* vegetables. HortScience 34:696-699.

Isenburg, F.M. 1969. The use of controlled atmosphere on cold crops. *In* D.H. Dewey, R.C. Herner, and D.R. Dilley, eds., Controlled Atmospheres for the Storage and Transport of Horticultural Crops, pp. 95-96. Horticulture Report 9, Michigan State University, East Lansing, MI.

Lipton, W.J., and B.E. Mackey. 1987. Physiological and quality response of Brussels sprouts to storage in controlled atmospheres. Proc. Amer. Soc. Hort. Sci. 112:491-496.

Lyons, J.M., and L. Rappaport. 1959. Effect of temperature on respiration and quality of Brussels sprouts during storage. Proc. Amer. Soc. Hort. Sci. 73:361-366.

Lyons, J.M., and L. Rappaport. 1962. Effect of controlled atmospheres on storage quality of Brussels sprouts. Proc. Amer. Soc. Hort. Sci. 81:324-331.

Maynard, D.N., and A.V. Barker. 1972. Internal browning of Brussels sprouts: a calcium deficiency disorder. J. Amer. Soc. Hort. Sci. 97:789-792.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation and Storage of Fruits and Vegetables, vol. 1, Vegetables and Melons. AVI Publishing Co., Westport, CT.

Snowdon, A.L. 1991. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables. Wolfe Publishing Ltd., London, U.K.

Stenvers, N. 1971. Preliminary experiments on vacuum cooling of vegetables and berries. Sprenger Institute Report 1630 (Suppl.), Sprenger Institute, Berlin, Germany.

Stewart, J.K., and W.R. Barger. 1963. Effects of cooling method, prepacking and top-icing on the quality of brussels sprouts. Proc. Amer. Soc. Hort. Sci. 83:488-494.

Cabbage

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Scientific Name and Introduction

Brassica oleracea L. var. *capitata* L. is red, green (domestic or Danish-type), and oxheart (conical or pointed-head type) cabbage; *B. oleracea* var. *sabauda* L. is savoy cabbage. All are biennials of the Brassicaceae (Cruciferae) family (Munro and Small 1997, Pritchard and Becker 1989). The edible portion includes the leaf blades, stalks, and core (stem) inside the head. Cabbage is grown in most major temperate vegetable-growing areas and is available year-round in most markets. The major cabbage-producing countries, in order of production, are China, the Russian Federation, India, Japan, and South Korea (Ghosh and Madhavi 1998). In the United States, the major fresh-cabbage-producing States are New York, California, and Texas; and the major sauerkraut-producing States are New York and Wisconsin. (NASS 2005).

Quality Characteristics and Criteria

Cabbage leaves should be green, dark purple, or crinkly, depending on the cultivar (Ryall and Lipton 1979, Pritchard and Becker 1989). The head should be firm and heavy for its size. The heads are crisp and fresh if they squeak when rubbed together (Ryall and Lipton 1979, Boyette et al. 2008a, Cantwell and Suslow 2008). The presence of a waxy bloom on the leaves is desirable. Yellow leaves on green cultivars suggest extensive trimming of the outer leaves. The presence of a seedstalk is undesirable.

Horticultural Maturity Indices

Determination of maturity in brassicas is not simple and no one index of maturity is reliable (Ludford and Isenberg 1987) At maturity, a cabbage head should be firm and weigh 0.5 to 3 kg (1 to 6.6 lb), depending on cabbage type and cultivar. The optimum head density of green cabbage destined for storage should range between 0.72 and 0.80 kg L^{-1} (Pritchard and Becker 1989). Immature heads, besides being smaller and softer, have an excessive tendency to wilt and a less characteristic odor (Pritchard and Becker 1989). Overmature heads are more susceptible to splitting, pathogens, physiological disorders, and seed stalk formation (IOS 1991, Pritchard and Becker 1989, Boyette et al. 2008a, Cantwell and Suslow 2008).

Grades, Sizes, and Packaging

Grades include U.S. No. 1 and U.S. Commercial, based on defects (physical and decay), excessive wrapper leaves, and off-size heads (AMS 1997). Size classification is optional. For the pointed-head-type (oxheart) cabbage, small is less than 0.7 kg (1.5 lb), medium is 0.7 to 1.4 kg (1.5 to 3 lb), and large is over 1.4 kg (3 lb). For domestic and Danish-type (green) cabbage, small is less than 0.9 kg (2 lb), medium is 0.9 to 2.3 kg (2 to 5 lb), and large is over 2.3 kg (5 lb). Cabbage heads are shipped in sacks, wax-coated corrugated cardboard cartons, and wire-bound crates of various sizes up to 22.7 kg (50 lb). Some cabbage is shipped in heavy fiberboard bulk pallet bins holding 227 to 455 kg (500 to 1,000 lb) (Boyette et al. 2008b).

Precooling Conditions

Cabbage should be cooled as soon as possible after harvest to preserve quality and reduce wilting. If cabbage is harvested under cool conditions, it can be placed in storage and cooled without precooling. Hydrocooling before storage or forced air-cooling in storage can be used to rapidly remove field heat (Boyette et al. 2008a).

Optimum Storage Conditions

Cabbage should be stored at 0 °C (32 °F) with 98 to 100% RH. Storage at -1 °C (31 °F) may cause freezing, while storage at 1 °C (34 °F) may promote senescence-related storage losses, especially if held in long-term storage—for example, 6 mo (R. Prange, unpublished data). High RH minimizes decay and trimming losses (van den Berg 1987). The presence of light in the storage room reduces physiological disorders such as leaf yellowing and weight loss (Prange and Lidster 1991). Cabbage is stored in bins or in bulk (IOS 1991). Only three to six wrapper leaves should be left on the head (Hardenberg et al. 1986). All loose leaves should be trimmed before storage because they will interfere with air circulation between heads. Air circulation in the storage should be sufficient to maintain constant and uniform temperature and RH around all cabbage heads. Bulk-stored cabbage should be ventilated in a vertical direction and the depth should not exceed 3 m (9.8 ft). Bin-stored cabbage should be arranged to maximize uniform air flow around each bin. Storage life depends on cultivar (for example, early-maturing cultivars tend to have shorter storage life than late-maturing cultivars), quality (for example, freedom from decay), and storage conditions (Pritchard and Becker 1989, IOS 1991, Boyette et al. 2008a). The end of storage life is signaled by increased respiration rate, core elongation, and sometimes rootlet development on the core butt (Guffy and Hicks 1985, Pritchard and Becker 1989).

Controlled Atmosphere (CA) Considerations

Cabbage is the most common vegetable stored under CA (Saltveit 1997, Thompson 1998). Wide ranges of O_2 levels from 1.5 to 5% and CO_2 levels from 0 to 8% have been recommended. Therefore, the mid range of 2 to 3% O_2 and 4 to 5% CO_2 is probably a good general recommendation. Low O_2 reduces color and trimming loss and inhibits root growth, while elevated CO_2 reduces rot, decay, and sprouting (Saltveit 1997). Atmospheres with lower than 1.5 to 2% O_2 and/or higher than 8 to 10% CO_2 may injure stored cabbage. Low-O_2 and high-CO_2 injury is slow to appear and the extent of the injury depends on the cultivar and maturity (Masters and Hicks 1990). For example, low-O_2 injury does not occur in oxheart cabbage until after 35 days when held in 0% O_2 (100% N_2) at 0 to 4 °C (32 to 39 °F) (Schouten et al. 1997), and green cabbage does not show low-O_2 injury until after 2, 3, or 6 mo, if held at 0 °C (32 °F) in 0.5, 1.0 or 1.5% O_2, respectively (Masters and Hicks 1990, Menniti et al. 1997). Similarly, CO_2 injury is seen after 2 mo if held at 0 °C (32 °F) in 20% CO_2 or after 2.5 mo (Menniti et al. 1997) or 6 mo (Masters and Hicks 1990) in 10% CO_2. Symptoms of low-O_2 and high-CO_2 injury are off flavors and off odors as well as visible damage (Lougheed 1987, Ludford and Isenberg 1987, Masters and Hicks 1990, Menniti et al. 1997, Schouten et al. 1997). Both low O_2 and high CO_2 produce very similar visible damage beginning in the meristematic tissue located at the apex of the stem in the middle of the cabbage. Damage spreads to outer leaves and appears as black spots (low O_2) (Schouten et al. 1997) or bronzing (high CO_2) (Masters and Hicks 1990). Lougheed (1987) suggested there may be no interaction between low O_2 and high CO_2 in injury, but Kaji et al. (1993) showed that high CO_2 (5 to 15%) keeps shredded cabbage in good condition if O_2 is high (5 to 10%).

Retail Outlet Display Considerations

Damaged outer wrapper leaves should be trimmed. Trimming may expose lighter green inner leaves, but natural or artificial light can increase the chlorophyll content and green color (Perrin 1982). The greatest concern is loss of moisture, which can be prevented by wrapping each head in a clear plastic film, frequent water sprinkling, and/or displaying in a refrigerated cabinet.

Chilling Sensitivity

Cabbage is not chilling sensitive. The freezing point is -0.9 to -0.83 °C (30.4 to 30.5 °F)

(Hardenburg et al. 1986, Pritchard and Becker 1989). Even though cabbage with core temperature of -1.1 °C (30 °F) before harvest can show no evidence of freeze damage (Pritchard and Becker 1989), storage at -1.0 °C (30.2 °F) is not advisable because it can produce freeze damage, especially on outer leaves (R. Prange, unpublished data). Temperature oscillations during cycling of mechanical refrigeration may expose tissue to freezing temperatures if the setpoint is too low or if the hystersis is too large.

Ethylene Production and Sensitivity

Cabbage produces very little ethylene (<0.1 µL kg^{-1} h^{-1} at 20 °C [68 °F]) (Kader 1992). Kubo et al. (1990) detected only a trace amount of ethylene from cabbage at 25 °C (77 °F). When heads are stored in the dark at 5 °C (41 °F) in sealed plastic bags, ethylene reaches only 1 µL L^{-1}, regardless of cultivar (Meinl and Bleiss 1986).

Cabbage should not be exposed to ethylene after harvest. Ethylene increases respiration (Inaba et al. 1989), and concentrations as low as 1 µL L^{-1} accelerate senescence and quality loss (for example, leaf yellowing, wilting, and abscission more in air than in CA) (Hicks and Ludford 1980, Pritchard and Becker 1989). Reduced ethylene production and phenylalanine ammonia-lyase (PAL) activation is linked to less tissue browning in shredded cabbage (Takahashi et al. 1996)

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	4 to 6
4 to 5 °C	9 to 12
10 °C	17 to 19
15 to 16 °C	20 to 32
20 to 21 °C	28 to 49
25 to 27 °C	49 to 63

Data from Hardenburg et al. (1986).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

The physiological cause is unknown for some disorders of stored cabbage (for example, black midrib, black speck of cabbage [pepper spot, spotted necrosis], gray speck, and necrotic spot) (Bérard 1994). The occurrence of these disorders is influenced by cultivar and cultural practices, especially mineral nutrition. Some storage disorders are clearly frost-induced (for example, black blotching, black spot, epidermal detachment, frost blemishing, and redheart). Bérard (1994) also describes storage disorders caused by dormancy, ethylene, and head maturity.

Postharvest Pathology

The major cause of postharvest decay in cabbages is the gray mold fungus *(Botrytis cinerea)* (Geeson 1983, Snowden 1991). Gray mold can be minimized by using resistant cultivars, using preharvest fungicides, practicing strict hygiene, avoiding mechanical or frost damage, rapid cooling to 0 °C (32 °F), and using CA storage (Snowden 1991). Alternaria rot, also known as dark, black, or gray leaf spot and caused by *Alternaria* spp., infects a wide range of cruciferous vegetables and can cause significant storage losses (Geeson 1983, Snowden 1991, Cerkauskas 1994). Since this disease is commonly transmitted through infected seed, it can be minimized by using disease-free seed, rotation with noncruciferous crops, applying preharvest fungicides, destruction of diseased material before storage, and using rapid cooling to 0 °C (32 °F). There are other fungi (such as ring spot), bacteria (bacterial rots and watery soft rot, for example), and a virus (tobacco mosaic virus) that cause significant losses (Dennis 1983, Ceponis et al. 1987, Snowden 1991).

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Shredded cabbage is suitable as a fresh-cut product, packaged in air or MAP. Gorny (1997) indicates MA treatment efficacy as good in extending storage life of shredded cabbage and provides respiration rates at different temperatures, atmospheres, and varying amounts of shredding.

Temperature	Atmosphere	Degree of shredding	mg CO_2 kg^{-1} h^{-1}
2 °C (35 °F)	air	quarter head	8
		rough cut (1 × 3 cm)	16 to 18
		fine cut (0.5-1.5 cm)	18 to 24
5 °C (41 °F)	air	quarter head	10 to 12
		rough cut (1 × 3 cm)	22 to 34
		fine cut (0.5-1.5 cm)	26 to 40
5 °C (41 °F)	5 % O_2 + 5 % CO_2	quarter head	12 to 14
		rough cut (1 × 3 cm)	26 to 30
		fine cut (0.5-1.5 cm)	30 to 40
10 °C (50 °F)	air	quarter head	19 to 23
		rough cut (1 × 3 cm)	42 to 48
		fine cut (0.5-1.5 cm)	51 to 57
23 °C (73 °F)	air	quarter head	54 to 63
		rough cut (1 × 3 cm)	117 to 153
		fine cut (0.5-1.5 cm)	153 to 171

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day. Data from Gorny (1997).

References

AMS [USDA Agricultural Marketing Service]. 1997. United States Standards for Grades of Cabbage. U.S. Department of Agriculture, Washington, DC. (http://www.ams.usda.gov/AMSv1.0/standards)

Bérard, L.S. 1994. Storage disorders. *In* R.J. Howard, J.A. Garland, and W.L. Seaman, eds., Diseases and Pests of Vegetable Crops in Canada, pp. 110-112. Canadian Phytopathological Society and Entomological Society of Canada, Ottawa, Canada.

Boyette, M.D., D.C. Sanders, and E.A. Estes. 2008a. Postharvest cooling and handling of cabbage and leafy greens. Postharvest Commodity Series. (http://www.bae.ncsu.edu/programs/extension/publicat/postharv/ag-413-5/index)

Boyette, M.D., D.C. Sanders, and G.A. Rutledge. 2008b. Packaging requirements for fresh fruits and vegetables. (http://www.bae.ncsu.edu/programs/extension/publicat/postharv/ag-414-8/index)

Cantwell, M., and T. Suslow 2008. Cabbages (round and Chinese types): recommendations for maintaining postharvest quality. (http://postharvest.ucdavis.edu/produce_information)

Ceponis, M.J., R.A. Cappellini, and G.W. Lightner. 1987. Disorders in cabbage, bunched broccoli and cauliflower shipments to the New York market, 1972-1985. Plant. Dis. 71:1151-1154.

Cerkauskas, R.F. 1994. Alternaria diseases. *In* R.J. Howard, J.A. Garland, and W.L. Seaman, eds., Diseases and Pests of Vegetable Crops in Canada, pp. 96-97. Canadian Phytopathological Society and Entomological Society of Canada, Ottawa, Canada.

Geeson, J.D. 1983. Brassica. *In* C. Dennis, ed., Postharvest Pathology of Fruits and Vegetables, pp. 125-126. Academic Press, New York, NY.

Ghosh, S.P., and D.L. Madhavi. 1998. Cabbage. *In* D.K. Salunkhe and S.S. Kadam, eds., Handbook of Vegetable Science and Technology, pp. 299-321. Marcel Dekker, New York, NY.

Gorny, J.R. 1997. A summary of CA and MA requirements and recommendations for fresh-cut (minimally processed) fruits and vegetables. *In* J.R. Gorny, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 5, pp. 30-66. University of California, Davis, CA.

Guffy, S.K., and J.R. Hicks. 1985. Effect of cultivar, maturity and storage on respiration, dry weight and glucosinolate content of cabbage. Acta Hort. 157:211-218.

Hardenburg, R.E., A.E. Watada, and C.Y Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Hicks, J.R., and P.M. Ludford. 1981. Effects of low ethylene levels on storage of cabbage. Acta Hort. 116:65-73.

Inaba, A., Y. Kubo, and R. Nakamura. 1989. Effect of exogenous ethylene on respiration in fruits and vegetables with special reference to temperature. J. Jap. Soc. Hort. Sci. 58:713-718.

IOS [International Organization for Standardization]. 1991. Round-headed cabbage—guide to cold storage and refrigerated transport. Intl. Std. Ref. No. ISO 2167:1991(E), Geneva, Switzerland.

Kader, A.A. 1992. Postharvest biology and technology: an overview. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, pp. 15-20. DANR Pub. no. 3311, University of California, Davis, CA.

Kaji, H., M. Ueno, and Y. Osajima. 1993. Storage of shredded cabbage under a dynamically controlled atmosphere of high O_2 and high CO_2. Biosci. Biotech. Biochem. 57:1049-1052.

Kubo, Y., A. Inaba, and R. Nakamura. 1990. Respiration and C_2H_4 production in various harvested crops held in CO_2-enriched atmospheres. J. Amer. Soc. Hort. Sci. 115:975-978.

Lougheed, E.C. 1987. Interactions of oxygen, carbon dioxide, temperature, and ethylene that may induce injuries in vegetables. HortScience 22:791-794.

Ludford, P.M., and F.M.R. Isenberg. 1987. Brassica crops. *In* J. Weichmann, ed., Postharvest Physiology of Vegetables, pp. 497-522. Marcel Dekker, New York, NY.

Masters, J.F., and J.R. Hicks. 1990. Cabbage. *In* P.D. Lidster, G.D. Blanpied, and R.K. Prange, eds., Controlled-Atmosphere Disorders of Commercial Fruits and Vegetables, pp. 29-30. 1847/E, Agriculture Canada, Ottawa, Canada.

Meinl, G., and W. Bleiss. 1986. Beobactungen zur Ethylenbildung und zur seiner Wirkung wahrend der lagerung von Kopfkohl (*Brassica oleracea* L. var. capitata) (Observations on ethylene synthesis and its effects during storage of cabbage [*Brassica oleracea* L. var. capitata]). Archiv für Zuchtungforschung 16:267-270.

Menniti, A.M., M. Maccaferi, and A. Folchi. 1997. Physio-pathological responses of cabbage stored under controlled atmospheres. Postharv. Biol. Technol 10:207-212.

NASS [USDA National Agricultural Statistics Service]. 2005. Agricultural Statistics. *At* http://www.nass.usda.gov/index.

Perrin, P.W. 1982. Poststorage effect of light, temperature and nutrient spray treatments on chlorophyll development in cabbage. Can. J. Plant Sci. 62:1023-1026.

Prange, R.K., and P.D. Lidster. 1991. Controlled atmosphere and lighting effects on storage of winter cabbage. Can. J. Plant Sci. 71:263-268.

Pritchard, M.K., and R.F. Becker. 1989. Cabbage. *In* N.A.M. Eskin, ed., Quality and Preservation of Vegetables, pp. 265-284. CRC Press, Boca Raton, FL.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California, Davis, CA.

Schouten, S.P., R.K. Prange, and T.R. Lammers. 1997. Quality aspects of apples and cabbages during anoxia. *In* E.J. Mitcham, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 2, pp. 189-192. University of California, Davis, CA.

Snowden, A.L. 1991. A Colour Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables. Wolfe Publishing, London, U.K.

Takahashi, T., K. Abe, and K. Chachin. 1996. Studies on the physiological and chemical changes in shredded cabbage. III. Effect of air-exposure at low temperature on physiological activities and browning of shredded cabbage. J. Jap. Soc. Hort. Sci. 43:663-667.

Thompson, A.K. 1998. Controlled Atmosphere Storage of Fruits and Vegetables. CAB Intl., Wallingford, U.K.

van den Berg, L. 1987. Water vapor pressure. *In* J. Weichmann, ed., Postharvest Physiology of Vegetables, pp. 203-230. Marcel Dekker, New York, NY.

Carambola

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Scientific Name and Introduction

The carambola (*Averrhoa carambola* L.) is a star-shaped fruit that has a waxy skin with several smooth brown seeds. The flesh and skin are crisp and juicy (Nakasone and Paull 1998). The carambola is also referred to as “star fruit.” However, the name is not preferred, because there is another tropical fruit called star fruit. Carambola is grown widely in the tropics and in the warmer areas of the subtropics.

Quality Characteristics and Criteria

The carambola is a firm, crisp fruit with shiny golden-yellow, orange, or yellow skin when ripe, with no brown discoloration on the skin or wings (ribs). Browning on the wing edges is due to mechanical injury and should not be included in the best grades. The shape is oval or elliptical in outline, 10 to 13 cm (4 to 5 in) long, and 5 to 8 cm (2 to 3 in) in diameter. The absence of fiber is desirable. Cultivars vary greatly in sweetness and acidity, from the tart ‘Golden Star’ and the sweeter ‘Arkin’ to the low-acid, sweet cultivars derived from Malay varieties (Nakasone and Paull 1998). Fruit showing wind, insect, or bird damage and poor shape are culled (Campbell 1989).

Horticultural Maturity Indices

Harvesting is based on physiological and horticultural maturity as indicated by skin color change from green to yellowish green, then to full yellow or yellowish orange (Campbell 1989). Optimum sugars are achieved at the full yellow color; however, ripe fruit are more fragile and easily damaged. Thus, fruit are frequently harvested at the color break stage (O’Hare 1993). Fruit that are 50 to 75% yellow are firmer than full-color fruit, and thus are regarded as commercially mature. Fruit continue to develop color after harvest, though there is little other change in quality.

Grades, Sizes, and Packaging

There are no U.S. or international grades. Carambola fruit are sold in 3.5-kg (7-lb) flats, 10-kg (22-lb) single layers, 9-kg (20-lb) suitcases, and clam shells (16 fruit in 1 layer or 32 fruit in 2 layers). Fruit require careful packing to reduce damage. A plastic or foam sleeve or wax paper should be used.

Precooling Conditions

Cool at 4 to 10 ºC (39 to 50 ºF) by forced air or room cooling as soon as possible.

Optimum Storage Conditions

Though a tropical crop, fruit can be stored at 4 to 5 ºC (39 to 41 ºF) with 90 to 95% RH for 21 to 35 days (Kader 1999). Length of storage varies with the ripeness when fruit are placed in storage. Lower RH results in more severe rib-edge browning. If held at 20 ºC (68 ºF) and 60% RH, fruit have a storage life of 3 to 4 days.

Controlled Atmosphere (CA) Considerations

Fruit held at 7 ºC (45 ºF) in 2.2 to 4.2% O_2 with 8 to 8.2% CO_2 retained color and firmness more than fruit held in air (Revel and Thompson 1994). Sealed polyethylene film bags delay degreening and have no effect on flavor after 1 week at 20 ºC (68 ºF) on either green or full-colored fruit (Wan and Lam 1984) when the final CO_2 content in the bag is 2.5 to 4.5% with 15% O_2 content. Waxing also delays water loss and degreening (Vines and Grierson 1966).

Retail Outlet Display Considerations

Do not display green fruit and do not stack more than two or three fruit high to avoid mechanical injury to the fragile wings (ribs). Misting is acceptable.

Chilling Sensitivity

During low-temperature storage at 0 ºC (32 ºF) and 5 ºC (41 ºF) for 2 and 6 weeks, respectively, some small surface pitting and rib-edge browning occurred, with severity of injury increasing with storage time (Wan and Lam 1984). Greener fruit are more susceptible to chilling injury (Wan and Lam 1984, Kenney and Hull 1986). Surface pitting and rib-edge browning can also be seen with desiccation, which may not be true chilling injury.

Ethylene Production and Sensitivity

These nonclimacteric fruit have a low production rate, under 3 µl C_2H_4 kg^{-1} h^{-1} at 20 ºC (68 ºF), depending on maturity (Oslund and Davenport 1983). Ethylene treatment (100 µL L^{-1} for 24 h) slightly hastens degreening but has little effect on flavor. Higher rates of ethylene production have been recorded after 12 days at 20 ºC (68 ºF) (Shiesh et al. 1987) and may be associated with decay.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
5 ºC	10 to 19
10 ºC	15 to 29
15 ºC	19 to 34
20 ºC	37 to 92

Data from Lam and Wan (1983, 1987).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Respiration rate and pattern depend on cultivar and maturity at harvest (Shiesh et al. 1987).

Physiological Disorders

The major problem is physical injury, especially on the rib edges, that leads to browning. Injury due to abrasion and impact can be avoided by careful handling. Browning due to mechanical injury can intensify with water loss. Fruit that have lost about 5% of their weight due to water loss show visible symptoms of dehydration.

Postharvest Pathology

Anthracnose *(Colletotrichum gloeosporioides)* is most common, and the symptoms are thin, light-brown patches on fruit edges (Watson et al. 1988). Diseases caused by *Alternaria alternata*, *Cladosporium cladosporioides,* and *Botryodiplodia theobroma* have been reported. These diseases mainly occur at physical injury sites with prolonged storage.

Quarantine Issues

Carambola is a fruit fly host. Irradiation and cold treatment (14 days at 1 ºC) are recommended.

Suitability as Fresh-Cut Product

Slices and pieces have been developed (Matthews 1989). Vacuum-packed slices held at 4 ºC retained color, texture, and flavor for 6 weeks if dipped in citrate.

References

Campbell, C.A. 1989. Storage and handling of Florida carambola. Proceedings of the Inter-American Society for Tropical Horticulture 33:79-82.

Kader, A.A. 1999. Carambola (star fruit). Produce Facts. Perishables Handling Quarterly, no. 93, pp. 19-20. University of California, Davis, CA.

Kenney, P., and L. Hull. 1986. Effect of storage condition on carambola quality. Proceedings of the Annual Meeting of the Florida State Horticultural Society 99:222-224.

Lam, P.F., and C.K. Wan. 1983. Climacteric nature of the carambola (*Averrhoa carambola* L.) fruit. Pertanicka 6:44-47.

Lam, P.F., and C.K. Wan. 1987. Ethylene and carbon dioxide production of starfuits (*Averrhoa carambola* L.) stored at various temperatures and in different gas and relative humidity atmospheres. Trop. Agric. 64:181-184.

Matthews, R.F. 1989. Processing of carambola. Proceedings of the Inter-American Society for Tropical Horticulture 33:89-90.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K.

O'Hare, T.J. 1993. Postharvest physiology and storage of carambola (starfruit): a review. Postharv. Biol. Technol. 2:257-267.

Oslund, C.R., and T.L. Davenport. 1983. Ethylene and carbon dioxide in ripening fruit of *Averrhoa carambola*. HortScience 18:229-230.

Revel, L., and A.K. Thompson. 1994. Carambola in controlled atmospheres. Trop. Fruits Newsletter, Inter-Amer. Inst. Coop. in Agric. 11:7.

Shiesh, C.C., T.S. Lin, and P.L. Tsai. 1987. Respiration and ethylene production of harvested carambola fruits (*Averrhoa carambola* L.). J. Chinese Soc. Hort. Sci. 33:139-150.

Vines, H.M., and W. Gierson. 1966. Handling and physiological studies with carambola. Proceedings of the Annual Meeting of the Florida State Horticultural Society 79:350-355.

Wan, C.K., and P.F. Lam. 1984. Biochemical changes, use of polyethylene bags and chilling injury of carambola (*Averrhoa carambola* L.) stored at various temperatures. Pertanika 7:39-46.

Watson, B.J., A.P. George, R.J. Nissen, and B.I. Brown. 1988. Carambola a star on the horizon. Queensland Agric. J. 114:45-51.

Carrot

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Scientific Name and Introduction

Carrots (*Daucus carata* L.) are biannuals of the Apiaceae (Umbelliferae) family. The edible portion is the storage taproot, which contains high levels of carbohydrates (sugars) and ß-carotene (previtamin A). Available year-round, most of the carrots in U.S. markets are produced in California, with limited production in Michigan, Texas, Colorado, Florida, and Washington (Schaffer 2000).

Quality Characteristics and Criteria

Quality criteria vary with use. High-quality carrots are firm, straight from “shoulder” to “tip,” smooth with little residual “hairiness,” sweet with no bitter or harsh taste, and show no signs of cracking or sprouting (Suslow and Cantwell 1998).

Horticultural Maturity Indices

Harvest maturity varies with the market outlet and use. Fresh market carrots are harvested partially mature, when the roots are about 1.8 cm (0.75 in) or larger in diameter at the upper end (Kotecha et al. 1998). Late harvesting may improve storability by reducing decay during extended storage (Suojara 1999). Fresh-cut processing carrots are harvested immature to ensure they are tender and sweet.

Grades, Sizes, and Packaging

Carrots can be harvested either bunched or top-trimmed; top-trimmed is the dominant method. The common grades for bunched carrots are U.S. No. 1 and U.S. Commercial. For topped carrots, the grades are U.S. Extra No. 1, U.S. No. 1, U.S. No. 1 Jumbo, and U.S. No. 2. Topped carrots are typically packed in 0.5- to 2.25-kg (1- to 5-lb) perforated plastic “Cello-pack” bags that are grouped in 11- or 22- to 22.7-kg (24- or 48- to 50-lb) cartons or master poly bags. Bunched carrots are packed loosely in 12-kg (26-lb) cartons.

Precooling Conditions

Prompt washing and hydrocooling to under 5 °C (41 °F) are essential to maintain carrot freshness and crispness. Typically, carrots pass through several wash and flume steps that remove field heat and are then hydrocooled in chlorinated water before packing.

Optimum Storage Conditions

Storage at 0 to 1 °C (32 to 34 °F) is essential to minimize decay and sprouting during storage. High RH is required to prevent desiccation and loss of crispness. Mature topped carrots can be stored for 7 to 9 mo at 0 °C (32 °F) with 98 to 100% RH. However, commercial storage and distribution conditions rarely achieve the optimum storage conditions and topped carrots are often stored for 5 to 6 mo at 0 to 5 °C (32 to 41 °F) with 90 to 95% RH. Common “Cello-pack” carrots are typically immature and may be stored successfully for 2 to 3 weeks at 3 to 5 °C (37 to 41 °F). Bunched carrots are highly perishable due to the presence of leaves and can be maintained for only 8 to 12 days. Bunched carrots are typically shipped and stored with shaved or flaked ice.

Controlled Atmosphere (CA) Considerations

CA does not extend storage life of carrots beyond that in air with high RH (Leshuk and Saltveit 1990). Low O_2 (1%) inhibited sprouting but also promoted decay (Abdel-Rahman and Isenberg 1974). CO_2 injury appears as soft brown spots upon exposure to air. CO_2 levels above 5% promote decay. Storage at O_2 levels below 3% can result in increased bacterial rot, off flavors, and off odors (Leshuk and Saltveit 1990).

Retail Outlet Display Considerations

Carrots are often displayed loosely on a shelf with mist or in perforated plastic "Cello-pack" consumer packages.

Chilling Sensitivity

Carrots are not chilling sensitive and should be stored as cold as possible without freezing. Their freezing point is -1.2 °C (29.8 °F).

Ethylene Production and Sensitivity

Carrots produce very little ethylene (<0.1 µL kg^{-1} h^{-1} at 20 °C [68 °F]). However, exposure to ethylene (~ 0.2 µL L^{-1}) induces development of the bitter compound isocoumarin (Lafuente et al. 1996, Talcott and Howard 1999). Induction and accumulation of isocoumarin is greatest in the peel of cut carrot sections. Exposure of peeled carrot to ethylene does not result in development of bitterness. Whole or sectioned carrots should not be exposed to ethylene in storage.

Respiration Rates

Temperature	Topped	Bunched
	mg CO_2 kg^{-1} h^{-1}	
0 °C	10 to 20	18 to 35
5 °C	13 to 26	25 to 51
10 °C	20 to 42	32 to 62
15 °C	26 to 54	55 to 106
20 °C	46 to 95	87 to 121

Data from Hardenburg et al. (1986).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Bruising, shatter-cracking, longitudinal cracking, and tip breakage are signs of excessively rough handling. Nantes-type carrots are particularly susceptible to mechanical damage (McGarry 1993). The severity of shatter-cracking is partially related to varietal background. Wilting, shriveling, and rubberiness are signs of moisture loss. Sprouting may occur on topped carrots if the storage temperature is too high. Bitterness can develop in storage due to the accumulation of isocoumarin, caused by disease or exposure to ethylene. Harsh flavor may be caused by high terpenoid content induced by preharvest water stress. Surface browning or oxidative discoloration often develops during storage, especially on carrots harvested when immature.

Postharvest Pathology

The most prominent storage decays are bacteria soft rot (induced by *Pectobacterium carotovora* or *Pseudomonas marginalis*), gray mold rot *(Botrytis cinerea),* rhizopus soft rot (*Rhizopus* spp.), watery soft rot *(Sclerotinia sclerotiorum),* and sour rot *(Geotrichum candidum)* (Snowden 1992). Ozone is a fungistatic against *Botrytis* and

Sclerotinia, but tissue damage and color loss occur after treatment (Liew and Prange 1994). Good sanitation during packing and storage at 0 °C (32 °F) minimizes postharvest diseases.

Quarantine Issues

None

Suitability as Fresh-Cut Product

A significant portion of fresh carrot production is used to produce fresh-cut products such as "baby carrots," carrot coins, shreds, and sticks. Carrots directed or consigned to fresh-cut processing are typically harvested at an immature stage for optimal texture and taste. Fresh-cut carrots typically have a shelf-life of 3 to 4 weeks at 0 °C (32 °F) and 2 to 3 weeks at 3 to 5 ºC (37 to 41 °F). Superficial whitening of the cut surface ("white blush") is caused by dehydration and remains a problem for processors and shippers (Cisneros-Zevallos et al. 1995). Low storage temperature and retention of surface moisture significantly delay development of white blush. Using sharp knives is important to reduce tissue damage and extend shelf-life (Barry-Ryan and O'Beirne 1998).

References

Abdel-Rahman, M. and F.M.R. Isenberg. 1973. Effect of growth regulators and controlled atmosphere on stored carrots. J. Agric. Sci., 53:635.

Barry-Ryan, C., and D. O'Beirne. 1998. Quality and shelf-life of fresh-cut carrot slices as affected by slicing method. J. Food Sci. 63:851-856.

Cisneros-Zevallos, L., M. Saltveit, and J. Krochta. 1995. Mechanism of surface white discoloration of peeled (minimally processed) carrots during storage. J. Food Sci. 60:320-323, 333.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66. U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Kotecha, P.M., B.B. Desai, and D.L. Madhavi. 1998. Carrot. *In* D.K. Salunke and S.S. Kadam, eds., Handbook of Vegetable Science and Technology, pp.119-139. Marcel Dekker, New York, NY.

Lafuente, M.T., G. López-Gálvez, M. Cantwell, and S.F. Yang. 1996. Factors influencing ethylene-induced isocoumarin formation and increased respiration in carrots. J. Amer. Soc. Hort. Sci. 121:537-542.

Leshuk, J.A., and M.E. Saltveit. 1990. Controlled atmosphere storage requirements and recommendations for vegetables. *In* M. Calderon and R. Barkai-Golan, eds., Food Preservation by Modified Atmospheres, pp. 315-352. CRC Press, Boca Raton, FL.

Liew, C.L., and R.K. Prange. 1994. Effect of ozone and storage temperature on postharvest diseases and physiology of carrots (*Daucus carota* L.). J. Amer. Soc. Hort. Sci. 119:5673-567.

Mazza, G. 1989. Carrots. *In* N.A.M. Eskin, ed., Quality and Preservation of Vegetables, pp. 75-119. CRC Press, Boca Raton, FL.

McGarry, A. 1993. Influence of water status on carrot (*Daucus carota* L.) fracture properties. J. Hort. Sci. 68:431-437.

Shaffer, E., ed. 2000. Produce Availability and Merchandising Guide. *In* The Packer. Vance Pub. Corp., Lenexa, KS.

Snowdon, A.L. 1992. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables, pp. 268-293. CRC Press, Boca Raton, FL.

Suojara, T. 1999. Effect of harvest time on the storage performance of carrot. J. Hort. Sci. Biotech. 74:484-492.

Suslow, T., J. Mitchell, and M. Cantwell. 1998. Carrot Produce Facts. Recommendations for Maintaining Postharvest Quality. *At* http://postharvest.ucdavis.edu/produce_information.

Talcott, S.T., and L.R. Howard. 1999. Determination and distribution of 6-methoxymellein in fresh and processed carrot puree by a rapid spectrophotometric assay. J. Agric. Food Chem. 47:3237-3242.

Cassava

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Scientific Name and Introduction

Cassava (*Manihot esculenta* Crantz) is a woody perennial shrub of the Euphorbiaceae family and is native to the Amazon region and Central America. It is widely grown throughout the tropics for its starchy root (Rubatsky and Yamaguchi 1997). Cassava is called "yuca" in Spanish, "mandioca" in Portuguese, "cassave" in Haitian Creole, and "manioc" in French. It is consumed in a variety of ways, but only after some form of processing. Cultivars are classified into two groups based on the amounts of hydrogen cyanide present. Sweet types contain less than 50 mg kg^{-1} HCN (fresh weight) and are generally sold as fresh roots, whereas bitter types have higher amounts of HCN along with higher yields and starch content (da Conceição 1980). These latter types are processed into products including flour (from coarse to finely textured), tapioca starch, and fermented starch. In 2002, 184 million tonnes of cassava was produced worldwide; major producers were Africa (Nigeria) (99 million tonnes), Asia (52 million tonnes), and Latin America and the Caribbean (32 million tonnes). Cassava is adapted to semiarid climates and has been a traditional crop for subsistence farmers, though it is increasingly cultivated as an agronomic crop.

Quality Characteristics and Criteria

Fresh cassava roots are highly perishable under ambient conditions, becoming unmarketable in 3 days or less. However, with proper handling, fresh roots can be stored up to 30 days, permitting export by marine container. The roots should be firm, turgid, fairly straight, and free from mechanical injury, decay, and vascular streaking. The pulp of most common cultivars varies from white to light yellow. Principal causes for loss are vascular streaking and decay. Extended storage can have two adverse effects on quality: starches are converted to sugars, and roots become fibrous, lengthening cooking time (Booth et al. 1976).

Horticultural Maturity Indices

Harvest maturity is based on the root size desired by the market and ranges from 6 to 18 mo after the stem sections are planted. Sweet types usually grow faster than bitter types. The main stem is often trimmed to approximately 1 m (39 in) in height a few days before harvest. Plants are manually pulled, or the root zone mechanically undercut to facilitate plant removal, and individual roots are cut. Cassava roots are turgid at harvest and must be handled carefully to avoid splitting the periderm. Harvest may be delayed until market, processing, or other conditions are favorable, since cassava roots can be stored in the ground for up to 24 mo.

Grades, Sizes, and Packaging

There are no U.S. grade standards for cassava. However, shippers should consult with buyers to define quality expectations. For example, root lengths in excess of 30 cm (11.8 in) are undesirable to many importers. Commercially, roots are cleaned by brushing, rinsing in water, surface-drying, and coating with paraffin wax prior to packing in corrugated cartons.

Precooling Conditions

Room cooling is generally sufficient, provided that the roots are not held too long at ambient temperatures prior to or after packing.

Optimum Storage Conditions

Cassava is very sensitive to water loss, and methods used to maintain high RH during storage include moist sawdust and plastic films (Booth

1976). Paraffin wax is applied to roots exported to the United States. Waxing and holding at 0 to 5 ºC (32 to 41 °F) extends shipping time to over 30 days with minimal vascular streaking. A water-based carnauba wax maintained postharvest quality equivalent to paraffin wax (Sargent et al. 1995).

Controlled Atmosphere (CA) Considerations

No commercial-scale CA recommendations have been reported. Vascular streaking during storage in air was reduced in unwaxed cassava roots by an initial 3-day exposure to 1% O_2 at 25 °C (77 °F) (Aracena 1993).

Retail Outlet Display Considerations

Cassava is normally displayed in bulk and should be held in refrigerated display cases.

Chilling Sensitivity

Cassava is chilling sensitive, but it can be stored at 0 to 5 ºC (32 to 41 °F) with minimal symptom development, as long as immediately consumed when removed from storage before symptoms have had time to develop (Ingram and Humphries 1972).

Ethylene Production and Sensitivity

Cassava roots (‘Valencia’) stored in air at 25 °C (77 °F) and 98% RH produced about 1.2 µL kg^{-1} h^{-1} of ethylene; however, ethylene production doubled at 65% RH (Aracena 1993). Ethylene production was 2.1 µL kg^{-1} h^{-1} for unwaxed roots after 4 days at 25 °C (77 °F) and 1.1 µL kg^{-1} h^{-1} for roots coated with paraffin wax. Exposure to ethylene promotes vascular streaking.

Respiration Rates

After 1 day of storage in air at 25 °C (77 °F) with 98% RH, unwaxed roots respired at a rate of 23 µL CO_2 kg^{-1} h^{-1}, whereas those treated with 75 µL L^{-1} ethylene respired at a rate of 32 µL kg^{-1} h^{-1}. After 4 days under the same conditions, internal CO_2 production was 8 and 11 µL kg^{-1} h^{-1}, while O_2 levels were 9 and 11.5 µL kg^{-1} h^{-1} for unwaxed and waxed roots, respectively (Aracena 1993).

Physiological Disorders

Vascular streaking appears as blue or purple spots when the root is cut transversely and is the result of oxidative processes in the vascular bundles. It typically develops at wound sites, such as at the apical end where the root is cut at harvest or under breaks in the peel that can occur during careless handling. Vascular streaking is related to oxidation of scopoletin, a phenolic compound (Wheatley and Schwabe 1985). Storage of unwaxed cassava roots in 1% O_2 at 25 °C (77 °F) for 3 days significantly reduced vascular streaking during storage in air (Aracena 1993). Exposure to 75 µL L^{-1} ethylene increased vascular streaking, and ethylene induced by wounding or water stress may be the immediate cause of vascular streaking.

Postharvest Pathology

There are two major postharvest fungal diseases of cassava. Botryodiplodia rot (*Botryodiplodia theobromae* Pat.) invades the pulp beneath the skin, initially developing white mold that later becomes dark grey (Snowdon 1992). Fusarium rot (*Fusarium solani*, Mart., Sacc.) also grows on the pulp, causing a brown discoloration. Other pathogens reported by Snowdon (1992) include aspergillus rot *(Aspergillus flavus)*, bacterial soft rot *(Erwinia carotovora* ssp. *carotovora)*, mucor rot *(Mucor hiemalis)*, phytophthora rot *(Phytophthora cryptogea)*, rhizopus rot *(Rhizopus oryzae)*, sclerotium rot *(Corticium rolfsii)*, and trichoderma rot (*Trichoderma harzianum* Rifai).

Quarantine Issues

There are no restrictions on imports from the major production areas.

Suitability as Fresh-Cut Product

There is potential for peeled intact or sliced roots, but shelf-life is currently limited to 2 or 3 days under ideal storage conditions due to vascular streaking.

References

Aracena, J.J. 1993. Mechanism of Vascular Streaking, a Postharvest Physiological Disorder of Cassava Roots. Thesis, Horticultural Sciences Department, University of Florida, Gainesville, FL.

Booth, R.H. 1976. Storage of fresh cassava *(Manihot esculenta).* I. Postharvest deterioration and its control. Exp. Agric. 12:103-111.

Booth, R.H., T.S. de Bucle, O.S. Cardenas, et al. 1976. Changes in quality of cassava roots during storage. J. Food Technol. 11:245-264.

da Conceição, A.C. 1981. A Mandioca. Livraria Nobel, Sao Paulo, Brazil.

Ingram, J.S. and J.R.O. Humphries. 1972. Cassava storage—a review. Trop. Sci. 14:131-148.

Rubatsky, V.E., and M. Yamaguchi. 1997. World Vegetables: Principles, Production, and Nutritive Values, 2nd ed. Chapman & Hall, New York, NY.

Sargent, S.A., T.B.S. Corrê, and A.G. Soares. 1995. Application of postharvest coatings to fresh cassava roots (*Manihot esculenta*, Crantz) for reduction of vascular streaking. *In* L. Kushwaha, R. Serwatowski, and R. Brook, eds., Harvest and Postharvest Technologies for Fresh Fruits and Vegetables, pp. 331-338. American Society of Agricultural Engineers, St. Joseph, MI.

Snowdon, A.L. 1992. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables. CRC Press, Boca Raton, FL.

Wheatley, C.C., and W.W. Schwabe. 1985. Scopoletin involvement in postharvest physiological deterioration of cassava root (*Manihot esculenta* Crantz). J. Expt. Bot. 36:783-791.

Cauliflower

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Scientific Name and Introduction

Brassica oleracea L., Botrytis group of the Brassicaceae (Cruciferae) family, is also known as cauliflower. It is derived from the wild cabbage that is native to southern Europe. Cauliflower produces an edible head of malformed and condensed flowers (the curd) whose stalks are short, fleshy, and closely crowded. Cauliflower is sensitive to its growing environment and requires cool temperatures, plenty of moisture, and good fertility to produce quality heads. Therefore, much of commercial production is in coastal areas having moderate temperatures, or the crop is grown to take advantage of the cooler times of the growing season.

Quality Characteristics and Criteria

Heads of high quality are white to cream in color, firm, and compact. The curds should be free of mechanical damage, decay, browning, or yellowing, which can result from sun exposure. Heads should be surrounded by a whorl of trimmed green, turgid leaves.

Horticultural Maturity Indices

Harvest maturity is based on head diameter and compactness. Mature heads are larger than 15 cm (6 in) in diameter. Signs of overmaturity include “riciness” caused by protruding immature floral parts and browning or spreading of the curds.

Grades, Sizes, and Packaging

There are two grades, U.S. No. 1 and U.S. Commercial. Grading is based on size, external appearance, decay, damage, and trimming (AMS 1968). Heads are normally well-trimmed and packed in a single layer with 12 to 24 heads in a carton weighing 11.4 to 13.6 kg (25 to 30 lb). Cauliflower may also be packed in 27-kg (60-lb) wire-bound crates or 23-kg (50-lb) cartons/crates (Boyette et al. 1996). Cauliflower is commonly packed in the field, where leaves are trimmed closely to the head and heads are overwrapped with a perforated plastic film. The overwrap should have four to six 6-mm (0.25-in) holes to allow adequate ventilation but minimize dehydration. Individual florets are also cut and packed in 2.3- and 4.6-kg (5- and 10-lb) film bags for institutional use, or smaller units for consumer packs.

Precooling Conditions

Cauliflower is mostly vacuum-cooled or hydrocooled prior to storage or marketing. Vacuum cooling works well for field-packed heads and is more effective if cauliflower is wetted before cooling (Stewart and Barger 1961). Forced-air cooling can also be used.

Optimum Storage Conditions

Commercial storage at 0 °C (32 °F) with 95 to 98% RH can maintain good quality for up to 3 weeks or more depending on initial quality. Increasing RH to 98 to 100% can further reduce weight loss and maintain turgidity of the heads (van der Berg and Lentz 1977), but free water accumulation on the curd must be avoided. Storage life is about 7 to 10 days at 5 °C (41 °F), 5 days at 10 °C (50 °F), and 3 days at 15 °C (59 °F) (Herregods 1964). Loss of quality during prolonged storage includes wilting, browning, and spreading of curds; yellowing of leaves; and decay.

Controlled Atmosphere (CA) Considerations

The benefits from CA and modified atmosphere are modest (Saltveit 1997). Low O_2 (below 2%) in combination with 3 to 5% CO_2 may delay leaf yellowing and the onset of curd browning (Romo-Parada et al. 1989). However, injury may occur at below 2% O_2 and/or above 5% CO_2 (Lipton et al. 1967, Lipton and Harris 1976). Injury may not be apparent until curds are cooked, when they become soft, grayish, and develop off flavors. Storage at CO_2 levels above 10% can induce injury within 2 days. Unlike broccoli, fresh cauliflower does not produce strong off odors when held in low-O_2 atmospheres (Forney and Jordan 1999).

Retail Outlet Display Considerations

Bottom-icing of refrigerated displays enhance shelf-life of cauliflower. Plastic overwraps are also important to minimize wilting during marketing.

Chilling Sensitivity

Cauliflower is not chilling sensitive.

Ethylene Production and Sensitivity

Cauliflower has a very low ethylene production rate, <1 µL kg^{-1} h^{-1} at 20 ºC (68 °F). It is extremely sensitive to ethylene, with the most prevalent symptoms being curd discoloration and leaf yellowing and abscission.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	16 to 18
5 °C	20 to 22
10 °C	32 to 36
15 °C	42 to 50
20 °C	74 to 84
25 °C	86 to 98

Data from Suslow and Cantwell (2008).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Black speck is a disorder in which necrotic lesions 0.5 to 4 mm (0.02 to 0.16 in) in diameter appear on the surface of branches or flower stalks in the interior of the curds. This disorder is more prevalent on certain cultivars and is most severe in cauliflower produced during warm weather and rapid growth (Loughton and Riekels 1988).

Boron deficiency can result in brownish discoloration of the curd and pith of the stems and may result in hollow stems. In addition, blisters and cracks may form on the midribs of leaves and curds may taste bitter (Dearborn and Raleigh 1935).

Riciness is a developmental disorder in which elongation of flower stems causes flower clusters to separate, making the head appear granular. Overmaturity and storage at elevated temperatures encourages development of riciness, which can be reduced by timely harvest and storage at 0 °C (32 °F).

Heads are susceptible to *freezing injury,* which appears as water-soaked and grayish curds, if held below 0.8 °C (30.6 °F).

Postharvest Pathology

The major causes of postharvest decay are bacterial soft rot caused by *Erwinia* and *Pseudomonas* spp. and brown rot caused by *Alternaria* spp. (Ceponis et al. 1987). Storing only good quality, disease-free heads and maintaining good temperature control can best control these decay organisms.

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Cauliflower is commonly converted to fresh-cut floret products.

Special Considerations

Growing conditions can strongly influence the quality of fresh cauliflower. Heads must be protected from the sun, normally by tying leaves subtending the head together, to prevent yellowing and strong flavor development in the curd. Only high-quality heads should be stored or shipped long distances. Heads must be handled gently to avoid bruising, which results in rapid browning and decay (Suslow and Cantwell 2008).

Acknowledgments

Some of the information in this chapter was obtained from the Oregon State University website for "Commercial Vegetable Production Guides" at http://horticulture.oregonstate.edu/content/vegetable-production-guides.

References

AMS [USDA Agricultural Marketing Service]. 1968. U.S. Standards for Grades of Cauliflower. U.S. Department of Agriculture, Washington, DC. (http://www.ams.usda.gov/AMSv1.0/standards)

Boyette, M.D., D.C. Sanders, and G.A. Rutledge. 1996. Packaging requirements for fresh fruits and vegetables. (http://www.bae.ncsu.edu/programs/extension/publicat/postharv/ag-414-8/index)

Ceponis, M.J., R.A. Cappellini, and G.W. Lightner. 1987. Disorders in cabbage, bunched broccoli, and cauliflower shipments to the New York market, 1972-1985. Plant Dis. 71:1151-1154.

Dearborn, C.H., and G.J. Raleigh. 1935. A preliminary note on the control of internal browning of cauliflower by the use of boron. Proc. Amer. Soc. Hort. Sci. 33:622-623.

Forney, C.F., and M.A. Jordan. 1999. Anaerobic production of methanethiol and other compounds by *Brassica* vegetables. HortScience 34(4):696-699.

Herregods, H. 1964. The storage of cauliflower. Tuinbouwberichten. 28:486-487.

Leshuk, J.A., and M.E. Saltveit. 1990. Controlled atmosphere storage requirements and recommendations for vegetables. *In* M. Calderon and R. Barkai-Golan, eds., Food Preservation by Modified Atmospheres, pp. 315-352. CRC Press, Boca Raton, FL.

Lipton, W.J., and C.M. Harris. 1976. Response of stored cauliflower (*Brassica oleracea* L., *Botrytis* group) to low-O_2 atmospheres. J. Amer. Soc. Hort. Sci. 101:208-211.

Lipton W.J., C.M. Harris, and H.M. Couey. 1967. Culinary quality of cauliflower stored in CO_2-enriched atmospheres. Proc. Amer. Soc. Hort. Sci. 91:852-859.

Loughton, A., and J.W. Riekels. 1988. Black speck in cauliflower. Can. J. Plant Sci. 68:291-294.

Romo-Parada, L., C. Willemot, F. Castaigne, et al. 1989. Effects of controlled atmospheres (low oxygen, high carbon dioxide) on storage of cauliflower (*Brassica oleracea* L., *Botrytis* Group). J. Food Sci. 54:122-124.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation and Storage of Fruits and Vegetables, vol. 1, Vegetables and Melons. AVI Publishing Co., Westport, CT.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California, Davis, CA.

Stewart, J.K., and W.R. Barger. 1961. Effects of cooling method on the quality of asparagus and cauliflower. Proc. Amer. Soc. Hort. Sci. 78:295-301.

Suslow, T., and M. Cantwell. 2008. Cauliflower: recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

van den Berg, L., and C.P. Lentz. 1977. Effect of relative humidity on storage-life of vegetables. Acta Hort. 62:197-208.

Celeriac

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Scientific Name and Introduction

Celeriac (*Apium graveolens* var. rapaceum Mill. Gaudin) is a member of the Umbelliferae (Apiaceae) family. The harvest portion is a bulbous tuber with a crisp texture and a white flesh that has a nutty, celerylike flavor. It is also known as celery root or apio and can be used fresh or cooked. It must be peeled to remove the rough, light-brown skin if used fresh. California is the primary source of U.S. celeriac.

Quality Characteristics and Criteria

The primary quality characteristics are a firm texture and tender flesh. Roots with a soft, spongy texture should be avoided.

Horticultural Maturity Indices

Celeriac is harvested when it meets market needs for size.

Grades, Sizes, and Packaging

Common packaging is 9.1-kg (20-lb) cartons, though 15.9-kg (35-lb) cartons are also used. There are no defined grading categories for celeriac; it is graded and packed based on relative size.

Precooling Conditions

Celeriac can benefit from precooling since it retains quality best when stored at 0 °C (32 °F). However, since celeriac has a relatively low respiration rate, the benefits of precooling must be balanced with the desired storage time before marketing and consumption.

Optimum Storage Conditions

Celeriac can be stored for 6 to 8 mo at 0 to 2 °C (32 to 36 °F) with RH of 97 to 98%. Storage life can be under 4 mo if temperature exceeds 3 °C (38 °F). High RH of 90 to 98% is needed to prevent moisture loss, which results in shriveling. Freezing injury can occur if celeriac is stored at temperatures below -1 °C (30 °F) and is manifested as water-soaked areas or softening.

Controlled Atmosphere (CA) Considerations

CA storage is not recommended for celeriac. Storage in low-O_2 and high-CO_2 atmospheres increased decay during 5 mo storage (Weichmann 1976, 1977). However, storage in 2% O_2 with 2 to 3% CO_2 may be beneficial (Cantwell 2001).

Retail Outlet Display Considerations

Water sprinkle and top ice are beneficial.

Chilling Sensitivity

Celeriac is not chilling sensitive and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Ethylene production is low, <0.1µL kg^{-1} h^{-1} at 20 °C (68 °F). However, celeriac may be slightly sensitive to ethylene. Therefore, celeriac should not be stored with other fruit or vegetables that produce high levels of ethylene.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	5 to 8
5 °C	11 to 15
10 °C	18 to 28
15 °C	32 to 38
20 °C	41 to 49

Data from Morris (2001).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Ethylene exposure may result in toughening of the root.

Postharvest Pathology

Decay may become a problem if celeriac is stored in a warm, humid environment.

Suitability as Fresh-Cut Product

No current potential is apparent.

Acknowledgments

Much of the information in this chapter was taken from the previous edition of this Handbook and from the Produce Marketing Association's "Fresh Produce Manual."

References

Cantwell, M. 2001. Celeriac. *At* http://postharvest.ucdavis.edu.

Kurki, L. 1971. Moisture in vegetable storage. Acta Hort. 20:146-151.

Morris, S. 2001. Fruit and vegetables storage and transport database. *At* http://www.postharvest.com.au/celeriac.pdf.

Weichmann, J. 1976. Storage of celeriac. Indus. Obst. Gemuseverwert. 61(8):205-207.

Weichman, J. 1977. CA storage of celeriac. Acta Hort. 62:109-118.

Wiersma, O. 1973. Storage of celeriac. Betrijfsouteikkeling 4:79-80.

Celery

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Scientific Name and Introduction

Celery (*Apium graveolens* L.) is a biennial of the Umbelliferae (Apiaceae) family but is planted and harvested as an annual crop. The edible portion is the long, thick, green fleshy petioles and, if present after trimming, associated leaves. California supplies 75% of U.S. production, with other significant production coming from Florida and Michigan (Schaffer 2000).

Quality Characteristics and Criteria

High-quality celery consists of petioles that are well-formed, thick, compact, straight, tender, and light green (Suslow and Cantwell 2002). Additional quality indices are stalk and midrib length; absence of defects such as blackheart, pithiness, seed stalks, and cracks; and absence of insect damage and decay. Any leaves remaining on the stalk after trimming should not be wilted, yellow, or decayed.

Horticultural Maturity Indices

Celery is harvested when the overall field reaches the desired marketable size of 35 to 41 cm (14 to 16 in) stalk length, and before the outer petioles develop "pithiness." Early harvests before the plants reach full size produce stalks with high market quality, and the prices received may more than compensate for lower yield.

Grades, Sizes, and Packaging

U.S. grades are U.S. Extra No. 1, U.S. No. 1, and U.S. No. 2. Celery may be sold as "unclassified" to designate a lot that has not been graded according to U.S. standards. In California, fresh-market celery is field-packed in 27.2-kg (60-lb) cartons containing 48 stalks or in 12.7-kg (28-lb) cartons containing 12 or 18 hearts. Florida celery is packed in seven size grades from 18 to 96 stalks per crate. Celery hearts are prepared from smaller stalks that are trimmed to 20, 25, or 30 cm (8, 10, or 12 in) in length, and packed in 8- or 13-kg (18- or 28-lb) cartons (Peirce 1987).

Precooling Conditions

Celery is typically hydrocooled or vacuum-cooled with a chilled water spray application. Prompt precooling to near 0 °C (32 °F) is essential to maintain freshness and crispness, as well as for extended storage.

Optimum Storage Conditions

Celery can be stored for up to 5 to 7 weeks at 0 °C (32 °F) and 95% RH. At optimum conditions, celery can be stored for up to 5 to 7 weeks with good quality (Hardenburg et al. 1986). Storage life is reduced to less than 2 weeks at 5 °C (41 °F). Inner petioles may continue to grow during storage at temperatures above 0 °C (32 °F), resulting in quality loss.

Controlled Atmosphere (CA) Considerations

CA and MA offer small to moderate benefits (Saltveit 1997). CA-stored stalks maintain better texture and crispness than those stored in air (Gariepy et al. 1984). Reduced O_2 (2 to 4%) and elevated CO_2 (3 to 5%) delay senescence, leaf yellowing, and decay (Leshuk and Saltveit 1990). However, low-O_2 or high-CO_2 injuries may occur when O_2 is under 2% or CO_2 is over 10%, resulting in off odors, off flavors, and internal leaf yellowing.

Retail Outlet Display Considerations

Celery stalks can be displayed as twist-tied stalks, with or without a plastic sleeve, or in prepackaged consumer bags typically used for celery hearts. The use of both top ice and misting are acceptable to reduce moisture loss and maintain freshness.

Chilling Sensitivity

Celery is not chilling sensitive and should be stored as cold as possible without freezing. The freezing point for celery is -0.5 °C (31.1 °F) (Whiteman 1957).

Ethylene Production and Sensitivity

Celery produces little ethylene, <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F). The effect of ethylene depends on temperature and concentration. Celery is not very sensitive to low concentrations of ethylene when exposed at low temperatures. Above 5 °C (41 °F), ethylene levels higher than 10 µL L^{-1} accelerate yellowing and development of pithiness.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	10 to 20
5 °C	13 to 26
10 °C	20 to 42
15 °C	26 to 54
20 °C	46 to 95

Data from Hardenburg et al. (1986).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Pithiness is a major source of quality loss and decreased shelf-life (Saltveit and Mangrich 1996). It is characterized by the appearance of whitish regions and air spaces within the tissues and reduced tissue density and is caused by the breakdown of the internal pith parenchyma tissues of the petiole to produce aerenchyma. Pithiness may be induced by preharvest factors, including cold stress, water stress, bolting (seed stalk induction), and root infection. Storage temperature has a major impact on development of pithiness after preharvest induction. Development of pithiness is delayed by storage at 0 °C (32 °F).

Blackheart is a physiological disorder caused by cell death resulting from calcium deficiency and preharvest water stress. Internal leaves develop brown discoloration, which eventually becomes deep black.

Brown check is a disorder related to boron deficiency. It appears as cracks on the inner petiole surface, and exposed tissues become brown and are susceptible to pathogen infection and decay.

Crushing or cracking of the petiole are signs of mechanical damage and may lead to rapid browning and decay. Harvesting, packing, and handling should be done with great care to prevent damage to the highly sensitive turgid petioles.

Freezing injury occurs below -0.5 °C (31.1 °F). Mild freezing causes depressions in the tissues that subsequently turn brown. Severely frozen tissues develop a wilted and water-soaked appearance on thawing.

Postharvest Pathology

The most prominent storage decay is bacteria soft rot (primarily caused by *Pectobacterium* or *Pseudomonas*), gray mold *(Botrytis cinerea)*, and watery soft rot (*Sclerotinia* spp.) (Snowden 1992). Storage at 0 °C (32 °F) is important to minimize losses due to postharvest decay. Controlled atmospheres (1.5% O_2 and 7.5% CO_2) suppress the growth of *Sclerotinia* and watery soft rot (Reys and Smith 1986, Reys and Smith 1987). However, careful maintenance of atmospheric composition is required as celery is susceptible to low-O_2 and high-CO_2 injury.

Quarantine Issues

None. However, export loads of celery may be fumigated at entry ports if common insects (aphids and thrips) are found.

Suitability as Fresh-Cut Product

The majority of fresh-cut celery is in the form of celery sticks (cut petioles). Fresh-cut celery can be packed alone or in combination with other vegetables, such as carrots and broccoli. The shelf-life of fresh-cut celery is typically 12 to 14 days at 0 to 5 °C (32 to 41 °F). Discoloration of vascular tissue, splitting of the cut ends, and bacteria decay are major problems limiting shelf-life of fresh-cut celery (Robbs et al. 1996, Saltveit and Mangrich 1996).

References

Gariepy, Y., G.S.V. Raghavan, R. Plasse, et al. 1984. Long-term storage of cabbage, celery, and leeks under controlled atmosphere. Acta Hort. 157:193-201.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Leshuk, J.A., and M.E. Saltveit. 1990. Controlled atmosphere storage requirements and recommendations for vegetables. *In* M. Calderon and R. Barkai-Golan, eds., Food Preservation by Modified Atmospheres, pp. 315-352. CRC Press, Boca Raton FL.

Peirce, L.C. 1987. Vegetables—Characteristics, Production, and Marketing, pp. 240-245. John Wiley & Sons, New York, NY.

Reys, A.A., and R.B. Smith. 1986. Suppression of sclerotinia and watery soft rot of celery by controlled atmosphere storage. Plant Dis. 72:790-792.

Reyes, A.A., and R.B. Smith. 1987. Effect of oxygen, carbon dioxide, and carbon monoxide on celery in storage. HortScience 22:270-271.

Robbs, P.G., J.A. Bartz, G. McFie, and N.C. Hodge. 1996. Causes of decay of fresh-cut celery. J. Food Sci. 61:444-448.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California, Davis, CA.

Saltveit, M.E., and M.E. Mangrich. 1996. Using density measurement to study the effect of excision, storage, abscisic acid, and ethylene on pithiness in celery petioles. J. Amer. Soc. Hort. Sci. 121:137-141.

Shaffer, E., ed. 2000. Produce Availability and Merchandising Guide. The Packer. Vance Publishing Corp., Lenexa, KS.

Snowdon, A.L. 1992. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables, pp. 182-195. CRC Press, Boca Raton, FL.

Suslow, T., and M. Cantwell. 2002. Celery Produce Facts. Recommendations for Maintaining Postharvest Quality. *At* http://postharvest.ucdavis.edu/produce_information.

Whiteman, T. 1957. Freezing Points of Fruits, Vegetables and Florist Stocks. Marketing Research Report 196, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Cherimoya

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Scientific Name and Introduction

The cherimoya (*Annona cherimola* Mill.) is a heart-shaped fruit having few seeds and a smooth skin that does not break apart during ripening. It is grown in Florida, California, and Hawaii.

Quality Characteristics and Criteria

Quality is determined by fruit size, shape, and skin color, as well as the absence of defects and decay. Fruit are very susceptible to mechanical injury. Sugar levels can vary from 14 to 18%, with moderate acid levels.

Horticultural Maturity Indices

Mature fruit are firm and become very soft during ripening. The skin changes color from dark green to light green or greenish yellow, and is associated with increased surface smoothness. Fruit are harvested when mature and are allowed to ripen during marketing.

Grades, Sizes, and Packaging

There are no U.S. or international standards. Pack fruit in single layers in fiberboard cartons with foam sleeve or paper wrapping to avoid bruising. Carton size is usually 4 to 8 kg (9 to 18 lb) with 12 to 24 count. Fruit weight is from 250 to 600 g (9 to 21 oz).

Precooling Conditions

Fruit should be precooled as soon as possible after harvest to about 12 ºC to 15 ºC (54 to 59 ºF), with room cooling or forced-air cooling used most often.

Optimum Storage Conditions

Store fruit at 10 to 13 ºC (50 to 55 ºF) with 90 to 95% RH for 2 to 3 weeks. If held at 20 ºC (68 ºF), fruit will last 3 to 4 days (Kader and Arpaia 1999). Storage is limited by skin darkening, desiccation, and disease due to chilling injury. Ripe, soft fruit should be held at 0 to 5 ºC (32 to 41 ºF).

Controlled Atmosphere (CA) Considerations

Fruit held in 5% O_2 for 30 days at 10 ºC (50 ºF) ripened in 11 days after removal to air storage at 20 ºC (68 ºF) versus 3 days for fruit held in 20% O_2 (Palma et al. 1993a). Addition of CO_2 at 3% or 6% can also extend storage life beyond that of storage in air (Alique and Oliveria 1994). However, not all results have been positive, and there may be varietal differences (Moreno and Dela Plaza 1983). O_2 levels under 1% can lead to off flavor.

Retail Outlet Display Considerations

Display at room temperature (approximately 20 to 23 ºC or 68 to 73 ºF) if not ripe. Do not use misting or ice.

Chilling Sensitivity

Fruit are chilling sensitive, especially at temperatures below 10 ºC (50 ºF). The extent of injury depends on duration. Symptoms include skin darkening and a failure to fully soften and develop full flavor.

Ethylene Production and Sensitivity

The cherimoya is a climacteric fruit and has high rates of ethylene production (100 to 300 µL kg^{-1} h^{-1} at 20 ºC [68 ºF]) (Palma et al. 1993b). Exposure to ethylene at 100 µL L^{-1} for 24 h leads to rapid ripening of mature green fruit.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
10 ºC	47 to 190
15 ºC	84 to 280
20 ºC	138 to 460

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Chilling injury is the major postharvest disorder, in which the skin darkens and the flesh fails to soften and can be "mealy" with poor flavor (Palma et al. 1993b). The degree of injury depends on variety and ripeness stage. Mechanical injury is a major problem during handling, which leads to unsightly black blemishes that can be sunken. Splitting can occur during ripening and provide sites for decay. Early-season fruit that frequently develop higher sugar levels are more susceptible to splitting.

Postharvest Pathology

Anthracnose *(Colletotrichum gloeosporioides)* appears as dark lesions and may produce pink spore masses under high RH. Black canker *(Phomopsis anonacearum)* appears as purple spots that become hard and cracked, while *Botryodiplodia* rot *(Botryodiplodia theobroma)* first appears as purple, then black, spots, and the flesh becomes brown and corky. These are preharvest diseases that require good orchard sanitation. Careful handling and sanitation with cooling, along with fungicides if approved, can minimize the problems.

Quarantine Issues

The cherimoya is a fruit fly host. Other quarantine pests include seed borers and scales. Heat treatments and irradiation are potential treatments.

Suitability as Fresh-Cut Product

The cherimoya is sold as a fresh-cut product, though the shelf-life is unknown. Ripe pieces can be held at 0 to 1 ºC (32 to 34 ºF).

References

Alique, R., and G.S. Oliveira. 1994. Changes in sugars and organic acids in cherimoya (*Annona cherimola* Mill.) fruit under controlled atmosphere storage. J. Agric. Food Chem. 42:799-803.

Kader, A.A., and M.L. Arpaia. 1999. Cherimoya, atemoya and sweet set-sop. Produce Facts. Perishables Handling Quarterly, no. 97, pp. 17-18. University of California, Davis, CA.

Moreno, J., and J.L. de la Plaza. 1983. The respiratory intensity of cherimoya during refrigerated storage: a special case of climacteric fruit. Acta Hort. 138:179-186.

Palma, T., D.W. Stanley, J.M. Aguilera, and J.P. Zoffoli. 1993a. Respiratory behavior of cherimoya (*Annona cherimola* Mill.) under controlled atmospheres. HortScience 28:647-649.

Palma, T., J.M. Aguilera, and D.W. Stanley. 1993b. A review of postharvest events in cherimoya. Postharv. Biol. Technol. 2:187-208.

Cherry (Sweet)

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Scientific Name and Introduction

Prunus avium L., the sweet cherry, is a stone fruit of the Rosaceae family. The edible portion consists of outer layers of the mature ovary wall, the flesh (mesocarp) and the skin (exocarp). The pit (endocarp) encloses the seed. Numerous cultivars are grown commercially including 'Attika,' 'Bing,' 'Brooks,' 'Burlat,' 'Chelan,' 'Lambert,' 'Lapins,' 'Rainier,' 'Tieton,' 'Skeena,' and 'Sweetheart.' Sweet cherries are primarily grown in the Western United States in California, Oregon, and Washington. Fruit harvest begins in California in May and continues through mid-August in Oregon and Washington.

Quality Characteristics and Criteria

Premium sweet cherries have a bright, shiny appearance. Fruit color can be dark red ('Bing'), red ('Sweetheart'), or yellow with a red blush ('Rainier' and 'Royal Ann'). The appearance of the stem, which should be green and free from brown discoloration, is also critical for marketing. Flavor is enhanced by highly soluble solids and titratable acid content with a firm, juicy fruit texture.

Horticultural Maturity Indices

Fruit color is the most consistent and reliable maturity index. Different cultivars can be harvested at slightly different color stages. For example, 'Bing' cherries should be a mahogany red color rather than lighter red (immature) or purplish red (overmature). 'Lambert' cherries can be harvested at a brighter, less dark-red color, while 'Van' cherries can be harvested at a darker red color than 'Bing' (Crisosto 1991).

Grades, Sizes, and Packaging

Grades include Washington No. 1 and 2, Northwest No. 1 and 2, and U.S. No. 1 and 2. Grades are based primarily on appearance, and the three grading systems differ in tolerance to defects. Sizes are typically expressed as row count and range from 9 to 12. Packages commonly are 20-lb cartons, though smaller units are becoming more available.

Precooling Conditions

Sweet cherries should be cooled to below 5 ºC by 4 h after harvest. Room cooling, forced-air cooling, and hydrocooling are all used to cool sweet cherry fruit. Of these, hydrocooling is the most rapid, and chlorine compounds can be added to the hydrocooler water to reduce decay potential (Do et al. 1966).

Optimum Storage Conditions

Recommended conditions for storage of sweet cherries are -1 to 0 ºC with RH at over 95%. Sweet cherries maintain good quality for 2 to 4 weeks under these conditions.

Controlled Atmosphere (CA) Considerations

Reduction in the amounts of color change (darkening), acid and firmness loss, incidence of decay, and stem browning are potential benefits of CA storage and MAP (modified atmosphere packaging). The effectiveness of these technologies is determined in part by fruit quality at harvest. Fruit harvested at a more advanced stage of maturity (low acid, dark color, low firmness) will not realize as much benefit from CA or MAP. Optimal atmosphere conditions for CA range from 1 to 5% O_2 with 5 to 20% CO_2 (Chen 1981, Patterson 1982, Mattheis et al. 1997). For MAP, 5 to 10% O_2 with 5 to 15% CO_2 is effective when fruit temperature is maintained at 0 to 5 ºC (Mattheis and Reed 1994, Meheriuk et al. 1995). Temperature control for MAP systems is critical because the risk of anaerobiosis increases as packaged fruit temperature increases.

Retail Outlet Display Considerations

Refrigeration during display is critical to reduce quality loss due to stem browning, shrivel, and development of decay. Fruit should be held at 5 ºC or less to slow deterioration. Fruit should be refrigerated but not wetted because continuous moisture on the surface can cause splitting.

Chilling Sensitivity

Sweet cherries are not sensitive to chilling and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Sweet cherries produce very low amounts of ethylene but will respond to exogenous or wound-induced ethylene with increased respiration and quality loss.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	6 to 10
5 °C	16 to 28
10 °C	20 to 36
15 °C	28 to 64
20 °C	40 to 90

Data from Gerhardt et al. (1942), Micke et al. (1965), and Mattheis (1998).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Pitting and bruising are common problems caused by harvest injury and rough postharvest handling (Facteau and Rowe 1979, Thompson et al. 1997). Fruit pitting is a manifestation of subsurface damage that develops into sunken areas near the fruit surface. Bruising can occur from excess compression, drops or large impacts during harvest, transport, or packing. Visual symptoms of pits and bruises often do not appear until well after the fruit have been packed, resulting in visible damage appearing in wholesale or retail markets.

Sweet cherries are also prone to shrivel and water loss due to the lack of a well-developed cuticle. Water loss can be minimized by prompt cooling and storage in a high-RH environment.

Stem browning is another potential physiological disorder. Stem browning can be minimized by proper temperature and RH management; however, packing procedures that scrape or injure stems create wounds that will brown. In addition to proper temperature management, use of chlorine dioxide in hydrocooler water can reduce development of stem browning (Roberts 1989).

Postharvest Pathology

Fungal pathogens including *Penicillium expansum* (blue mold), *Botrytis cinerea* (gray mold), *Alternaria* sp., *Monilinia fructiocola* (brown rot), *Rhizopus stolonifer, Cladosporium* sp., and *Aspergillus niger* are the main causes of sweet cherry decay (Crisosto 1991, Adaskaveg and Ogawa 1994, Dugan and Roberts 1997). Many of these pathogens infect fruit early in development and are present as quiescent infections at harvest (Dugan and Roberts 1994). Fruit can also be infected via rain splits or wounds that occur at harvest or during packing. The use of postharvest sanitation and fungicides minimizes postharvest decay (Willet et al. 1989). Low-temperature storage, fungicide application, and MAP with high CO_2 (5 to 20%) all slow pathogen growth (English and Gerhardt 1942, Gerhardt et al. 1942, 1956, DeVries-Patterson et al. 1991, Brash et al. 1992, Spotts et al. 1998).

Quarantine Issues

Fruit exported to Japan must be fumigated with methyl bromide to control codling moth larvae. Fruit shipped into California must be inspected and certified free from cherry fruit fly infestation.

Suitability as Fresh-Cut Product

No current potential.

Special Considerations

Sweet cherries must be cooled promptly after harvest and low temperatures maintained throughout packing, storage, and transport. Low temperatures minimize quality loss as well as physiological and pathological disorders. Maintenance of low temperature is critical when using MAP systems to avoid anaerobic conditions and off-flavor development.

References

Adaskaveg, J.E., and J.M. Ogawa. 1994. Penetration of iprodione into mesocarp fruit tissue and suppression of gray mold and brown rot of sweet cherries. Plant Dis. 78:293-296.

Brash, D.W., L.H. Chea, and W. Hunt. 1992. Controlled atmospheres inhibit storage rot of cherries. *In* A.J. Popay, ed., Proceedings of the 45th New Zealand Plant Protection Conference, August 11-13, 1992, pp. 136-137. New Zealand Plant Protection Society, Auckland, New Zealand.

Chen, P.M., W.M. Mellenthin, S.B. Kelly, and T.J. Facteau. 1981. Effects of low oxygen and temperature on quality retention of ‘Bing’ cherries during prolonged storage. J. Amer. Soc. Hort. Sci. 106:533-535.

Crisosto, C.H. 1991. Sweet cherry harvesting, postharvest handling and storage. Perishables Handling Quarterly, no. 71. University of California, Davis, CA.

DeVries-Patterson, R.M., A.L. Jones, and A.C. Cameron. 1991. Fungistatic effects of carbon dioxide in a package environment on the decay of Michigan sweet cherries by *Monilinia fructicola*. Plant Dis. 75:943-946.

Do, J.Y., D.K. Salunkhe, D.V. Sisson, and A.A. Boe. 1966. Effects of hydrocooling, chemical, and packaging treatments on refrigerated life and quality of sweet cherries. Food Technol. 20:115-118.

Dugan, F.M., and R.G. Roberts. 1994. Etiology of preharvest colonization of Bing cherry fruit by fungi. Phytopathology 84:1031-1036.

Dugan, F.M., and R.G. Roberts. 1997. Preharvest fungal colonization affects storage-life of Bing Cherry Fruit. J. Phytopathology 145:225-230.

English, H., and F. Gerhardt. 1942. Effect of carbon dioxide and temperature on the decay of sweet cherries under simulated transit conditions. Proc. Am. Soc. Hort. Sci. 40:172-176.

Facteau, T.J., and K.E. Rowe. 1979. Factors associated with surface pitting of sweet cherry. J. Amer. Soc. Hort. Sci 10:706-710.

Gerhardt, F., H. English, and E. Smith. 1942. Respiration, internal atmosphere and moisture studies of sweet cherries during storage. Proc. Amer. Soc. Hort. Sci. 41:119-123.

Gerhardt, F., H. Schomer, and T.R. Wright. 1956. Sealed Film Lug Liners for Packing Bing Cherries. Pub. no. 121, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Mattheis, J.P., and N. Reed. 1994. Response of ‘Bing’ sweet cherries to modified atmosphere packaging. Proceedings of the Oregon Horticultural Society, January 1994, pp. 22-28.

Mattheis, J.P., D.A. Buchanan, and J.K. Fellman. 1997. Volatile constituents of ‘Bing’ sweet cherry fruit following controlled atmosphere storage. J. Agric. Food Chem. 45:12-216.

Mattheis, J.P. 1998. ‘Bing’ cherry respiration. *In* Interesting and Valuable Fruit Stuff. *At* http://www.ars.usda.gov/Main/site_main.htm?modecode=53-50-00-00.

Meheriuk, M., B. Girard, L. Moyls, et al. 1995. Modified atmosphere packaging of ‘Lapins’ sweet cherry. Food Res. Int. 28:239-244.

Patterson, M.E. 1982. CA storage of cherries. *In* D.G. Richardson, M. Meheriuk, and S. Blankenship, eds., Controlled Atmospheres for Storage and Transport of Perishable Agricultural Commodities, pp. 149-154. Timber Press, Beaverton, OR.

Roberts, R.G. 1989. The potential for use of chlorine dioxide as a postharvest tool for the Pacific Northwest fruit industry. *In* Proceedings of the 5th Annual Warehouse Seminar and Trade Show, Wenatchee, WA, 1989, pp. 37-40. Washington State Horticultural Association, Wenatchee, WA.

Spotts, R.A., L.A. Cervantes, T.J. Facteau, and T. Chand-Goyal. 1998. Control of brown rot and blue mold of sweet cherry with preharvest iprodione, postharvest *Cryptococcus informo-miniatus*, and modified atmosphere packaging. Plant Disease 82:1158-1160.

Thompson, J.F., J.A. Grant, E.M. Kupferman, and J. Knutson. 1997. Reducing sweet cherry damage in postharvest operations. HortTechnology 7:134-138.

Willett, M., G. Kupferman, R. Roberts, et al. 1989. Integrated management of postharvest diseases and disorders of apple, pears and cherries. Washington State University Postharvest Pomology Newsletter 7:1-15.

Chicory (Belgian Endive or Witloof Chicory)

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Scientific Name and Introduction

Belgium endive or witloof chicory (*Cichorium intybus* L.) is a biennial herbaceous plant belonging to the Asteraceae family. In addition to chicory's use a leafy salad vegetable, the roots of some cultivars are grown for use as a coffee substitute. Related vegetables of commercial value include lettuce (*Lactuca sativa* L., Cichorium tribe), endive and escarole (*Cichorium endivia* L.), and radicchio (*Cichorium intybus* L.). The edible portion of chicory is the young, enlarged, compact, and etiolated terminal bud that is composed of young leaves and the partially suppressed but enlarging floral stem. In the trade, this product is called a chicon. This large bud results from the forced growth of the apical bud on a defoliated and vernalized root in storage. The roots are harvested after a year of growth, partially defoliated except for the apical bud, and stored until ready for forcing.

Belgium endive is a popular vegetable in northern European countries, where it is available year-round. The crop is mostly for European consumption and of little interest elsewhere. In the United States, it is not well known or appreciated by the general public. Accordingly, production is minor and supply is augmented by air shipments from Europe.

Quality Characteristics and Criteria

High-quality chicons are compact and turgid with closely overlapping outer leaves having a mother-of-pearl luster or milky-white appearance and a light yellow tinge on leaf margins. They should be sound, free of reddish blemish, frost damage, or traces of bruises, disease, insects, parasites, or rodent attack. A chicon should feel heavy for its size. Leaf tips should not curl back, and the base should be well-trimmed perpendicular to the upright axis and without discoloration. It should be lanceolate in shape, with the length ranging from 2 to 3 times the maximum width. Quality is decreased by flower stem development in excess of three-fourths of the bud's length.

Development of green leaf color is a quality defect. Though leaf greening constitutes quality loss for many markets, U.S. consumers tolerate a slight amount without significant penalty. A small number of cultivars produce anthocyanin and are reddish-purple in coloration. Elevated temperatures during holding and retail presentation are more important than exposure to light in inducing greening.

Horticultural Maturity Indices

Depending on temperature, optimum harvest is 20 to 30 days after forcing. Harvest delays result in elongated chicon and loss of compaction. Chicons are harvested when outer leaves are tightly appressed and density is maximal. The basal portions of the outermost leaves should be well sheathed. Leaf margins should be thin and smooth. Timely harvest maximizes potential shelf-life compared to harvesting at a later stage of development. Deterioration is mainly due to marginal leaf drying or browning, which can occur rapidly (Herregods 1971).

Grades, Sizes, and Packaging

Grading is largely determined by uniformity of shape, overall appearance, and the ratio of length to width. Highest quality chicons are 9 to 17 cm (3.5 to 6.8 in) in length and have a maximum diameter of 6 cm (2.5 in). The typical ratio of length to width is 2:1 to 3:1.

U.S. grades are Extra, Standard, and Baby, while European standards are Extra, Class

I, II, and II irregular. Extra category chicons are uniformly shaped, meet appropriate size dimensions, have outer leaves that measure at least half of the chicon length, are firm, and do not exhibit greening or a glassy appearance. Lesser quality involves less uniformity, less favorable appearance, deterioration, and loss of compaction.

Precooling Conditions

Trays holding the forced roots can be moved to a cold room for a day or overnight before snapping (that is, removal of chicons from the roots). Condensation on the chicons when transferred to a warmer packing area is undesirable. Precooling in this manner wastes energy because the entire roots of both marketable and unmarketable chicons are cooled. Hydrocooling is very effective, but water infiltration is difficult to remove and reduces shelf-life. Vacuum cooling is seldom used since it is expensive and results in a loss of moisture accounting for 2 to 3% of the product's fresh weight. Forced-air cooling is occasionally used, but it is not effective in cooling product in film packages. Conventional room cooling is the most commonly used method. It is the least expensive but is relatively slow compared with other precooling techniques.

In the United States, chicons are packed in pasteboard containers that contain 4.5 kg (10 lb) of product. Perforated plastic film bags are also used for packaging, as are film-overwrapped trays. Perforations account for about 0.5% of the bags surface and are intended to limit condensation because moisture on the chicons is detrimental to maintaining quality. Bags are opaque or covered with translucent blue or green paraffin paper to exclude light.

Optimum Storage Conditions

Chicons should be stored in the dark at 0 °C (32 °F) and 95 to 100% RH (Hardenburg et al. 1986). Storage life is reduced to 2 to 4 weeks at 2 ºC (36 °F), 1 to 2 weeks At 5 ºC (41 °F), and 1 week or less at 15 ºC (59 °F). There is little greening at 0 °C (32 °F), even in the presence of light, but greening increases with increasing temperature.

Controlled Atmosphere (CA) Considerations

Storage life can almost be doubled by storage in 3 to 4% O_2 with 4 to 5% CO_2 at 0 °C (32 °F). CA storage delays greening of leaf tips in light and leaf spreading.

Retail Outlet Display Considerations

Maintain cold conditions to maximize storage and shelf-life and minimize dehydration, but do not sprinkle or otherwise wet the product. Packaged chicons should be held in conditions similar to those of packaged mushrooms, not in wet storage areas.

Chilling Sensitivity

Chicory is not chilling sensitive, but it freezes at -0.5 °C (31 °F).

Ethylene Production and Sensitivity

Ethylene production is very low, but exposure to ethylene can produce physiological disorders such as russet spotting and accelerated senescence.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	2 to 3
5 °C	5 to 6
10 °C	12 to 14
15 °C	20 to 22
20 °C	35 to 38

Data from Saltveit (2002, unpublished).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production,

multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Disorders include brown or hollow core, blackheart, foliage pinking, and red discoloration of tissue that has been bruised or cut. A similar reddish-orange coloration occurs when leaves split or are torn. Additional disorders include russet spotting, the formation of light hairlike growth on leaves, and leaf greening. Other causes of chicon deterioration are continued growth of the stem, resulting in leaf spreading and opening; leaf greening, loss of turgor, and wilting that results in a loss of weight, grade, and quality; and the appearance of bruises at the base or on the leaves that become more apparent at retail. Chicons showing any signs of cuts, drying, burses, or torn tissue should be excluded from sale.

Postharvest Pathology

The most common decays are *Erwinia carotovora*, *Botrytis cinerea*, and other pathogens such as *Phytophthora cryptogea*, *Sclerotinia sclerotiorum*, *Phoma exigua*, and several *Pseudomonas* spp. Infection of the chicons in the forcing facilities is most often due to the disease organism being introduced on the roots.

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Potential is low, but loose leaves are occasionally marketed in some prepackaged salad mixes. The marketing of detached leaves is occasionally done to recover some value from fresh market product that is damaged or otherwise would be wasted.

Special Considerations

Chicons must be handled with care to avoid mechanical damage to minimize discoloration and pathological problems. Temperatures must be kept low, and light must be excluded to prevent greening. High RH is necessary to prevent loss of turgor and wilting.

References

Corey, K.A., D.J. Marchant, and L.F. Whitney. 1990. Witloof chicory: a new vegetable crop in the United States. *In* J. Janick and J.E. Simon, eds., Advances in New Crops, pp. 414-418. Timber Press, Portland, OR.

De Proft, M., J. De Greef, K. Van Nerum, and G. Goffings. 1986. Ethylene in the production of Belgian endive. HortScience 21:1132-1133.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Herregods, M. 1971. The effect of some factors on witloof during storage. Acta Hort. 20:36-42.

Rubatzky, V.E., and M. Yamaguchi. 1997. Witloof chicory. *In* World Vegetables—Principles, Production, and Nutritive Values, pp. 351-354. Chapman & Hall, New York, NY.

Ryder, E.J. 1979. Leafy Salad Vegetables, pp. 171-194. AVI Pub. Co., Westport, CT.

Chinese Cabbage

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Scientific Name and Introduction

Chinese cabbage, *Brassica rapa* L. (*B. campestris* L.) subsp. *pekinensis* (Lour.) Hanelt, is an annual of the Brassicaceae (Cruciferae) family (Munro and Small 1997). The edible portion includes the leaf blades and stalks. Two head shapes predominate: the wong bok or napa types (which are short and broad) and the michihli types (which are long and tapered) (Wang and Cerkauskas 1999). Chinese cabbage is grown in small acreages in most major temperate vegetable-growing regions and is available year round in most markets.

Quality Characteristics and Criteria

Chinese cabbage should have uniform, tightly formed heads with crinkly, yellow-green leaf blades. Head shape and leaf characteristics can vary, depending on the cultivar. There should be no evidence of leaf wilting or discoloration.

Horticultural Maturity Indices

Determination of maturity in species of *Brassica* is not simple, and no single index of maturity is reliable (Ludford and Isenberg 1987). Harvesting consists of cutting the whole plant at the soil surface when the heads are firm and the outer leaves are bright green (Munro and Small 1997). In some cultivars, the outer leaves may be tied a few weeks before harvest to promote a tighter, upright head. Ludford and Isenberg (1987) cite reports that Chinese cabbage store better when heads are more compact at harvest.

Grades, Sizes, and Packaging

There are no published U.S. standards for grades of Chinese cabbage. The wong bok or napa types are about 20 to 25 cm (8 to 10 in) in length, 15 to 20 cm (6 to 8 in) in diameter, and weigh 1.3 to 4.1 kg (3 to 9 lb). The michihli types are about 38 to 51 cm (15 to 20 in) in length, 7.6 to 12.7 cm (3 to 5 in) in diameter, and weigh 0.9 to 2.3 kg (2 to 5 lb) (Kelley 1999). They are shipped in wax-coated corrugated cardboard cartons and wire-bound crates of various sizes.

Precooling Conditions

Damaged leaves should be removed, and the heads packed into shipping containers and quickly cooled (vacuum or hydrovac cooling, forced-air cooling, or hydrocooling) to maximize shelf-life (Kasmire and Cantwell 1992).

Optimum Storage Conditions

Depending primarily on cultivar, Chinese cabbage can be held for 3 to 6 mo at 0 ºC (32 ºF) and 98% RH (Fritz and Weichmann 1980, Apeland 1985, van den Berg 1987). The storage temperature should be as close as possible to 0 ºC (32 ºF) without freezing (Kasmire and Cantwell 1992). Water loss is reduced and storage life extended when heads are enclosed in perforated plastic bags (Sozzi et al. 1981). Storage life is extended by growing Chinese cabbage during cooler growing seasons and placing the heads upside down during storage (Jin-Cheol Jeong, 1998, personal communication).

Controlled Atmosphere (CA) Considerations

An atmosphere of 1 to 2% O_2 and 2 to 6% CO_2 is effective at extending storage life (Adamicki 1997, Saltveit 1997). Decay increases and offensive odors are produced during continuous exposure to 7.5% CO_2, or 5 to 10 days exposure to 30 to 40% (Herner 1987). Specific CA recommendations depend on cultivar, temperature, and storage duration. CA storage retains green color and ascorbate and sugar content in leaves and decreases decay (Wang 1983, Ludford and Isenberg 1987).

Retail Outlet Display Considerations

Chinese cabbage is displayed as individual heads with the outer leaves removed, frequently with a band around the equator to maintain a compressed head shape. Heads should be kept as cool as possible without freezing and sprinkled with water to minimize moisture loss. Exposure to ethylene should be avoided.

Chilling Sensitivity

Chinese cabbage may be chilling sensitive. A physiological disorder (brown midrib) developed after prolonged storage at 0 °C (32 °F) (Apeland 1985). The critical temperature was 1.5 to 3.0 °C (35 to 37 °F) in the three cultivars studied. A 50% loss of product occurred after about 150 degree-days (°F) below the cultivar-specific critical temperature.

Ethylene Production and Sensitivity

Chinese cabbage produces very little ethylene, <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F) (Kader 1992), but exposure to less than 0.1 µL L^{-1} can accelerate senescence in air storage. Levels inside cartons of Chinese cabbage in wholesale markets have been measured at 1.09 µL L^{-1} (Wills 1998). Ethylene-induced leaf abscission can be minimized by storage in 1% O_2 (Wang 1983).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	6 to 14
5 °C	8 to 16
10 °C	15 to 19
15 °C	19 to 30
20 °C	25 to 45

Data from Apeland (1985) and Cantwell and Suslow (2001).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Brown midrib, a physiological disorder causing significant storage losses, is a symptom of chilling injury (Apeland 1985). Elevated levels of CO_2 can increase decay and the occurrence of offensive odors (Herner 1987).

Postharvest Pathology

Geeson (1983) reported the occurrence of leaf spots caused by *Alternaria* spp., bacterial soft rot *(Erwinia carotovora)*, and black discoloration of leaf veins, which may be due to *Xanthomonas campestris*.

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Chinese cabbage is suitable as a fresh-cut product packaged in air or modified atmosphere packaging (MAP). Gorny (1997) rates MAP treatment as moderately effective in extending the storage life of shredded Chinese cabbage and provides respiration rates at different temperatures, atmospheres, and varying amounts of shredding (table 1). Kleiber and Kim (1998) state that MAP is not essential for shredded Chinese cabbage held at 0 or 5 °C (32 or 41 °F), as there is only a transient increase in ethylene production and respiration that peaks after 6 to 12 h and 0 to 3 h, respectively. The shelf-life-limiting factors are browning on cut surfaces and leaf surfaces, as well as appearance of black speck (gomasho). If 1% citrate is used as a dip, a commercially acceptable shelf-life of 21 days at 0 °C (32 °F) or 14 days at 5 °C (41 °F) can be achieved without MA.

Table 1. Respiration of cut Chinese cabbage under various conditions

Temperature	Atmosphere	Degree of shredding	Respiration
			mg CO_2 kg^{-1} h^{-1}
2 °C	air	half head	10
		rough cut (0.5 x 3 cm)	18
		fine cut (0.25 - 1.5 cm)	24
5 °C	air	half head	16
		rough cut (0.5 x 3 cm)	32
		fine cut (0.25 - 1.5 cm)	40
5 °C	5 % O_2	half head	10
	+ 5 % CO_2	rough cut (0.5 x 3 cm)	22
		fine cut (0.25 - 1.5 cm)	28
10 °C	air	half head	17
		rough cut (0.5 x 3 cm)	48
		fine cut (0.25 - 1.5 cm)	57
23 °C	air	half head	31 to 36
		rough cut (0.5 x 3 cm)	90 to 99
		fine cut (0.25 - 1.5 cm)	117 to 126

References

Apeland, J. 1985. Chilling injury in Chinese cabbage *Brassica campestris pekinensis* (Lour) Olsson. Acta Hort. 157:261-270.

Adamicki, F. 1997. Effect of ultra low oxygen on the storage and quality of some vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 26-33. University of California, Davis, CA..

Cantwell, M., and T. Suslow. 2001. Cabbages (Round and Chinese types). *In* Fresh Produce Facts. *At* http://postharvest.ucdavis.edu/postharvest_information.

Fritz, D., and J. Weichmann. 1981. Influence of weather conditions during growth on storage ability of different Chinese cabbage cultivars. Chinese Cabbage. *In* R.L. Villareal and T.D. Griggs, eds., Proceedings of the First International Symposium of the Asian Vegetable Research and Development Center, Shanhua, Tainan, Taiwan, pp. 271-278.

Geeson, J.D. 1983. Brassicas. *In* C. Dennis, ed., Postharvest Pathology of Fruits and Vegetables, pp. 125-126. Academic Press, New York, NY.

Gorny, J.R. 1997. A summary of CA and MA requirements and recommendations for fresh-cut (minimally processed) fruits and vegetables. *In* J.R. Gorny, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 5, pp. 30-66. University of California, Davis, CA.

Herner, R.C. 1987. High CO_2 effects on plant organs. *In* J. Weichmann, ed., Postharvest Physiology of Vegetables, pp. 239-253. Marcel Dekker, New York, NY.

Kader, A.A. 1992. Postharvest biology and technology: an overview. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, pp. 15-20. DANR Pub. no. 3311, University of California, Davis, CA.

Kasmire, R.F., and M. Cantwell. 1992. Postharvest handling systems: flower, leafy and stem vegetables. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, pp. 267-270. DANR Pub. no. 3311, University of California, Davis, CA.

Kelley, William T. 1999. Specialty crops: chinese cabbage and related oriental crops. Commercial vegetable production. University of Georgia College of Agricultural and Environmental Sciences. *At* http://pubs.caes.uga.edu/caespubs/pubcd/c809-w.htm#chinese_cabbage.

Kleiber, A., and B.-S. Kim. 1998. Minimal processing of Chinese cabbage. Acta Hort. 464:249-251.

Ludford, P.M., and F.M.R. Isenberg. 1987. Brassica crops. *In* J. Weichmann, ed., Postharvest Physiology of Vegetables, pp. 497-522. Marcel Dekker, New York, NY.

Munro, D.B., and E. Small. 1997. Vegetables of Canada. National Research Council, Ottawa, Ontario, Canada.

Saltveit, M.E. 1997. A summary of requirements and recommendations for the controlled and modified atmosphere storage of harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, vol. 4, Vegetables and Ornamentals, July 13-18, 1997, University of California, Davis, CA.

Sozzi, A., F.L. Gorini, and L. Uncini. 1981. Storage suitability of the Chinese cabbage as affected by lining. Acta Hort. 116:157-162.

van den Berg, L. 1987. Water vapor pressure. *In* J. Weichmann, ed., Postharvest Physiology of Vegetables, pp. 203-230. Marcel Dekker, New York, NY.

Wang, C.Y. 1983. Postharevst response of Chinese cabbage to high CO_2 treatment or low O_2 storage. J. Amer. Soc. Hort. Sci. 108:125-129.

Wang, S.L., and R.F. Cerkauskas. 1999. Recent development of production and processing of oriental vegetables in Canada. Acta Hort. 483:429-436.

Wills, R.B.H. 1998. Enhancement of senescence in nonclimacteric fruit and vegetables by low ethylene levels. Acta Hort. 464:159-162.

Coconut

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Scientific Name and Introduction

Coconut (*Cocos nucifera* L.) is marketed at two stages of development. At an immature stage, the fruit (water coconut) contains mainly water and a little jellylike meat instead of the hard, white flesh (meat/endosperm) found in mature coconuts. In Thailand, and now marketed in the United States, immature green nuts are trimmed and shaped, removing most of the husk. The final product has a flat bottom, round body with a pyramid top, and the eyes showing. To prevent browning of the remaining husk, nuts are dipped in 1 to 3% sodium meta-bisulfite for 2 to 5 min and then wrapped in plastic film (Tongdee et al. 1991). Sometimes fungicide is included in the sulfite solution. Alternatively, the husk is removed before dipping in sulfite solution. Fruit are available year round from most tropical countries (Seelig 1970).

Quality Characteristics and Criteria

Major quality characteristics are maturity, size, and freedom from blemishes, cracking, fiber of husked coconuts, and wet or moldy eyes. Check for a sloshing sound for presence of coconut water in the nut. Coconut milk is obtained by removing and grating the hard, white flesh and squeezing out the milky juice. Immature, dehusked coconuts are about 10 cm (4 in) in diameter, weigh about 500 g (1.1 lb), have 100 g (3.5 oz) endosperm, 120 g (4.2 oz) shell, and 250 g (8.8 oz) water.

Horticultural Maturity Indices

Young coconuts are harvested 6 to 9 mo after flowering as they approach full size and the skin is still green (Consignado et al. 1976, Srivichai 1997) and the short stem (rachillae) on the top of individual coconuts that originally held the male flowers ("rat-tail" in Thai) becomes half green and brown. In immature nuts, the skin surface around the calyx (cap) on the top of the coconut is creamy white or a whitish yellow. When the area surrounding the cap is green, the coconut is considered mature and is 10 to 12 mo old. At maturity the skin begins to change from green to yellow, then brown, and the "rat-tail" is entirely brown.

Grades, Sizes, and Packaging

There are no specific grades; informal grades are generally based on size and weight. Mature U.S. dehusked coconuts are sold in 34- to 36-kg (75- to 80-lb) woven plastic or burlap sacks containing 40 to 50 coconuts, plastic mesh bags of 12 coconuts, and cartons with 20 to 25 film-wrapped coconuts weighing 17 to 18 kg (37 to 40 lbs). Immature coconuts (water coconuts) are shaped, dipped in bisulphate, and film-wrapped. They are sold in single-piece cartons containing 10 to 16 nuts. For young coconuts, the entire husk is removed, and the nuts are then dipped in sodium bisulfite before packing.

Precooling Conditions

Room cooling is generally used for mature husked nuts. Forced-air cooling and hydrocooling are acceptable. A rapid temperature change of 8 ºC (14 °F) or greater can cause cracking.

Optimum Storage Conditions

Mature coconuts with husk can be kept at ambient conditions for 3 to 5 mo before the liquid endosperm evaporates or before the shell cracks due to desiccation or sprouting. Storage at 0 to 1.5 ºC (32 to 35 ºF) and 75 to 85% RH is possible for up to 60 days for mature, dehusked coconuts (Maliyar and Marar 1963), and 13 to 16 ºC (55 to 60 ºF) and 80 to 85% RH for 2 weeks or less. Low RH and high temperature should be avoided.

Young coconuts are normally held at 3 to 6 ºC (37 to 43 ºF) with 90 to 95% RH, while wrapped and shaped fruit can be held for 3 to 4 weeks. Shaped young coconuts treated with 0.5 to 1.0% sodium meta-bisulfite can be held at ambient temperature for 2 days before browning occurs, while those treated with 2% sodium meta-bisulfite can be held at ambient temperature for 2 to 7 days (Tongdee et al. 1992). Young coconuts that have not been dehusked can be stored for a longer period than dehusked or shaped young coconuts. In dehusked or shaped coconuts, soluble solids content (SSC) declines and total acidity (TA) increases more rapidly than in nondehusked coconuts. Thus, the taste of dehusked or shaped coconuts sours more rapidly than nondehusked coconuts during storage (Somboonsup 1985). The husk acts as an insulator and may increase the storage life of young coconuts.

Controlled Atmosphere (CA) Considerations

No data are available on CA storage. Mature dehusked coconuts are waxed or film-wrapped to reduce water loss. Immature husked nuts can also be film-wrapped or waxed; however, the outside color changes rapidly from white to brown unless they are dipped in sodium bisulfite (Tongdee et al. 1992).

Retail Outlet Display Considerations

Display coconuts at ambient temperatures and do not mist. Nonwrapped or individually wrapped shaped coconuts are displayed at ambient temperatures or at 10 °C (50 °F).

Chilling Sensitivity

When stored at 0 °C (32 °F), immature nuts have green skins that turn brown after 7 days. Few other changes occur in other quality characteristics at this temperature (Consignado et al. 1976).

Ethylene Production and Sensitivity

Ethylene production is very low to near zero for mature husked coconut. There are no reports of sensitivity to ethylene.

Respiration Rates

	Temperature	mg CO_2 kg^{-1} h^{-1}
Immature	10 ºC	7 to 8
	20 ºC	13 to 24
Mature	10 ºC	6 to 7
	20 ºC	13 to 26

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Mechanical damage to immature coconuts will cause the white coir (the stiff fiber from the outer husk) to turn brown and the nut to crack. Younger nuts have a lower rupture force than mature nuts (Tongdee 1991). A rapid temperature change of 8 °C (15 °F) or more during storage of mature husked coconut can lead to cracking (Burton 1982), while freezing occurs at -3 °C (27 °F).

Moisture loss causes a loss of water in the nut; this loss can be reduced by RH control, film wrapping, or waxing of mature nuts.

Postharvest Pathology

Superficial mold growth can occur on wet coconuts.

Quarantine Issues

There are no quarantine issues if the nuts are mature, have a dry husk, and are free of surface insects and soil. Some restrictions exist on the importation into certain tropical and subtropical countries from regions affected by palm diseases.

Suitability as Fresh-Cut Product

Meat from both immature (jellylike) and mature (hard) nuts is sold in trays with overwrap or plastic bags for use in desserts. Immature coconuts' jellylike meat and water have to be held at 3 to 5 °C (37 to 41 °F) to avoid spoilage. The jellylike meat and coconut water packaged in small plastic bags are frequently seen held on ice in Southeast Asian markets and roadside stalls. Nonshredded and shredded meat of mature coconuts is packaged in plastic bags for cooking and for use in desserts.

References

Burton, B.D. 1982. Prevention of postharvest studies cracks in husked coconuts during transit. J. Amer. Soc. Hort. Sci. 107:905-907.

Consignado, T.O., P.C. Tabora, and R.P. Creencia. 1976. Physio-chemical changes in stored young coconut. The Phillipine Agriculturist 60:256-270.

Marar, M.M.K., and C.A. Kurhiraman. 1957. Studies on the keeping quality of ripe coconut in storage. Coconut J. 10(4):37-51.

Muliyar, M.K., and M.M.K. Marar. 1963. Studies on the keeping quality of ripe coconuts in storage. Indian Coconut J. 17:13-18.

Seelig, R.A. 1970. Coconuts: Fruits and Vegetable Facts and Pointers. United Fresh Fruit and Vegetable Association, Washington, DC.

Somboonsup, S. 1985. Effect of some postharvest handling on quality of fresh coconuts. Undergraduate Special Project, Department of Horticulture, Kasetsart University, Bangkok, Thailand.

Srivichai, S. 1997. Planting Coconut Palm. Agricultural Commodity Publishing, Bangkok, Thailand 95 pp. (In Thai).

Tongdee, S.C. 1991. Postharvest handling of tender coconut. ASEAN Food J. 6:74-75.

Tongdee, S.C., A. Suwanagul, and S. Neamprem. 1992. Control of browning in trimmed green coconuts. *In* B.R. Champ, E. Highley, and G.I. Johnson, eds., Postharvest Handling of Tropical Fruits. International Conference on Postharvest Handling of Tropical Fruits, Chiang Mai, Thailand, July 1993, p. 15. ACIAR Proceedings no. 50, ACIAR, Canberra, Australia.

Cranberry

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Scientific Name and Introduction

Vaccinium macrocarpon Ait., the American cranberry, is a perennial, woody, creeping, evergreen species in the Vacciniaceae (Blueberry) family (Dana 1990). It is native to acid bogs from Newfoundland south to North Carolina and west to Minnesota. It is popular for its tart-flavored red fruit. Canada and the United States produce almost all of the world's commercial crop of cranberries. Between 92 and 95% is processed; the remainder is sold fresh during the autumn and early winter. The major U.S. cranberry-growing States are, in order of production, Wisconsin, Massachusetts, New Jersey, Oregon, and Washington (NASS 2005).

Quality Characteristics and Criteria

Color intensity, glossiness, uniformity, and freedom from defects are the major quality characteristics for fresh and frozen cranberries (Spayd et al. 1990).

Horticultural Maturity Indices

Since the amount of red color (anthocyanin content) in the fruit is the major factor determining cranberry crop value, harvesting is timed to achieve the maximum red color without allowing the fruit to become too overmature (Eck 1990). Overmaturity results in physiological breakdown (see *Physiological Disorders*).

Grades, Sizes, and Packaging

There is only one grade standard for fresh cranberries: U.S. No. 1. Criteria include color (no less than 75% of the fruit surface pink or red), size (minimum diameter of 10.3 mm or 13/32 in), absence of soft or decayed fruit, and freedom from other defects. Fresh cranberries are commonly packed in cartons containing 24 12-oz polybags, or in cartons of 20, 25, or 30 lb (9.0, 11.4, or 13.2 kg) (AMS 1997). Occasionally, 9 2-lb (0.9-kg) and 4 5-lb (2.3-kg) polybag cartons are used for some retail customers, and wood totes may be used for sale of bulk cranberries.

Precooling Conditions

The storage length can be increased if the fruit are immediately cooled after harvest and packaged just before shipment (Kaufman et al. 1958, Ringel et al. 1959). If cranberries are not at the desired temperature, they can be forced-air cooled (Spayd et al. 1990, Kasmire and Thompson 1992).

Optimum Storage Conditions

The minimum recommended storage temperature is 2 °C (35.6 °F). The maximum recommended temperature is 4 to 5 °C (39 to 41 °F) (Hardenburg et al. 1986, Lidster et al. 1988, Spayd et al. 1990, Kader 1997), though there is one recommendation of 7 °C (45 °F) (Kasmire and Thompson 1992). The recommended RH is 90 to 95% (Hardenburg et al. 1986, Spayd et al. 1990, Kader 1997). Some researchers have recommended lower RH in the belief that it may reduce fungal decay: for example, 65 to 70% (Stark et al. 1974), 70 to 75% (Wright et al. 1937), and 80 to 90% (Lidster et al. 1988). Red color can be increased after harvest by holding fruit, especially early harvested fruit, at 7 to 10 °C (45 to 50 °F) for a few weeks rather than at the lower recommended temperatures (Levine et al. 1941). The expected storage life is 2 to 4 mo.

Controlled Atmosphere (CA) Considerations

There is no known commercial use of CA in cranberry storage. Some research suggests CA containing various combinations of O_2 and CO_2 does not extend cranberry storage life compared with ambient air (Anderson et al. 1963, Stark et al. 1969). Conversely, Kader (1992, 1997) suggested that a CA condition of 1 to 2% O_2 and 0 to 5% CO_2 is beneficial. The maximum CO_2 tolerance may be above 5%, as Stark et al. (1969) used 10% CO_2 without detrimental effects. In a 2-mo test at 3 °C (37 °F) with 98% RH using 10 CA combinations of 2%, 21%, and 70% O_2 with 0%, 15%, and 30% CO_2. Gunes and Watkins (2001) concluded that 21% O_2 with 30% CO_2 was optimal. Cranberries can be held in an anaerobic condition (100% N_2) for up to 14 mo at 3.3 °C (38 °F) in low RH (Stark et al. 1974). Such fruit have little decay but a high amount of physiological breakdown, making them unacceptable for fresh or juice use but still acceptable for use in cranberry sauce.

Retail Outlet Display Considerations

Water sprinkling or top-icing are not recommended.

Chilling Sensitivity

Cranberry is considered to be a chilling sensitive fruit (Wright et al. 1937, Levine et al. 1941, Kader 1992). Storage at temperatures near 0 °C for more than about 4 weeks may result in low-temperature breakdown (Lidster et al. 1988). Chilling injury symptoms include dull appearance, rubbery texture, and increased decay (Mitcham et al. 1999). If fruit are held at 0 °C, intermittent warming to 21 °C (70 °F) for 1 day a month can reduce chilling injury (Hruschka 1970).

Ethylene Production and Sensitivity

Cranberry has a low ethylene production rate of 0.1 to 1.0 µL kg^{-1} h^{-1} at 5 °C (41 °F) (Kader 1992, Mitcham et al. 1999). Postharvest treatment of fruit with as little as 10 µL L^{-1} markedly increases anthocyanin content, which is enhanced further if the fruit are treated in the presence of light (Fudge 1930, Craker 1971). Eck (1990) and Reid (1992) indicate the use of ethephon, a source of ethylene approved in some areas of the United States, which accelerates cranberry maturity and/or red color development. A 1995 U.S. Environmental Protection Agency "Reregistration Eligibility Decision (RED) on Ethephon" indicates that cranberries have been deleted from ethephon product labels.

Respiration Rates

Cranberries have a low respiration rate compared to other berry crops, which have a moderate to high rate (Kader 1992).

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	4
4 to 5 °C	4 to 5
10 °C	8
15 to 16 °C	—
20 to 21 °C	11 to 18

Data from Hardenburg et al. (1986) and Mitcham et al. (1999).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Physiological breakdown of cranberry is manifested by a soft and rubbery condition, dull external appearance, and diffusion of red anthocyanin pigment throughout internal tissues (Ceponis and Stretch 1981). No fungal organisms are associated with this condition. It is correlated with one or more of the following: impact bruising; late-harvested, more intensely colored fruit; and immersion of free berries for 8 h or more in a flooded bog or similar smothering effects where cranberries are held in poorly ventilated conditions (Graham et al. 1967, Patterson et al. 1967, Ceponis and Stretch 1981, Massey et al. 1981). Chilling injury can have the same symptoms.

Postharvest Pathology

Postharvest cranberry diseases are almost entirely caused by fungi, with the exception of ringspot, which is thought to be a virus-induced disease (Caruso and Ramsdell 1995, Prange and DeEll 1997). Cranberry is not only attacked by several common postharvest fungi but also by a large number of fungi that are unknown on other fruit crops (Caruso and Ramsdell 1995, Prange and DeEll 1997). The principal storage rots, which can be found in all the major cranberry-growing areas, are end rot, black rot, viscid rot, yellow rot, and botryosphaeria fruit rot (Eck 1990, Prange and DeEll 1997). Since the occurrence of these fungi can vary with location and season and some are not easily identified visually, confirmation of the causal organism(s) usually requires extensive culturing and spore examination. Decay may be reduced if storage O_2 is below 1%, since there is no decay control at 1% (Anderson et al. 1963), but 100% N_2 for 3 weeks at 3 °C (38 °F) reduced the number of pathogenic species and decay compared with air-stored fruit (Lockhart et al. 1971).

Quarantine Issues

There are no current restrictions for shipments within Canada and the United States. There has been little, if any, international trade in fresh cranberries. Such future trade may be subjected to quarantine restrictions, depending on the countries involved.

Suitability as Fresh-Cut Product

No current potential.

Special Considerations

Cranberries can be stored fresh for 2 to 4 mo, depending on season, cultivar, maturity, handling, and storage conditions (Hardenburg et al. 1986). The storage life of cranberries is limited by the development of decay, shrinkage resulting from moisture loss, and physiological breakdown (Lidster et al. 1988). Early-harvested fruit usually have a longer storage potential than late-harvested fruit (Doughty et al. 1967). Physical damage, which can occur during mechanical harvesting or rough hand-harvesting, transport, or mechanical cleaning, sorting, and packing, increases physiological breakdown, postharvest softening, and decay and reduces storage life (Graham et al. 1967, Patterson et al. 1967, Massey et al. 1981). There is more fungal decay and physiological breakdown in water-harvested than in hand-harvested cranberries, especially if cranberries are kept in the water more than 1 h after detachment from the plant (Mitcham et al. 1999; Blake Johnson, 2000, personal communication).

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References

AMS [USDA Agricultural Marketing Service]. 1997. United States standards for grades of fresh cranberries. U.S. Department of Agriculture, Washington, DC. (http://www.ams.usda.gov/AMSv1.0/standards)

Anderson, R.E., R.E. Hardenburg, and H.C. Vaught. 1963. Controlled atmosphere storage studies with cranberries. Proc. Amer. Soc. Hort. Sci. 83:416-422.

Caruso, F.L., and D.C. Ramsdell. 1995. Compendium of Blueberry and Cranberry Diseases. APS Press, St. Paul, MN.

Ceponis, M.J., and A.W. Stretch. 1981. The influence of water immersion time at harvest on physiological breakdown of 'Early Black' cranberries in storage. HortScience 16:60-61.

Craker, L.E. 1971. Postharvest color promotion in cranberry with ethylene. HortScience 6:137-139.

Dana, M.N. 1990. Cranberry management. *In* G.J. Galleta and D.G. Himelrick, eds., Small Fruit Crop Management, pp. 334-262. Prentice Hall, Upper Saddle River, NJ.

Doughty, C.C., M.E. Patterson, and A.Y. Shawa. 1967. Storage longevity of the 'McFarlin' cranberry as influenced by certain growth retardants and stage of maturity. Proc. Amer. Soc. Hort. Sci. 91:192-204.

Eck, P. 1990. The American Cranberry. Rutgers University Press, New Brunswick, NJ.

Fudge, B.R. 1930. Increasing the color of cranberries after removal from the vines. Bull. 504, New Jersey Agricultural Experiment Station, New Brunswick, NJ.

Graham, S.O., M.E. Patterson, and B. Allan. 1967. Bruising as a predisposing factor in the decay of stored cranberries. Phytopathology 57:497-501.

Gunes, G., and C.B. Watkins. 2001. Postharvest quality of cranberries as affected by controlled atmosphere. HortScience 36:571 (Abstract).

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Hruschka, H.W. 1970. Physiological breakdown in cranberries—inhibition by intermittent warming during cold storage. Plant Dis. Rptr. 54:219-222.

Kader, A.A. 1992. Postharvest biology and technology: an overview. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, pp. 15-20. DANR Pub. no. 3311, University of California, Davis, CA.

Kader, A.A. 1997. A summary of CA requirements and recommendations for fruits other than apples and pears. *In* A.A. Kader, 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 3, pp. 1-34. University of California, Davis, CA.

Kasmire, R.F., and J.F. Thompson. 1992. Selecting a cooling method. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, pp. 63-68. DANR Pub. no. 3311, University of California, Davis, CA.

Kaufman, J., S.M. Ringel, A.A. Hamer, et al. 1958. Effect of Precooling on Market Quality of Cranberries Shipped by Rail or Truck. Marketing Research Report 287, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Levine, A.S., C.R. Fellers, and C.I. Gunness. 1941. Carbon dioxide-oxygen and storage relationships in cranberries. Proc. Amer. Soc. Hort. Sci. 38:239-242.

Lidster, P.D., P.D. Hildebrand, L.S. Bérard, and S.W. Porritt. 1988. Commercial Storage of Fruits and Vegetables. Pub. no. 1532/E, Agriculture and Agri-Food Canada, Ottawa, Ontario, Canada.

Lockhart, CL., F.R. Forsyth, R. Stark, and I.V. Hall. 1971. Nitrogen gas suppresses microorganisms on cranberries in short term storage. Phytopathology 61:335-336.

Massey, L.M., B.R. Chase, and M.S. Starr. 1981. Impact-induced breakdown in commercially screened 'Howes' cranberries. J. Amer. Soc. Hort. Sci. 106:200-203.

Mitcham, E.J., C.H. Crisosto, and A.A. Kader. 1999. Bushberries: blackberry, blueberry, cranberry, raspberry. *In* Fresh Produce Facts. *At* http://postharvest.ucdavis.edu/produce_information.

NASS [USDA National Agricultural Statistics Service]. 2005. Agricultural Statistics. *At* http://www.usda.gov/nass/pubs/agstats.

Patterson, M.E., C.C. Doughty, S.O. Graham, and B. Allan. 1967. Effect of bruising on postharvest softening, color changes, and detection of polygalacturonase enzyme in cranberries. Proc. Amer. Soc. Hort. Sci. 90:98-505.

Prange, R.K., and J.R. DeEll. 1997. Preharvest factors affecting postharvest quality of berry crops. HortScience 32:824-830.

Reid, M.S. 1992. Ethylene in postharvest technology. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, pp. 97-108. DANR 3311, University of California, Davis, CA.

Ringel, S.M., J. Kaufman, and M.J. Jaffe. 1959. Refrigerated Storage of Cranberries. Marketing Research Report 312, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Spayd, S.E., J.R. Morris, W.E. Ballinger, and D.G. Himelrick. 1990. Maturity standards, harvesting, postharvest handling and storage. *In* G.J. Galleta and D.G. Himelrick, eds., Small Fruit Crop Management, pp. 504-531. Prentice Hall, Upper Saddle River, NJ.

Stark, R., I.V. Hall, F.R. Forsyth, and P.R. Dean. 1969. Cranberries evaluated for fresh fruit and processing quality after reduced O_2 storage. Cranberries 34(6):14,16 and 34(7):14,16.

Stark, R., F.R. Forsyth, C.L. Lockhart, and I.V. Hall. 1974. Processing quality of cranberries after extended storage in N_2 atmosphere with low and high relative humidities. Can. Inst. Food Sci. Technol. J. 7:9-10.

Wright, R.C., J.B. Demaree, and M.S. Wilcox. 1937. Some effects of different storage temperatures on the keeping of cranberries. Proc. Amer. Soc. Hort. Sci. 34:397-401.

Cucumber

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Scientific Name and Introduction

Cucumber (*Cucumis sativus* L) is a member of the Cucurbitaceae family, along with melons, squashes, and many other horticulturally important species. The fruit are borne on indeterminate, tendril-bearing vines of subtropical and tropical origin (Robinson and Decker-Walters 1997). The inferior ovary has three united carpels in most cultivars. Compact, determinate cultivars have been developed for home gardeners and for once-over mechanical harvesting (Miller and Wehner 1989).

Quality Characteristics and Criteria

Fruit are round to oblong or narrowly cylindrical, with small tubercles (warts) and spines of trichome origin on the rind of some cultivars (Miller and Wehner 1989). The rind of slicing cucumbers should be dark green and firm with no pits or wrinkled (pinched) ends. Spine color is associated with mature fruit color and fruit netting. Fruit of white-spined cultivars are light green to yellow when mature and not netted. Black-spined fruit are orange or brown when mature and may be netted. The flesh is crisp and white, except in a few cultivars where it is pale orange.

Horticultural Maturity Indices

Fruit are harvested at various stages of development. Immature fruit are green at the edible stage, except for a few cultivars that are white or yellow. Fruit are generally harvested immature (that is, before the seeds are fully enlarged and hardened) with a diameter of <5 cm (2 in) for picklers and <6 cm (2 3/8 in) for slicers. The minimum length is 14 cm (5.5 in) for slicers. Fruit firmness, external glossiness, and formation of jellylike material around the seeds are indicators of proper harvest maturity. Greenhouse-grown parthenocarpic (produced without pollination) fruit are harvested 10 to 14 days after anthesis after they turn bright green (Kanellis et al. 1988). Straight, uniformly cylindrical fruit slightly tapered at both ends are of highest quality. Cucumbers are listed as nonclimacteric, yet there is a burst of ethylene production that precedes a rapid loss of chlorophyll in harvested fruit (Saltveit and McFeeters 1980).

Grades, Sizes, and Packaging

Grades for table or slicing cucumbers are based on length, shape, fruit color, and diameter and include U.S. Fancy, Extra 1, No. 1, No. 1 Small, No. 1 Large, and No. 2. Pickling cucumbers are graded by fruit diameter: No. 1 (up to 2.5 cm [1 in]), No. 2 (2.5 to 3.8 cm [1.0 to 1.5 in]), and No. 3 (3.8 to 5.0 cm [1.5 to 2.0 in]). Fruit over 5 cm (2 in) are too large. Additional quality indices include size, freedom from growth or handling defects, freedom from decay, and lack of yellowing. Most fresh-market cucumbers are packed in fiberboard boxes. Fresh market slicers are often waxed to reduce moisture loss, while greenhouse slicers are wrapped in shrink-plastic to reduce water loss. Pickling cucumbers are usually transported from the field to the brining facility in large field bins.

Precooling Conditions

The chilling sensitivity of cucumbers does not preclude precooling with cold water (hydrocooling) or air (forced-air) (Ryall and Lipton 1979). However, even though fruit can tolerate brief exposure to chilling temperatures, they should not be maintained at chilling temperatures for more than 6 h.

Optimum Storage Conditions

Recommended conditions for commercial storage of cucumbers are 10 to 12.5 ºC (50 to 54 °F) at 95% RH (Hardenburg et al. 1986). Storage life is generally less than 14 days, with visual and sensory quality rapidly declining thereafter. Chilling sensitivity limits storage temperatures to a narrow range. Storage below 10 °C (50 °F) results in chilling injury in as little as 2 or 3 days, while storage at 15 °C (59 °F) results in rapid yellowing and loss of quality.

Controlled Atmosphere (CA) Considerations

Little benefit is realized from the CA storage of cucumber fruit (Leshuk and Saltveit 1990, Saltveit 1997). O_2 levels of 3 to 5% delay yellowing and decay for a few days (Wang and Qi 1997). Cucumbers tolerate CO_2 up to 10%, but the benefits are not more than those realized by reduced O_2. Parthenocarpic fruit can be stored for 1 to 3 weeks in 0.5 to 2% O_2 at 12.5 °C (54.5 °F) (Kanellis et al. 1988).

Retail Outlet Display Considerations

Chilling temperatures should be avoided. Periodic sprays of water or packaging the fruit in ventilated films can minimize water loss. Fresh market slicers are often waxed to reduce moisture loss, while greenhouse slicers are wrapped in shrink plastic to reduce water loss. High RH retards softening and pitting, symptoms of chilling injury.

Chilling Sensitivity

Cucumbers are chilling sensitive and most fruit will be injured if stored below 10 °C (50 °F) for more than 2 or 3 days. Sensitivity varies greatly with duration of exposure, temperature, cultivar, growing conditions, and storage environment (Cabrera et al. 1992). CA during chilling and high RH after chilling can reduce symptom expression. Intermittent warming to nonchilling temperatures for 12 h every 2 or 3 days can reduce chilling injury of fruit held at 0 to 2 °C (32 to 36 °F) (Cabrera and Saltveit 1990). Development of chilling injury symptoms can be avoided if chilled fruit are used immediately after removal from storage.

Ethylene Production and Sensitivity

Cucumber fruit produce little ethylene, about 0.1 to 1.0 µL kg^{-1} h^{-1} at 20 °C (68 °F), but they are very sensitive to it. Exposure to 1 to 5 µL L^{-1} ethylene accelerates yellowing and decay. Reduced O_2 and elevated CO_2 minimize the response to ethylene exposure.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
10 °C	23 to 29
15 °C	24 to 33
20 °C	14 to 48
25 °C	19 to 55

Data from Cantwell and Suslow (2006).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Chilling injury is characterized by surface pitting, increased yellowing and disease susceptibility, and development of water-soaked areas of the flesh. Bruising and compression injuries are common when careful harvest and handling procedures are not followed.

Postharvest Pathology

Diseases are a significant source of postharvest loss, especially in fruit weakened by chilling injury. The many bacterial and fungal pathogens responsible for postharvest losses include *Alternaria* spp., *Didymella* black rot, *Pythium* cottony leak, and *Rhizopus* soft rot.

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Sliced cucumbers are available for the commercial food service industry but are not yet on the retail market.

Special Considerations

Cucumber fruit are usually treated with approved waxes or oils to reduce water loss, reduce abrasion injury, and improve appearance. Surface pitting and yellowing are common defects that follow exposure to chilling temperatures and ethylene. Harvesting at the proper maturity and storing at temperatures above 10 °C (50 °F) in an ethylene-free atmosphere are necessary for optimal quality retention and maximum market life.

The postharvest conditions for slicing cucumbers generally apply to fruit intended for pickling. However, damage incurred during the mechanical harvesting of pickling cultivars increases the rate of respiration (from 6 to 20%), the rate of water loss, and disease susceptibility. Also, since pickling cucumbers are commonly shipped in large field bins, prompt precooling is very important to remove field heat and prevent respiratory activity from raising fruit temperature in transit. Hydrocooling is effective for precooling, but storage life is halved because of the spread of inoculum. Sanitization of water is therefore very important. Fruit can be held at chilling temperatures for a few days if used immediately after removal from storage.

Acknowledgments

Some of the information in this chapter is from the Produce Marketing Association's "Fresh Produce Manual."

References

Cabrera, R.M., and M.E. Saltveit. 1990. Physiological response to chilling temperatures of intermittently warmed cucumber fruit. J. Amer. Soc. Horti. Sci. 115:256-261.

Cabrera, R.M., M.E. Saltveit, and K. Owens. 1992. Cucumber cultivars differ in their response to chilling temperatures. J. Amer. Soc. Horti. Sci. 117:802-807.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Kanellis, A.K., L.L. Morris, and M.E. Saltveit. 1988. Responses of parthenocarpic cucumbers to low-oxygen storage. J. Amer. Soc. Horti. Sci. 113:734-737.

Leshuk, J.A., and M.E. Saltveit. 1990. Controlled atmospheres and modified atmospheres for preservation of vegetables. *In* M. Calderon, ed., Food Preservation by Modified Atmospheres, pp. 315-352. CRC Press, Boca Raton, FL.

Miller, C.H., and T.C. Wehner. 1989. Cucumbers. *In* N.A.M. Eskin, ed., Quality and Preservation of Vegetables, pp. 245-264. CRC Press, Boca Raton, FL.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation and Storage of Fruits and Vegetables, 2nd ed., vol. 1, Vegetables and Melons. AVI Publishing Co., Westport, CT.

Robinson, R.W., and D.S. Decker-Walters. 1997. Cucurbits. CAB Intl., Wallingford, U.K.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California, Davis, CA.

Saltveit, M.E., and R.F. McFeeters. 1980. Polygalacturonase activity and ethylene synthesis during cucumber fruit development and maturation. Plant Physiol. 66:1019-1023.

Suslow, T., and M. Cantwell. 2006. Cucumber: recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

Wang, C.Y., and L. Qi. 1997. Controlled atmosphere storage affects quality and chilling susceptibility of cucumbers. J. Food Quality 20:559-566.

Currant, Gooseberry, and Elderberry

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Scientific Name and Introduction

Currants and gooseberries are closely related, berry-bearing deciduous shrubs in the *Ribes* L. genus of the Saxifragaceae family. Gooseberries are sometimes placed in a separate genus, *Grossularia* Mill.

The most common species are *R. sativum* Syme (red, white, and pink currants) and *R. nigrum* L. (black currant) (Harmat et al. 1990). White currant, an albino form of red currant, is of lower acidity and thus is suitable for eating fresh. Pink currants have a colorless skin and a pink flesh. Black currant fruit differ from red currants in being more astringent but having a distinct aroma, making it very desirable in processed products. Gooseberry cultivars are derived from *R. uva-crispa* L. (European gooseberry) and *R. hirtellum* Michx. (American gooseberry). The European gooseberry is much larger than the American gooseberry. European cultivars are from *R. uva-crispa*, but American cultivars are virtually all from crosses of *R. uva-crispa* and *R. hirtellum*.

A gooseberry fruit may be green, white (gray-green), yellow, or shades of red from pink to purple to almost black. Skin color is most intense on fruit in full sunlight. The four countries producing both the most currants and the most gooseberries are Germany, Czech Republic, Poland, and the Russian Federation. North American production of currant and gooseberry has been hampered by adaptation and disease problems (Harmat et al. 1990). Currant and gooseberry are available fresh from mid-May to August or longer if stored properly. Virtually all commercial production is put into processed products with only a small proportion consumed fresh. Also, brownish-purple fruit from a native western U.S. species, *R. aureum* Pursh (buffalo currant, albol currant, golden currant) or from a hybrid of *R. nigrum* and *R. hirtellum* (jostaberry) may be available in some local markets.

Sambucus canadensis L., the elderberry, is a moderately tall deciduous shrub of the Caprifoliaceae family, native to North America. The ease in harvesting the purplish-black fruit from wild plants may in part account for the lack of commercial plantings. Most of the fruit is processed, since the uncooked berries are astringent and not very edible (Way 1981). Selection and breeding, primarily in New York and Nova Scotia, have resulted in a number of cultivars (Craig 1978, Way 1981, Stang 1990), and small-scale production has been reported in New York, Ohio, and Oregon (Way 1981).

Quality Characteristics and Criteria

Currant and elderberry fruit are produced on the plant in clusters, and gooseberry fruit are borne singly or in pairs. Ideally, fruit throughout each cluster should be firm and bright, with the proper cultivar-specific color, and free of decay or mechanical or insect injury. For the fresh market, it is also important to have large and uniform fruit throughout the cluster. A long shelf-life with retention of both firmness and flavor is also desirable for the fresh-fruit market.

Horticultural Maturity Indices

Currants and gooseberries are harvested from mid-May through August. Red currants are usually harvested before the color changes from bright red to a dull red color (Spayd et al. 1990, Audette and Lareau 1996). Soluble solids are usually about 9.5 to 14% and acidity is around 2%. Generally, entire clusters of red currant are harvested, as modern cultivars have uniform ripening of all berries on a cluster. Black currants, which at maturity have an opaque, very dark blue color with a soluble solids content of 15 to 26%, do not mature evenly in the cluster: the larger ones at the base of each cluster mature first (Audette and Lareau 1996, http://www.crfg.org/pubs/ff). The entire cluster can be harvested, or only mature berries can be picked over several harvests. At maturity, gooseberry cultivars may be green, white, yellow, or various shades of red (pink to purple to almost black). Since both immature (green) and ripe gooseberries are used, harvest maturity depends entirely on end use (Ryall and Pentzer 1982). Green gooseberries are very firm and tart, whereas some cultivars, when fully mature and soft, are quite sweet. Elderberries are harvested in late August and September, when the fruit is sufficiently large and has changed to an acceptable purplish-black color. The fruit do not mature at the same time, so several pickings are necessary over a 1- to 2-week period (Craig 1978, Way 1981). Harvesting occurs in late August and September, depending on climate and cultivar. Postharvest decay of currant, gooseberry, and elderberry can be minimized by avoiding picking wet or overripe fruit.

Grades, Sizes, and Packaging

There are no U.S. fresh fruit standards for these fruit. There is a U.S. grade standard for processing currants, based on color, attachment of stem, and freedom from decay and insect or mechanical damage. Processors, who use most of the commercial production, may have their own standards. Since fresh market volumes are not large, container sizes and packaging for the fresh market tend to be those used for similar but more common berries (for example, raspberries).

Precooling Conditions

Currant, gooseberry, and elderberry fruit are relatively perishable. Quick cooling after harvest to recommended storage temperatures is desirable, using forced-air cooling with 95% RH (Kasmire and Thompson 1992, Batzer and Helm 1999).

Optimum Storage Conditions

Since currant, gooseberry, and elderberry are not chilling sensitive, the recommended storage temperature and RH for all three are -0.5 to 0 °C (31 to 32 °F) with RH of 95% (Hardenburg et al. 1986, Story and Simons 1989). Batzer and Helm (1999) recommended slightly warmer temperatures of 0 to 1 °C (32 to 34 °C) for red currant and gooseberry and 0 to 2 °C (32 to 36 °F) for black currant, perhaps to avoid accidental freezing. With proper cooling, the storage duration can be 1.5 , 2.5, and 3 weeks for black currant, red currant, and gooseberry, respectively (Batzer and Helm 1999).

Controlled Atmosphere (CA) Considerations

As summarized by Batzer and Helm (1999) and Thompson (1998), research indicates that red currant and gooseberry respond very well to CA, while black currant benefits only slightly. Storage duration of red currant can be extended to 8 to 14 weeks, depending on cultivar, using 18 to 20% CO_2 with 2% O_2 at 1 °C (34 °F). For gooseberry, storage duration is extended to 6 to 8 weeks using 10 to 15% CO_2 with 1.5% O_2 at 1 °C. Increasing the CO_2 up to 20% reduces incidence of storage rots (Thompson 1998, Batzer and Helm 1999), and lowering the O_2 reduces respiration rate (Robinson et al. 1975). Compared with red currant and gooseberry, black currant does not respond as well to low O_2 and its storage can only be extended to 3 weeks at 0 to 2 °C (32 to 36 °F) and 15 to 20% CO_2.

There is no known information on the effect of CA on elderberry.

Retail Outlet Display Considerations

Currant, gooseberry, and elderberry should be kept in a refrigerated display but not sprinkled with water or top-iced.

Chilling Sensitivity

Currant, gooseberry, and elderberry are not chilling sensitive (Kader 1992).

Ethylene Production and Sensitivity

No data available.

Respiration Rates

Temperature	Gooseberry	Black currant
	---------mg CO_2 kg^{-1} h^{-1}---------	
0 °C	5 to 7	16
4 to 5 °C	8 to 16	27
10°C	12 to 32	40
15 to 16°C	28 to 69	89
20 to 21°C	41 to 105	128

Gooseberry data from Smith (1967), Robinson et al. (1975), and Hardenburg et al. (1986); black currant data from Robinson et al. (1975).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

CO_2 above 20% results in internal breakdown and fruit discoloration in some red currant cultivars after 13 weeks of storage (Thompson 1998). Low O_2 further increases these symptoms. Smith (1967) showed that green gooseberry fruit held at 0 °C (32 °F) in air are damaged by CO_2 that was increased from 8 to 12%. Fruit turned yellow and had an abnormal flavor. Increasing the temperature from 0 to 5 °C (32 to 41 °F) eliminates the disorder.

Postharvest Pathology

The main postharvest disease is gray mold rot *(Botrytis cinerea)*, which can appear as small brown spots on currant and gooseberry fruit (Ryall and Pentzer 1982, Dennis 1983, Harmat et al. 1990). These enlarge rapidly at temperatures above 10 °C (50 °F) and gradually affect the entire berry with a soft rot. Currant and gooseberry fruit can be susceptible to American powdery mildew *(Sphaerotheca mors-uva)* (Harmat et al. 1990, Audette and Lareau 1996). Fruit that become contaminated by soil splash after heavy rain are frequently infected by *Mucor piriformis* (Dennis 1983). Dennis (1983) also reports a fruit disease in gooseberry caused by *Alternaria* and *Stemphyllum*. The infection is usually confined to the seeds enclosed in the pericarp. If, however, the fruit is stored for a few days at ambient temperatures prior to consumption or processing, the fungus invades the pericarp tissue.

Several insects can attack the fruit: currant maggot or fruit fly *(Epochra canadensis)* (North America), gooseberry fruitworm *(Zophodia convolutella)* (North America), and currant moth *(Incurvaria capitella)* (Europe) (Harmat et al. 1990). In addition, slugs and snails (*Helix aspersa* and *Cepaea* spp.) will attack fruit (North America and Europe) (Harmat et al. 1990). Diseases and insects are not generally serious on elderberries (Way 1981), perhaps because of the absence of extensive plantings. An unidentified mildew can be a problem on ripe fruit, especially if the weather is cool during ripening and there is poor air circulation around the plants (Way 1981).

Birds feeding on ripe currant, gooseberry, and elderberry fruit can be a serious pest problem (Way 1981, Harmat et al. 1990, Stang 1990). In addition to prompt harvesting of ripe fruit, various bird repellent measures may have to be considered.

Quarantine Issues

None

Suitability as Fresh-Cut Product

No current potential

Special Considerations

Ribes species are hosts for the white pine blister rust, which causes few problems for currants or gooseberries but is dangerous to 5-needle pine species. Thus, commercial production of *Ribes* species, especially black currant, may be banned in some U.S. municipalities (California Rare Fruit Growers 1996).

References

Audette, M., and M.J. Lareau. 1996. Currants and Gooseberries Culture Guide. Conseil des Productions Végétales du Québec, Inc., Québec City, Québec, Canada.

Batzer, U., and H.-U. Helm. 1999. Lagerung von Beerenobst (Storage of small fruits). Erwerbsobstbau 41:51-55.

California Rare Fruit Growers. 1996. CRFG fruit facts: currants. *At* http://www.crfg.org/pubs/ff/currants.

Craig, D.L. 1978. Elderberry culture in eastern Canada. Pub. no. 1280, Agriculture Canada, Ottawa, Ontario, Canada.

Dennis, C. 1983. Soft fruits. *In* C. Dennis, ed., Postharvest Pathology of Fruits and Vegetables, pp. 23-42. Academic Press, New York, NY.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Harmat, L., A Porpaczy, D.G. Himelrick, and G.J. Galleta. 1990. Currant and gooseberry management. *In* G.J. Galleta and D.G. Himelrick, eds., Small Fruit Crop Management, pp. 245-272. Prentice Hall, Upper Saddle River, NJ.

Kader, A.A. 1992. Postharvest biology and technology: an overview. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, pp. 15-20. DANR Pub. no. 3311, University of California, Davis, CA.

Kasmire, R.F., and J.F. Thompson. 1992. Selecting a cooling method. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, pp. 63-68. DANR Pub. no. 3311, University of California, Davis, CA.

Robinson, J.E., K.M. Browne, and W.G. Burton. 1975. Storage characteristics of some vegetables and soft fruits. Ann. Appl. Biol. 81:339-408.

Ryall, A.L., and W.T. Pentzer. 1982. Handling, Transportation and Storage of Fruits and Vegetables, 2nd ed., vol. 2, Fruits and Tree Nuts. AVI Publishing Co., Westport, CT.

Spayd, S.E., J.R. Morris, W.E. Ballinger, and D.G. Himelrick. 1990. Maturity standards, harvesting, postharvest handling, and storage. *In* G.J. Galleta and D.G. Himelrick, eds., Small Fruit Crop Management, pp. 504-531. Prentice Hall, Upper Saddle River, NJ.

Smith, W.H. 1967. The storage of gooseberries. Agricultural Research Council (U.K.) Ditton and Covent Garden Laboratories Annual Report 1965-66, pp. 13-14.

Stang, E.J. 1990. Elderberry, highbush cranberry, and juneberry management. *In* G.J. Galleta and D.G. Himelrick, eds., Small Fruit Crop Management, pp. 363-382. Prentice Hall, Upper Saddle River, NJ.

Story, A., and D.H. Simons. 1989. Handling and Storage Practices for Fresh Fruit and Vegetables. Australian United Fresh Fruit and Vegetable Association Ltd., Victoria, Australia.

Thompson, A.K. 1998. Controlled Atmosphere Storage of Fruits and Vegetables. CAB Intl., Wallingford, U.K.

Way, R.D. 1981. Elderberry culture in New York State. Food Life Sci. Bull. 91, New York State Agricultural Experiment Station, Geneva, NY.

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Scientific Name and Introduction

Phoenix dactylifera L., the date palm, has been a staple in the Middle East and North Africa for thousands of years. Date fruit is a drupe with a single seed or pit. The fruit has an oblong shape, measures about 2.5 to 7.5 cm (1 to 3 in) long, and has thick or thin flesh. It tastes astringent when premature and becomes sweet when ripe. Dates are rich in carbohydrate and other nutrients and are a high-energy food.

Quality Characteristics and Criteria

High-quality fresh dates should be of an adequate size and proper color and have a small pit and thick flesh. They should not be contaminated by dirt, sand, or leaf particles or exhibit damage by birds, insects, or rodents. There should be no fungi or mold infestation nor sugar crystal formation or other apparent alterations (Dowson 1982). The skin should be smooth with little or no shriveling. The color should be golden brown, amber, green, or black, depending on the variety. The texture may be soft and syrupy or firm and dry, depending on the cultivar.

Horticultural Maturity Indices

Fruit growth follows a sigmoidal curve and is usually divided into five stages of development known by their Arabic terms: hababouk, kimri, khalal, rutab, and tamr. Most dates are harvested in the tamr stage when the fruit has about 60 to 80% sugar content, depending on location and cultivars. At this stage, fruit can be harvested soft, semidry, or dry depending on destination and use. Some varieties with low tannins but high sugar content can be harvested at the khalal stage ("balah" in North African countries or "bisr" in Oman). For other varieties, dates that are harvested before reaching full maturity must be ripened artificially. Very immature dates cannot be properly ripened artificially and will thus be of poor quality.

Grades, Sizes, and Packaging

Dates are graded based on uniformity of color and size and extent of defects or damage, which include discoloration of the flesh, rupture of the skin, deformity of the fruit, puffiness of the skin, scars, sunburn, insect damage, decay, black scald, fermentation, improper ripening, mechanical damage, and presence of dirt or other foreign material. These criteria are the bases for Codex and U.S. grades A, B, C, standard, and substandard applied to whole, pitted, or dry dates. In general, the total amounts of sugar for different grades are usually the same when expressed as a percentage of dry weight, but the higher grades usually contain higher amounts of sugar per date. 'Medjool' dates in the United States are classified into three size categories: jumbo (fewer than 10 dates per lb or per 0.45 kg), mixed (10 to 15 dates per lb), and conventional (more than 15 dates per lb).

Some dates are marketed in 15-lb (6.8-kg) flats of fiberboard or wood, others in 5- or 10-lb (2.3- or 4.5-kg) cartons. Large, reinforced cartons are used for packing dry dates, especially for export. Consumer packages are widely used and consist of various sizes and shapes, including bags of transparent film and trays overwrapped with film. Round fiberboard cans with metal tops and bottoms containing 500 to 1,000 g (1.1 to 2.2 lb) are also used. Rigid, transparent plastic containers with a capacity of 200 to 300 g (0.44 to 0.66 lb) are commonly used. Small consumer packages are also used, such as bags containing 50 to 60 g (about 2 oz).

Optimum Storage Conditions

Pathological and physiological deterioration increases with increasing moisture content and storage temperature. Relatively small differences in moisture content may have an important effect on keeping the quality of 'Deglet Noor' fruit. At 24 °C (75 °F), 'Deglet Noor' dates show darkening of the skin 4 times faster when they have 24% versus 20% moisture content (Rygg 1975). At 0 °C (32 °F), dates can be stored in good conditions up to 1 year, but some varieties may develop sugar spots or crystals. Fully mature soft and firm 'Deglet Noor' dates can be kept for more than 1 year when stored at -17.5 °C (0 °F) but will not stand more than 1 mo at 27 °C (80 °F), 3 mo at 15 °C (59 °F), or 8 mo at 5 °C (41 °F) (Rygg 1956). Partially dried dates can be kept for 1 year at 0 °C (32 °F) or lower, or for a few weeks at ambient temperature. Dry dates can be kept at 20 °C (68 °F) for years without significant quality losses. Optimum RH is 70 to 75%.

Chilling Sensitivity

Ripe dates at the rutab or tamr stages (see *Horticultural Maturity Indices*), commonly handled in the world market, are not sensitive to chilling and freezing temperatures. However, freezing temperatures can injure dates at early stages of kimri and khalal.

Ethylene Production and Sensitivity

At 20 °C (68 °F), dates produce less than 0.1 µL kg^{-1} h^{-1} ethylene at the khalal stage and none at the rutab and tamr stages. Ripe dates are not sensitive to ethylene exposure.

Respiration Rates

Respiration rates of dates are very low: <5 mg CO_2 kg^{-1} h^{-1} at 20 °C (68 °F) at the khalal stage and <2 mg kg^{-1} h^{-1} at the rutab and tamr stages. Respiration rates increase as moisture content of the fruit increases. Cured 'Deglet Noor' dates, with 20 to 22% moisture, produced 0.4 mg CO_2 kg^{-1} h^{-1} at 24 °C and 2 mg CO_2 kg^{-1} h^{-1} when moisture content increased to 27%. (Rygg 1975).

Physiological Disorders

Darkening is a major problem in dates. Its rate varies with cultivar, temperature, and moisture content; and it is affected by several treatments. It can be reduced by storage in low temperatures, low moisture content, or in an inert gas. Temperatures above 60 °C (140 °F) cause a reddish color and increase the astringency and off flavors in 'Deglet Noor.'

Blacknose, or sugartip, is a severe checking of the skin in some cultivars, especially in 'Deglet Noor.' It is induced by high RH just before the beginning of the khalal stage and is characterized by darkening, shriveling, and hardening of the flesh at the tip of the fruit (Rygg 1975). Black scald is characterized by blackening of the flesh and a sunken area with a definite line of demarcation at the tip or on the sides of the fruit.

Puffiness, or sunken separation, is caused by high temperatures and/or high RH before the beginning of ripening and may increase during curing. This disorder affects only soft cultivars.

Sugar spotting is characterized by light-colored spots under the skin and is restricted to the invert sugar dates. Almost all dry cultivars, and several of the semidry cultivars, contain large amounts of sucrose and are less sensitive to sugar spotting. Sugar spotting decreases as the temperature decreases and when moisture falls below 22%. Sugar spots affect appearance and texture. They can be removed by warming but can reappear if unfavorable conditions persist (Rygg 1975).

Freezing of dates at a higher temperature range results in the rupture of various cellular compartments and the appearance of bright, yellow-brown spots of crystallized solutes (Shomer et al. 1998). Intercellular membranes and cell walls can be kept intact even after 10 mo when fruits are frozen at a lower temperature range.

Postharvest Pathology

The most common pathological deterioration of dates includes fermentation by yeast and molding by fungi. Steam-hydrated dates are more resistant to attack by microorganisms than natural or nonhydrated dates because of the partial sterilization of steam-dehydrated fruit. Fungi include *Aspergillus* spp., *Alternaria* spp., *Stemphylium botryosum*, *Cladosporium* sp., *Macrosporium* sp., *Citromyces ramosus*, *Phomopsis diopspyri*, and *Penicillium* spp. These fungi can cause significant losses before or just after harvest during rainy or high-RH periods and can attack fruit at the khalal or rutab stages. However, most of these fungi, except *Catenularia fuliginia* Saito, will not grow on dried dates.

Insect Pests

Oligonychus afrasiaticus McGregor and *O. pratensis* Banks are mites referred to as “Bou Faroua” or “Old World date mite.” They affect dates at the hababouk stage. The larva develops around the fruit with a white filament netting, which in turn causes the fruit to drop prematurely. The same is caused by *Coccotrypes daclyliperda*, which leads to fruit drop-off at the immature green stage. *Parlatoria blanchardi* scale also attacks the fruit while it is still green. Date or carob moth *Ectomyelois ceratoniae* Zeller, another Lepidoptera widely present in different date-producing areas, causes important postharvest losses on stored dates. Several other insects, such as *Batrachedra amydraula* Meyr, date stone beetle (*Coccotrypes dactyliperda* F.), *Carpophilus hemipterius*, *Carpophilus multilatus*, *Urophorus humeralis*, and *Heptoncus luteolus*, can cause serious damage to dates on the bunch or after harvest. Other pests include *Vespa orientalis*, *Cadra figulilella*, *Arenipes sabella*, and mushroom mites (*Tyrophagus lintaeri* Osborn), which can infest stored dates.

Quarantine Issues

Fumigation by phosphine, ionizing radiation, the use of low or high temperatures, and MA treatments are registered to be used for insect control in dates.

Special Considerations

Dates may require postharvest ripening if picked early. Soft and semidry cultivars need to be dehydrated to eliminate excess RH if they are not intended for immediate consumption. Hydration is used to soften the texture of hard-type cultivars.

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References

Dowson, V.H.W. 1982. Date production and protection with special reference to North Africa and the Near East. Plant Production and Protection Paper 35, United Nations, Food and Agriculture Organization, Rome, Italy.

Rygg, G.L. 1975. Date Development, Handling and Packing in the United States. Agriculture Handbook 482, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Rygg, G.L. 1956. Effect of temperature and moisture content on the rate of deterioration in Deglet Noor dates. Date Growers’ Institute Report 33.

Further Reading

Abbas, M.F., and M.A. Ibrahim. 1996. The role of ethylene in the regulation of fruit ripening in the Hillawi date palm *(Phoenix dactylifera)*. J. Sci. Food Agric. 72:306-308.

Ahmed, M.S.H., Z.S. Al-Hakkak, S.R. Ali, et al. 1982. Disinfection of commercially packed dates, Zahdi, by ionizing radiation. Date Palm J. 1:249.

Al-Taweel, A.A., M.S.H. Ahmed, M.A. Shawki, and M.J. Nasser. 1993. Effects of sublethal doses of gamma radiation on the mating ability and spermatophore transfer of *Ephesia cautella* (Lepidoptera: Pyralidae). Insect Sci. Appl. 14:7-10.

Barreveld, W.H. 1993. Date palm product. Agric. Serv. Bull.101, United Nations, Food and Agriculture Organization, Rome, Italy.

Benjamin, N.D., H.R. Shabana, A.A. Mahdi Hassan, et al. 1976. Effect of different temperatures and types of containers on the storage of commercial varieties of dates in Iraq. Technical Bull. 13, Palm and Dates Research Center, Baghdad, Iraq.

Coggins, C.W. Jr., J.C.F. Knapp, and A.L. Ricker. 1968. Postharvest softening of 'Deglet Noor' dates: physical, chemical and histological changes. Date Growers' Institute Report 45:3.

Coggins, C.W. Jr., and J.C.F. Knapp. 1969. Growth, development and softening of the Deglet Noor date fruit. Date Growers' Institute Report 46:11-14.

Hasegawa, S., D.C. Smolensky, and V.P. Maier. 1932. Hydrolytic enzymes in dates and their application in softening of tough dates and sugarwall dates. Date Growers' Institute Report 29:6.

Hasegawa, S., and D.C. Smolensky. 1970. Date invertase: properties and activity associated with maturation and quality. J. Agr. Food Chem. 18:902-904.

Hasegawa, S., and D.C. Smolensky. 1971. Cellulase in dates and its role in fruit softening. J. Fd. Sci. 36:966.

Rygg, G.L., J.R. Furr, R.W. Nixon, and W.W. Armstrong. 1953. Factors affecting the spoilage of dates at room temperature. Date Growers' Institute Report 30:10-14.

Shomer, I., H. Borchov-Neori, B. Luzki, and U. Merin. 1998. Morphological, structural and membrane changes in frozen tissues of Madjhoul date (*Phoenix dactylifera* L.) fruits. Postharv. Biol. Technol. 14:207-215.

Vandercook, C.E., S. Hasegawa, and V.P. Maier. 1980. Dates. *In* S. Nagy and P.E. Shaw, eds., Tropical and Subtropical Fruits. AVI Publishing Co., Westport, CT.

Dragon Fruit

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Scientific Name and Introduction

Dragon fruit (*Hylocereus* spp.), also known as strawberry pear or thang loy (Vietnamese), pitaya roja (Spanish), and la pitahaya rouge (French), grows on a tropical climbing cactus. There is some confusion as to what species is being grown as they are all referred to as "pitahaya" in Spanish. The normally white-fleshed *Hylocereus undatus* is grown commercially, as are the red- or purple-fleshed *H. costaricensis* (grown in Nicaragua and possibly Guatemala) and *H. polyhizus* (grown in Israel). There are yellow clones of *H. undatus* named "pitaya amarilla" (yellow pitaya) in Mexico and other Latin-American countries. Pitaya amarilla is a different species from the other yellow pitaya, *Selenicereus megalanthus* (Mizrahi et al. 1997). Dragon fruit is a self-compatible cultivar in Vietnam (Mizrahi et al. 1997, Nerd and Mizrahi 1997).

Quality Characteristics and Criteria

Dragon fruit is a large, oblong fruit with a red peel and large, green scales. The scales turn yellow on ripening. The skin begins to change color 25 to 30 days after flowering in both *H. undatus* and *H. polyhizus*. At about the same time flesh firmness approaches a minimum, and eating quality approaches a maximum 33 to 37 days after flowering (Nerd et al. 1999). Fruit can be harvested 25 to 45 days after flowering; 32 to 35 days was recommended by Nerd et al. (1999). Fruit size depends on seed number (Weiss et al. 1994).

The flesh of different species can vary from white to various hues of red to very dark red. As the fruit matures, acidity reaches a peak just as the skin color change occurs, then declines 25 to 30 days after flowering (Nerd et al. 1999, Le et al. 2000). At this stage, soluble solids content (SSC) increases to about 14% (Nerd et al. 1999, Le et al. 2000).

Horticultural Maturity Indices

A common index of maturity is skin color change to almost full red (Nerd et al. 1999). Harvesting indices include color, SSC, total acidity (TA), and days from flowering (minimum 32 days). An SSC:TA of 40 has been suggested as a harvest index.

Grades, Sizes, and Packaging

There are no U.S. or international standards. Fruit are generally graded by size and color. Size grades suggested for Vietnam are extra large (over 1.1 lb or 500 g), large (0.84 lb-1.1 lb or 380-500 g), regular (0.66-0.84 lb or 300-380 g), medium (0.57-0.66 lb or 260-300 g), and small (under 0.57 lb or 260 g) (Le et al. 2000). Fruit exported from Israel to Europe are graded by number of fruit per 8.8-lb (4-kg) cardboard box: 6, 8, 10, 12, 14, and 16.

Precooling Conditions

There are no reported data. Room cooling and hydrocooling are possible.

Optimum Storage Conditions

The recommended storage temperature for dragon fruit is 10 °C (50 °F), since 6 °C (43 °F) can induce chilling injury (Nerd et al. 1999). The lower temperature (6 °C) has been recommended for the yellow pitaya *Selenicereus megalanthus* (Nerd and Mizrahi 1999), and this agrees with minimum growth temperature of 7 °C (45 °F) for this species (Nerd and Mizrahi 1998). Dragon fruit has a storage life of about 14 days at 10 °C (50 °F); while at 5 °C (41 °F) and 90% RH, a storage life of 17 days can be achieved (Le et al. 2000) if fruit are harvested 30 to 35 days after flowering. However, 5 °C (41 °F) may lead to chilling injury on return to 20 °C (68 °F), as indicated by peel and flesh deterioration and inferior taste (Nerd et al. 1999). Thus, 10 °C (50 °F) for a maximum of 14 days may be a better recommended storage temperature.

Controlled Atmosphere (CA) Considerations

No reported CA data are available. Fruit harvested 28 to 30 days after flowering and stored in a modified atmosphere (MA) bag (O_2 transmission rate 4,000 mL m^{-2} day^{-1}) can be held for 35 days at 10 °C (50 °F), versus 14 days for air controls (Le et al. 2000b). More mature fruit (40 days after flowering) in the same MA bag had 50% of the shelf-life.

Retail Outlet Display Considerations

Display dragon fruit at 10 ºC (50 °F). Do not mist.

Chilling Sensitivity

Flesh translucency is a symptom of chilling injury. Other symptoms include softening, wilting, darkening of scales, browning of the outer flesh, and poor flavor. These symptoms rapidly develop on *H. undatus* and *H. polyhizus* fruit held at 6 °C (42.8 °F) for 2 weeks then transferred to 20 °C (68 °F) (Nerd et al. 1999). Fruit harvested 25 days after flowering are more sensitive to chilling (6 °C, 7 days). Sensitivity is significantly reduced when fruit are harvested 30 to 35 days after flowering (6 °C, 17 days).

Ethylene Production and Sensitivity

Dragon fruit are nonclimacteric, with ethylene production rates of 0.025 to 0.091 µL kg^{-1} h^{-1} (Nerd et al. 1999). Ethylene treatment does not initiate color development (Le et al. 2002).

Respiration Rates

The maximum respiration rate of these nonclimacteric fruit *(H. undatus* and *H. polyhizus)* occurs during early fruit growth (Nerd et al. 1999, Le et al. 2000). The following respiration rates are for mature fruit:

Temperature	mg CO_2 kg^{-1} h^{-1}
20 °C	95 to 144
23 °C	75 to 100

Data from Nerd et al. (1999) and Le et al. (2000), respectively.

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Chilling injury, mechanical injury, and water loss are the three major disorders. Mechanical injury leads to development of sunken areas. More mature fruit are more susceptible to mechanical injury (Le et al. 2000). Splitting is a problem in fruit more than 35 days after flowering that received rainfall or excessive irrigation during ripening (Le et al. 2000).

Postharvest Pathology

Bacterial *(Xanthomonas campestris)* and *Dothiorella* spp. diseases have been reported (Barbeau 1990). Postharvest disease has been associated with *Fusarium lateritium*, *Aspergillus riger*, and *Aspergillus flavus* (Le et al. 2000). No commercially significant bacterial or fungal diseases have been experienced in Israel.

Quarantine Issues

Dragon fruit are a fruit fly host. Irradiation at 300 grays has potential for disinfestation. In Israel, no insect problems have been observed in commercial production, and the fruit's status as a fruit fly host may need to be reevaluated.

Suitability as Fresh-Cut Product

Dragon fruit are often available as a fresh-cut product in Southeast Asian markets in trays with overwrap. There is some potential, as fresh-cut fruit can be stored at 4 °C (39 °F) for 8 days (Le et al. 2002).

Special Considerations

Fruit are very low in vitamin C but rich in potassium (Le et al. 2000).

References

Barbeau, G. 1990. La pitahaya rouge, un nouveau fruit exotique. Fruits 45:141-147.

Le, V.T., N. Nguyen, D.D. Nguyen, et al. 2000. Quality assurance system for dragon fruit. *In* G.I. Johnson, V.T. Le, D.D. Nguyen, and M.C. Webb, Quality Assurance in Agricultural Produce. 19th ASEAN/1st APEC Seminar on Postharvest Technology, Ho Chi Minh City, Vietnam, November 9-12, 1999, pp. 101-114. ACIAR Proceedings no. 100, ACIAR, Canberra, Australia.

Le, V.T., N. Nguyen, D.D. Nguyen, and T.T.H. Ha. 2002. Dragon fruit quality and storage life: effect of harvesting time, use of plant growth regulators and modified atmosphere packages. Acta Hort. 575:611-621.

Mizrahi, Y., A. Nerd, and P.S. Nobel. 1997. Cacti as crops. Hort. Rev. 18:291-319.

Nerd, A., and Y. Mizrahi. 1997. Reproductive biology of cactus fruit crops. Hort. Rev. 18:321-346.

Nerd, A., and Y. Mizrahi. 1998. Fruit development and ripening in yellow pitaya. J. Amer. Soc. Hort. Sci. 123:560-562.

Nerd, A., and Y. Mizrahi. 1999. The effect of ripening stage of fruit quality after storage of yellow pitaya. Postharv. Biol. Technol. 15:99-105.

Nerd, A., F. Gutman, and Y. Mizrahi. 1999. Ripening and postharvest behaviour of fruits of two *Hylocereus* species (Cactaceae). Postharv. Biol. Technol. 17:39-45.

Weiss, J., A. Nerd, and Y. Mizrahi. 1994. Flowering behavior and pollination requirements in climbing cactus with fruit crop potential. HortScience 29:1487-1492.

Durian

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Scientific Name and Introduction

The durian (*Durio zibethinus* Murray [syn. *D. acuminatissina* Merr]) is often referred to as the "King of Fruits" in Southeast Asia. Its qualities promote considerable discussion because of its unique odor, which can be offensive to some people. (The fruit has a strong onion-garlic odor.) *"Zibethinus"* is derived from the word "zibetto," Italian for the civet, a catlike animal with a musky odor. This tropical tree is mainly cultivated in Sri Lanka, southern India, southern Burma, Thailand, Cambodia, Vietnam, Malaysia, Indonesia, Borneo, the Philippines (on Mindanao Island), and New Guinea. It has spread throughout the tropical world under the general name of "durian" (Indo-Malay) or variants thereof, such as "duren" (Indonesian), "duyin" (Burmese), "thureen" (Cambodian), "thurian" (Thai), "saurieng" (Vietnamese), "dulian" (Filipino), "stinkvrucht" (Dutch), and "kadu" (Sudan). Limited supplies are available from the Caribbean and Central and South America. Commercial supplies are available from Thailand and Malaysia.

Quality Characteristics and Criteria

Weighing up to 8 kg (18 lb), the oval or ellipsoid, green to brownish fruit can measure up to 30 cm (12 in) long and 20 cm (8 in) in diameter. It is densely covered with stout, sharp, pyramidal spines 1 cm (0.5 in) long on its thick, fibrous rind. Fruit are divided into 3 to 5 smooth-walled compartments, each containing 1 to 6 glossy, creamy to red-brown seeds 2 to 6 cm (0.8 to 2.4 in) long covered by a white to yellowish, soft, sweet pulp (aril). The pulp can be odorless or have a strong odor suggesting garlic, onion, or pungent cheese with a hint of fruitiness. The edible pulp (20 to 35% total mass) has a smooth, custardlike texture. In some fruit, seeds are rudimentary or small compared with wild types.

Quality criteria include a pulp with sweet flavor and good texture, few or small seeds, large aril percentage, and marketable weight of 1.5 to 3.5 kg (3.3 to 7.7 lb), elongated to round shape, good shelf-life, good rind color and thickness, reduced rind splitting, and freedom from disease and insects. Superior varieties have thick, yellow, fiberless, and custardlike pulp.

The Thai cultivar 'Chanee' has a stronger aroma and is smaller than the preferred 'Monthong' (Golden Pillow). Malaysian cultivars include D-2 'Dato Nina,' D-7 'Repok B-2,' D-10 'Durian Hyan,' and D-24 and D-98 'Katoi.'

Horticultural Maturity Indices

At maturity, the fruit naturally falls from the tree at the articulation of the fruit stem with the fruit, then ripens in 2 to 4 days, with the fruit normally splitting into segments of irregular widths at the stylar end. Ripening results in an increase in soluble sugars and a decrease in starch and pulp firmness that occurs before natural fruit splitting starts.

To prevent natural fruit fall, fruit may be tied to the limb or harvested at maturity. Maturity is judged by appearance (fruit stalk thickness and flexibility, abscission zone, or carpel sutures), number of days after flowering, and a hollow sound when tapped with a wood or rattan stick or knife. The number of days after flowering and tapping are the most reliable criteria (Siriphanich 1996). 'Chanee' durian takes 2 to 4 days, while 'Monthong' durian takes 4 to 6 days to ripen after harvest, depending on maturity. Fruit at 85% maturity, based on days from anthesis and rind characteristics, ripen to excellent quality in under 1 week at 28 to 31 °C (82 to 88 °F). Ripening takes longer than 1 week at 22 °C (72 °F). Fruit that are 95% mature when harvested have already commenced ripening, while 75% mature fruit may ripen with an inferior quality. Compared with fruit picked from the tree, fruit collected from the ground after falling are more subject to disease and fracture and have a shorter shelf-life (2 to 3 days instead of the 7 to 8 days for fruit picked from the tree). In Thailand, the fruit is harvested with the stem (peduncle) attached, and the stem is wrapped in a leaf or paper to reduce wilting and maintain the fresh appearance of the stem, since stem appearance is also used as a measure of freshness. 'Chanee' is at optimum eating stage for only a few days while 'Mon Tong' is at this stage for a longer period.

Grades, Sizes, and Packaging

Durian fruit are graded on weight, shape, size, and defects (Nanthachai 1994). Defects include disease, insects, mechanical injury, and flesh disorders. Grades vary with variety (Hiranpradit et al. 1992). The fruit is packed into cardboard cartons (4 to 6 fruit per carton) or in cartons fitted with fiberboard dividers.

Precooling Conditions

Use forced-air or room cooling to 15 °C (59 °F).

Optimum Storage Conditions

This climacteric fruit, when stored at 15 ºC (59 ºF), has extended shelf-life (Brooncherm and Siriphanich 1991); RH of 85 to 95% is best (Ketsa and Pangkool 1994, Sriyook et al. 1994). Fruit can be waxed to reduce water loss (Sriyook et al. 1994). Fruit ripened at a lower RH (75%) have a better eating quality and are less juicy and easier to dehusk than fruit ripened at a higher RH (Ketsa and Pangkool 1994).

Controlled Atmosphere (CA) Considerations

Ripening is inhibited by 2% O_2, and fruit fail to ripen when removed to air. Fruit stored in up to 20% CO_2 in air were not affected in terms of ripening or quality (Tongdee et al. 1990). Low O_2 (10%) reduces respiration rate and ethylene production but does not affect the onset of ripening, and ripe fruit quality is not affected. The aril remains hard in less mature fruit stored in 10% O_2 and 15 or 20% CO_2. The commercial potential of CA or MA is still unclear (Siriphanich 1996).

Retail Outlet Display Considerations

Display at ambient temperature or hold at 15 to 18 °C (59 to 64 °F), if available. Do not mist or ice. Avoid mixing with other produce during storage. The husk can be removed and the whole pulp and seed segment can be removed and sold in trays with a plastic overwrap. Remove the husk as soon as the fruit starts to produce aroma or is half-ripe and the pulp is still firm. If fruit splitting has started, the pulp is generally too soft and has a very short shelf-life.

Chilling Sensitivity

The pulp of half-ripe or nearly fully ripe fruit is much less sensitive to chilling injury than the peel, and the pulp can be stored for 4 weeks at 5 °C (41 °F). Whole fruit stored at under 15 °C (59 °F) develop chilling injury shown by the peel turning black or dark brown starting at the groove between the spines (Brooncherm and Siriphanich 1991). Chilling-injured pulp suffers a loss of aroma, does not soften, and may develop sunken areas on the surface (Siriphanich 1996).

Ethylene Production and Sensitivity

Production of ethylene varies from near zero in immature fruit up to 40 µL kg^{-1} hr^{-1} at the climacteric peak and varies with cultivar (Tongdee et al. 1987a,b). Most of the ethylene production is associated with the husk, as the pulp has a very low rate (Siriphanich 1996). Durian can be ripened with ethylene gas (Ketsa and Pangkool 1995) or ethephon (Atantee 1995). The husk of ripened durians will turn yellow or brown if ethylene concentration is too high. Thai consumers prefer to buy naturally ripened durians since the husk remains light green or olive. Durians with a yellowish or brownish husk are not regarded as fresh.

Respiration Rates

The respiration rate for durian is 80 to 450 mg (45 to 254 µL) CO_2 kg^{-1} h^{-1} at 22 °C. To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day. The peel has a much higher respiration rate and ethylene production than the pulp (Brooncherm and Siriphanich 1991). The climacteric rise seems to occur first in the pulp. In 'Chanee' and 'Kan Yao,' the respiration and ethylene production increase during ripening but decline when the fruit is overripe, while in 'Mon Tong,' the climacteric peak does not occur until the fruit is overripe (Tongdee et al. 1987b).

Physiological Disorders

Failure of the aril to soften, or the aril softening unevenly, is a frequently observed disorder. Another disorder, which occurs especially during the rainy season, results in a watery aril that has a dull, flat taste. The cause of both disorders is unknown (Nanthachai 1994).

Postharvest Pathology

Phytophthora spp. are a major cause of rot in immature and mature fruit that leads to high losses during rainy weather and if fruit come in contact with soil. Another major cause of fruit rot is *Lasiodiplodia* spp. (Tongdee et al. 1987a). Fruit on the ground can also be attacked by *Sclerotum rolfsii*. Fruit diseases due to *Phomopsis*, *Collectrichum*, *Fusarium*, and *Rhizopus* can sometimes be severe (Siriphanich 1996). Sanitation, avoidance of mechanical injury, and fungicide can be used for control (Lim 1990).

Quarantine Issues

If the skin is not broken or split, durian is not a fruit fly host. The skin must be free of other insects such as scales.

Suitability as Fresh-Cut Product

The fruit is most frequently eaten fresh. The aril contains 64% water, 2.7% protein, 3.4% fat, 27.9% carbohydrate, and 23 mg per 1,000 g vitamin C. Choice varieties fetch higher prices than others. Roadside and market stalls in Southeast Asia may cut open the fruit and package the soft aril and seed in a shrink-wrapped or stretch-wrapped tray. Ripe fruit and soft arils are also frozen for export. Partially ripe fruit are difficult to open without damaging the pulp.

Special Considerations

Thailand is the largest producer, followed by Indonesia and the Malaysian Peninsula. Durian is highly prized in Southeast Asia. Consumers in Singapore prefer fully ripe fruit with no splitting, while Thais prefer the firmer pulp of less ripe fruit with less volatiles. Others may prefer the strong-flavored durian over the milder cultivars. There is a demand among ethnic groups familiar with the fruit in large temperate cities.

The pulp is dehydrated and sold as "durian cake" boiled with sugar, fermented, or salted. Dried aril is used as flavoring in ice cream, confectionery, pastry, and soft drinks (Nakasone and Paull 1998). Boiled or roasted seeds are eaten as snacks. Durian chips can be made from the immature and unripe durian pulp, as the lighter-colored flesh makes more attractive chips. Durian should not be shipped in mixed loads.

References

Atantee, S. 1995. Effect of ethephon on ripening and quality of durians. Graduate Special Problem, Department of Horticulture, Kasetsart University, Bangkok, Thailand.

Brooncherm, P., and J. Siriphanich. 1991. Postharvest physiology of durian pulp and husk. Kasetsart J. (Natural Sci.) 25:119-125.

Hiranpradit, H., N. Lee-Ungulasatian, S. Chandraparnik, and S. Jantigoo. 1992. Quality standardization of Thai durian, *Durio zibethinus* Murr. Acta Hort. 321:695-704.

Ketsa, S., and S. Pangkool. 1994. The effect of humidity on ripening of durians. Postharv. Biol. Technol. 4:159-165.

Ketsa, S., and S. Pongkool. 2001. Effect of maturity stages and ethylene treatment on ripening of durian fruits. *In* C. Frisina, K. Mason, and J. Faragher, eds., Proceedings of the Australasian Postharvest Horticulture Conference, held at Monash University, Melbourne, Australia, 18 September to 22 September, 1995, pp. 67-72. Department of Natural Resources and Environment, Institute for Horticultural Development, Knoxfield, Victoria, Australia.

Lim, T.K. 1990. Durian—Diseases and Disorders, pp. 60-72. Tropical Press, Kuala Lumpur, Malaysia.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K.

Nanthachai, S., ed. 1994. Durian: Fruit Development, Postharvest Physiology, Handling and Marketing in ASEAN. ASEAN Food Handling Bureau, Kuala Lumpur, Malaysia.

Salakpetch, S., S. Chandraparnik, H. Hiranpradit, and U. Punnachit. 1992. Source-sink relationship affecting fruit development and fruit quality in durian, *Durio zibethinus* Murr. Acta Hort. 321:691-694.

Siriphanich, J. 1996. Storage and transportation of tropical fruits: a case study on durian. *In* S. Vijaysegaran, M. Pauziah, M.S. Mohamed, and S. Ahmed Tarmizi, Proceedings of the International Conference on Tropical Fruits, 23-26 July 1996, Kuala Lumpur, Malaysia, vol. 1, pp. 439-451. MARDI, Kuala Lumpur, Malaysia.

Sriyook, S., S. Siriatiwat, and J. Siriphanich. 1994. Durian fruit dehiscence—water status and ethylene. HortScience 29:1195-1198.

Tongdee, S.C., A. Chayasombat, and S. Neamprem. 1987a. Effects of harvest maturity on respiration, ethylene production, and composition of internal atmospheres of Durian (*Durio zibethinus*, Murray). Proceedings of the Durian Workshop, Bangkok, Thailand, pp. 31-36. Thailand Institute of Scientific and Technological Research, Bangkok, Thailand.

Tongdee, S.C., S. Neamprem, and A. Chayasombat. 1987b. Control of postharvest infection of phytophthora fruit rot in durian with fosetyl-Al and residue levels in fruit. Proceedings of the Durian Workshop, Bangkok, Thailand, pp. 55-66. Thailand Institute of Scientific and Technological Research, Bangkok, Thailand.

Tongdee, S.C., A. Suwanagul, S. Neamprem, and U. Bunruengsri. 1990. Effect of surface coatings on weight loss and internal atmosphere of durian (*Durio zibethinus* Murray) fruit. ASEAN Food J. 5:103-107.

Eggplant

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Scientific Name and Introduction

The eggplant (*Solanum melongena* L.) is an annual plant of the Solanaceae or nightshade family. The edible portion is the immature fleshy pulp of the fruit. The fruit may be oval, round, long or pear-shaped. The skin is smooth and shiny, and the color may be black and purple, yellow, white, or striped. The main types include Standard (American), Japanese, Italian, Philippine, Thai, and Chinese. Available year-round, eggplants are grown primarily in Mexico, the United States (mostly in Florida and New Jersey), the Dominican Republic, and Jamaica.

Quality Characteristics and Criteria

A high-quality American eggplant is uniformly egg-shaped or globular and has a fresh green calyx, firm flesh, and dark purple skin. Additional quality indices are size, freedom from growth or handling defects, and decay. Characteristics of other eggplant types include Japanese (elongated, slender, and light to dark purple), White (small, egg-shaped to globular, and thin-skinned), Mini-Japanese (small, elongated, striated purple and violet), Chinese (elongated, slender, and light purple), and Thai (small, round, and striated dark green).

Horticultural Maturity Indices

Eggplant fruit are harvested at a range of developmental stages. The time from flowering to harvest depends on cultivar and temperature and may be 10 to 40 days. Fruit are harvested immature before seeds begin to significantly enlarge and harden. Firmness and external glossiness are also used as harvest indicators. Overmature fruit become pithy and bitter.

Grades, Sizes, and Packing

Grades include Fancy, U.S. No. 1, U.S. No. 2, and Unclassified. Distinction among grades is based solely on size, external appearance, and firmness. Size is classified as “small”—32 fruit per box with fruit length 12 to 14 cm (4.75 to 5.5 in), “medium”—24 fruit per box with fruit length 19 to 21 cm (7.5 to 8.25 in), “large”—18 fruit per box with fruit length 21 to 24 cm (8.25 to 9.5 in), and “extra large”—16 fruit per box with fruit length 24 to 26 cm (9.5 to 10.25 in) (Siller et al. 1995). One-piece waxed fiberboard boxes and wire-bound crates that can hold up to 15 kg (33 lb) are commonly used. Fruit are individually wrapped with paper to reduce desiccation and mechanical injury.

Precooling Conditions

Rapid cooling to 10 °C (50 °F) immediately after harvest is necessary to retard discoloration, weight loss, drying of calyx, and decay (Ryall and Lipton 1979). Hydrocooling and forced-air cooling are most effective, but room cooling after washing or hydrocooling is common.

Optimum Storage Conditions

Fruit are stored at 10 to 12 °C (50 to 54 °F) with 90 to 95% RH because they are chilling sensitive (Ryall and Lipton 1979). Visual and sensory qualities deteriorate rapidly after 14 days of storage, especially if chilled during storage. Short-term storage or transit temperatures below 10 °C (50 °F) are often used to reduce weight loss but result in chilling injury after transfer to retail conditions.

Controlled Atmosphere (CA) Considerations

CA storage or shipping offers little benefit. Low O_2 levels (3 to 5%) delay deterioration and the onset of decay by only a few days. Eggplant tolerates up to 10% CO_2, but storage life is not extended beyond that under reduced O_2. Wrapping fruit with plastic film to create modified atmosphere (MA) reduces weight loss and maintains firmness due to the high RH, especially on Japanese eggplant types, which have a high transpiration rate (Díaz Pérez 1998a). Eggplant fruit wrapped in high-density polyethylene (HDPE) films maintain a fresher flavor, firmness, and quality for a longer period than nonwrapped fruit (Ben-Yehoshua et al. 1985, Díaz Pérez 1998b).

Retail Outlet Display Considerations

Eggplants should never be held in contact with ice. Odor from ginger, and possibly other odor-producing commodities such as onions, can be absorbed by eggplants. Thus, these products should not be placed in close proximity to eggplants (Cantwell and Suslow 2006).

Chilling Sensitivity

Eggplants will develop chilling injury after storage for 6 to 8 days at 5 °C (41 °F) (table 1). Surface pitting and scald are definite external symptoms (McColloch 1966). Scald refers to brown spots or areas that are first flush with the surface but may become sunken with time. Browning of the flesh and seeds is a conspicuous internal symptom of chilling injury, almost invariably followed by decay caused by *Alternaria* sp. (Ryan and Lipton 1979). Chilling injury is cumulative and may be initiated in the field prior to harvest. Symptom development can be reduced by storage in polyethylene bags or polymeric film overwraps that retard water loss; however, increased decay from *Botrytis* is a potential risk.

Table 1. Chilling susceptablity of eggplant by type

Temperature	Days to visible chilling symptoms		
	American eggplant	Japanese eggplant	Chinese eggplant
0.0 °C	1 to 2	2 to 3	—
2.5 °C	4 to 5	5 to 6	5 to 6
5.0 °C	6 to 7	8 to 9	10 to 12
7.5 °C	12	12 to 14	15 to 16

Respiration Rates

Temperature	American eggplant	White eggplant	Japanese eggplant
	----------(mg CO_2 kg^{-1} h^{-1})----------		
12.5 °C	60 to 78	104 to 122	124 to 138

Data from Cantwell and Suslow (1998).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Ethylene Production and Sensitivity

Rates of ethylene production vary from 0.1 to 0.7 µL kg^{-1} h^{-1} at 12.5 °C (55 °F). Eggplant fruit have a moderate to high sensitivity to ethylene exposure. Calyx abscission and increased deterioration, particularly browning, may be a problem if eggplant fruit are exposed to greater than 1 µL L^{-1} ethylene during distribution and short-term storage.

Freezing Injury

Eggplant fruit freeze at -0.8 °C (30.6 °F). Symptoms include water-soaked pulp that becomes brown and desiccated over time.

Physiological Disorders

Harvesting should be done by cutting the calyx-stem free from the plant rather than by tearing. Cotton gloves are often worn to protect the fruit. Bruising and compression injury is very common when not enough attention is paid to careful harvest and handling practices. Eggplant fruit cannot withstand stacking in bulk containers.

Postharvest Pathology

Postharvest diseases often occur in combination with chilling stress. Common fungal pathogens are *Alternaria* (black mold rot), *Botrytis* (gray mold rot), *Rhizopus* (hairy rot), *Phomopsis* rot, and *Phytophtora* (soft rot).

Quarantine Issues

None.

Suitability as Fresh-Cut Product

No current potential.

Special Considerations

Moistened paper or waxed cartons are often used to reduce water loss. Japanese eggplants lose water three times more rapidly than American types. Visible signs of water loss are reduction of surface sheen, skin wrinkling, spongy flesh, and browning of the calyx. Dipping the calyx or the whole fruit in dilute aqueous solutions of 1-naphthalene acetic acid and prochloraz retarded calyx senescence (Temkin-Gorodeiski et al. 1993, Muy et al. 1998).

References

Ben-Yehoshua, S. 1985. Individual seal-packing of fruits and vegetables in plastic film—a new postharvest technique. HortScience 20:32-37.

Cantwell, M., and T. Suslow. 2006. Eggplant. *In* Fresh Produce Facts. *At* http://postharvest.ucdavis.edu/produce_information.

Díaz-Pérez, J.C. 1998a. Transpiration rates in eggplant fruit as affected by fruit and calyx size. Postharv. Biol. Technol. 12:76-82.

Díaz-Pérez, J.C. 1998b. Empaque de berenjena (*Solanum melongena* L.) ‘Clásica’ y ‘Japonesa’ con películas de polietileno. Agrociencia 32:71-74.

McColloch, L.P. 1966. Chilling injury of eggplant fruits. Marketing Research Report 749, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Muy, R.D., J. Siller, M. Báez, and V. Pérez. 1998. Aplicación de tratamientos químicos para reducir oxidación del cáliz en Berenjena (*Solanum melongena* L.). *In* Abstracts of the XXIX National Congress of Food Science Technology, vol. 33, pp. 61-62. Tecnología de Alimentos, Aguascalientes, Mexico.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation and Storage of Fruits and Vegetables, vol. 1, Vegetables and Melons. AVI Publishing Co., Westport, CT.

Siller, J., E. Araiza, M. Báez, et al. 1995. Dinámica de crecimiento de berenjena tipo ‘Clásica.’ *In* Abstracts of the VI Congress of the Mexican Society of Horticultural Sciences, Sonora, Mexico, p. 37. Mexican Society of Horticultural Sciences, Sonora, Mexico.

Temkin-Gorodeiski, N., B. Shapiro, S. Grinberg, et al. 1993. Postharvest treatments to control eggplant deterioration during storage. J. Hort. Sci. 68:689-693.

Endive and Escarole

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Scientific Name and Introduction

Endive (*Cichorium endiva* L.) is an herbaceous member of the Asteraceae family, as are its relatives chicory (*Cichorium intybus* L.), lettuce (*Lactuca sativa* L., Cichorium tribe), and radicchio (*Cichorium intybus* L.). It has two forms, a narrow-leafed form called curly endive, which resembles dandelion leaves, and a broad-leafed form called escarole. The outer leaves of endive are dark green and bitter. The inner leaves are light green to creamy white and milder in flavor. It is used to spice up salads made from more blandly flavored lettuces. Endive is grown and handled like leaf lettuces.

Quality Characteristics and Criteria

High-quality endive heads should be clean, free of browning, crisp, and bright green. Young, tender leaves are preferred over tough, older leaves.

Horticultural Maturity Indices

Harvesting is usually by hand when the heads reach mature size. The plants are cut at the base when fully developed—25 to 30 cm (10 to 12 in) across and the center leaves blanched. The heads are packed into corrugated paper cartons in the field. The leafy heads should be kept clean of soil and mud. The leaves should have a spicy and mildly bitter taste. Toughness and a strong bitter taste develop if harvest is delayed and the crop becomes overmature. The product then becomes unmarketable.

Grades, Sizes, and Packaging

Similar to those of leaf lettuces.

Precooling Conditions

Vacuum cooling and hydrocooling to 0 °C (32 °F) are preferred.

Optimum Storage Conditions

These crops are not adapted to prolonged storage and will not keep more than 2 to 3 weeks even at the optimal storage temperature of 0 °C (32 °F) with 95 to 100% RH (Hardenburg et al. 1986). Storage life is halved at 5 °C (41 °F). Proper RH is essential to prevent wilting. Though endive, specialty lettuces, and other leafy greens have usually been hand harvested, some mechanical harvesters are available for product destined for bag mixes. However, the greater degree of injury produced by mechanical harvesting may shorten shelf-life unless optimal storage conditions are strictly maintained. Top ice or package ice is desirable for maintaining proper temperature and RH. Endive and escarole are often shipped in mixed loads with other produce since most orders for these products are less than truckload lots.

Controlled Atmosphere (CA) Considerations

There are currently no recommended CA atmospheres for endive and escarole. However, a CA useful to maintain the quality of packaged fresh-cut lettuce may be beneficial for either whole or fresh-cut endive and escarole.

Retail Outlet Display Considerations

Maintain cold conditions to maximize storage and shelf-life, and minimize dehydration with periodic sprays of cold water. Conditions should be similar to those used for leaf lettuces.

Chilling Sensitivity

Endive and escarole are not chilling sensitive, but freezing at -0.1 °C (31.8 °F) must be avoided.

Ethylene Production and Sensitivity

Production is very low, but exposure can result in leaf yellowing.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	45
5 °C	52
10 °C	73
15 °C	100
20 °C	133
25 °C	200

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Similar to those of leaf lettuces.

Postharvest Pathology

Similar to those of leaf lettuces.

Quarantine Issues

There are no quarantine issues.

Suitability as Fresh-Cut Product

Very high, especially in salad mixes with other leafy greens and lettuces.

Special Considerations

Endive and escarole must be handled with care to avoid mechanical damage and to minimize discoloration and pathological problems. Temperatures must be kept low and RH high to prevent loss of turgor and wilting.

References

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation and Storage of Fruits and Vegetables, 2nd ed., vol. 1, Vegetables and Melons. AVI Publishing Co., Westport, CT.

Ryder, E.J. 1979. Endive and chicory. Leafy Salad Vegetables, pp. 171-194. AVI Publishing Co., Westport, CT.

Fennel

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Scientific Name and Introduction

Fennel (*Foeniculum vulgaris* Mill.) belongs to the Umbelliferae family and originated in the Mediterranean region. There are two varieties: seed fennel is var. *sativum* and edible fennel is var. *dulce*. The edible portion is the white, enlarged basal parts of the leaf sheaths that are fleshy, turgid, and crisp. The leafy sheaths form a “grumolo” that is white, spherical, and the source of green stems and fuzzy leaves. Italian production accounts for 85% of the world market. Fennel is a source of fiber, potassium, and vitamin C.

Quality Characteristics and Criteria

There are no published quality standards, but extra fancy fennel is characterized by uniform and brilliant white leafy sheaths that are turgid and crisp, with no symptoms of cracking or darkening.

Horticultural Maturity Indices

Fennel is harvested by hand when the plant reaches a specified size by cutting the plant from the taproot. Outer leaves are removed, and the remaining leaves are trimmed to 10 to 15 cm (4 to 6 in) in length. It is harvested year-round, except in June and July.

Grades, Sizes, and Packaging

Fennel is sized by the packer and placed in plastic or cardboard boxes. Careful packing is necessary to avoid scratching the sheaths. Mechanical injury produces rapid browning of the leaves.

Precooling Conditions

Hydrocooling is needed in the summer to reduce field heat and water loss. Aqueous citrate solutions control browning of cut surfaces. Avoid excess water infiltration during packing. Forced-air cooling can be used, but only when fennel is plastic-wrapped. Vacuum cooling was tested with mixed results (Sozzi and Ilardi 1992).

Optimum Storage Conditions

Fennel can last for 2 weeks if stored at 0 °C (32 °F) and 90 to 95% RH.

Controlled Atmosphere (CA) Considerations

No CA applications have been reported.

Retail Outlet Display Considerations

Fennel must be kept refrigerated and periodically moistened with water sprays. Removal of injured sheaths and brown cut surfaces may be needed.

Chilling Sensitivity

Fennel is not chilling sensitive.

Ethylene Production and Sensitivity

Ethylene production is low at 0 to 2 °C (32 to 36 °F)—about 0.5 to 1.0 μL kg^{-1} h^{-1}—and increases to 2.5 to 6 μL kg^{-1} h^{-1} at 20 °C (68 °F) (Mencarelli et al. 1996). No data exist on sensitivity to ethylene.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
2 °C	18 to 20
20 °C	24 to 40

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Growth after harvest can cause the leaf sheaths to loosen and separate (Mencarelli et al. 1996). Freezing results in water-soaked spots on the outside sheaths and decay of internal young sheaths.

Postharvest Pathology

Fennel is resistant to pathogen attack after harvest. Free water inside the plant can promote bacterial growth.

Quarantine Issues

There are no quarantine issues at this time.

Suitability as Fresh-Cut Product

Browning of cut surfaces is a problem with fresh-cut fennel.

Special Considerations

Special attention must be given to mechanical harvesting and postharvest handling because fennel is highly sensitive to physical injury. Removal of the outer sheath at retail markets reduces the problem, but the process is time consuming.

References

Bianco, V.V. 1990. Il finocchio. *In* V.V. Bianco and F. Pimpini, eds., Orticoltura, pp. 168-183. Patron Press, Bologna, Italy.

Mencarelli, F., R. Massantini, and F. Garosi. 1996. Aspetti fisiologici della postraccolta del finocchio fresco. Procedura Giornate di Studio sulla Coltivazione del Finocchio, 3:29-30, pp. 131-136. Italian Horticultural Society, Tarquinia, Viterbo, Italy.

Sozzi, A., and V. Ilardi. 1992. Conservazione con film microperforato e prerefrigerazione con vacuum del finocchio. Colture Protette 4:73-76.

Fig

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Scientific Name and Introduction

Edible figs are the multiple or compound fruits of *Ficus carica* L., a member of the family Moraceae. The plant is a tree or shrub native to Asia Minor, from where it spread into the Mediterranean region. It was known to the ancient Egyptians in 4000 B.C., and later Herodotus (c. 485 to 425 B.C.) wrote about its cultivation.

Figs were introduced from Europe to North America as early as 1600, but commercial cultivation did not start until about 1900. The largest center of cultivation in the United States is in California. Figs thrive only in the hotter parts of the moderate zones, while in tropical countries they can be cultivated only at higher altitudes.

The best-known cultivated varieties are the common, or Adriatic, fig and the Smyrna fig. The common fig produces seedless fruit by parthenocarpy (production of fruit without fertilization), while the Smyrna fig must be pollinated in spite of the fact that it does not develop any male flowers. The figs are pear-shaped structures formed from the rolled-up discs of the capitula so that the florets of the capitulum occur inside the aperture and are not visible from the outside. The capitulum is connected to the outside by a small aperture at the top of the fig. The female florets develop into tiny achenes. The achenes inside the fig represent the infructescence, and the edible part is the swollen, fleshy disc of the capitulum forming the fruit wall.

Quality Characteristics and Criteria

Skin color and flesh firmness of fresh figs are related to their quality and postharvest life. Flavor is influenced by stage of ripeness, and overripe figs can become undesirable due to fermentative products. Other quality indices include absence of defects (such as bird-peck, sunburn, scab, skin break, and stem shrivel), insects, and decay.

Horticultural Maturity Indices

Fresh market figs must be harvested when almost fully ripe and firm to be of good eating quality. Skin color and flesh firmness are dependable maturity and ripeness indices. ‘Black Mission’ figs should be light to dark purple rather than black, and should yield to slight pressure. ‘Calimyrna’ figs should be yellowish white to light yellow and firm. Figs for drying should be allowed to fully ripen and partially dry on the tree before harvesting and drying to about 17% moisture using either solar drying or a dehydrator at 60 ºC (140 ºF).

Grades, Sizes, and Packaging

Fully mature fresh figs are soft, easily bruised, and highly perishable. Figs are hand-picked and packed in a one-layer box. Pickers wear gloves to protect against fig juice. ‘Mission’ fig, a black fig with distinctive flavor, and ‘Calimyrna’ fig, a large yellowish fig, are the main cultivars sold fresh in the United States.

Optimum Storage Conditions

Store at -1 to 0 ºC (30 to 32 ºF) with 90 to 95% RH. Expedited forced-air cooling to 0 ºC (32 ºF) is strongly recommended.

Controlled Atmosphere (CA) Considerations

CA combinations of 5 to 10% O_2 with 15 to 20% CO_2 are effective in decay control, firmness retention, and reduction of respiration and ethylene production. Postharvest life at optimum temperature and RH depends on cultivar and ripeness at harvest, but ranges from 1 to 2 weeks in air and 3 to 4 weeks in CA for California-grown 'Black Mission' and 'Calimyrna' figs.

Retail Outlet Display Considerations

Figs should be displayed at 0 to 2 ºC (32 to 36 ºF) and dried with an RH of 90 to 95%.

Chilling Sensitivity

Figs are not chilling sensitive.

Rates of Ethylene Production and Sensitivity

Temperature	µL kg^{-1} h^{-1}
0 ºC	0.4 to 0.8
5 ºC	0.8 to 1.5
10 ºC	1.5 to 3.0
20 ºC	4.0 to 6.0

Figs are climacteric fruit and are slightly sensitive to ethylene action on stimulating softening and decay severity, especially if kept at 5 ºC (41 ºF) or higher temperatures.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 ºC	4 to 8
5 ºC	10 to 16
10 ºC	18 to 24
20 ºC	40 to 60

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Extended storage in CA can result in loss of characteristic flavor. Figs exposed to <2% O_2 or >25% CO_2 develop off flavors due to fermentative metabolism.

Postharvest Pathology

Alternaria rot, caused by *Alternaria tenuis*, appears as small, round, brown to black spots over the fruit surface. Any cracks on the skin make the fruit more susceptible to the rot.

Black mold rot, caused by *Aspergillus niger*, appears as dark or yellowish spots in the flesh with no external symptoms. At advanced stages the skin and flesh turn a slightly pink color and white mycelia with black spore masses follow.

Endosepsis (soft rot), caused by *Fusarium moniliforms*, appears in the cavity of the fig making the pulp soft, watery, and brown with sometimes an offensive odor.

Souring is a preharvest problem resulting from yeasts and bacteria carried into figs by insects, especially vinegar flies, resulting in odors of alcohol or acetic acid.

Recommendations to reduce postharvest diseases are the following: controlling orchard insects to reduce fruit damage and transmission of fungi; using effective control of preharvest diseases; enforcing strict sanitation of picking and transporting containers; supervising careful handling to minimize abrasions, cracks, and other physical damage; avoiding picking figs from the ground for fresh market; and enforcing prompt cooling to 0 ºC (32 ºF) and maintaining the cold chain all the way to the consumer.

Quarantine Issues

Currently, there is limited export to Canada. There is no import of fresh figs into the United States. Issues associated with exotic pest quarantine addressing both imported and exported fruit change rapidly. The USDA Animal and Plant Health Inspection Service (APHIS) issues rules regarding import requirements. APHIS provides information to assist exporters in targeting markets and defining what entry requirements a foreign country might have for fruit. In cooperation with State plant boards, the agency developed the database "Excerpt" to track phytosanitary requirements for each country. APHIS also provides phytosanitary inspections and certifications that declare that fruit are free of pests to facilitate compliance with foreign regulatory requirements.

Suitability as Fresh-Cut Product

Fresh figs are not well-adapted for use as a fresh-cut product.

Special Considerations

Handling figs to avoid infection with *Aspergillus* species is very important to minimize formation of mycotoxins. Solar heating reduces insect infestations in ripening and drying figs.

Acknowledgments

Most of the information in this chapter is from the University of California, Davis, website on "Fresh Produce Facts" at http://postharvest.ucdavis.edu/produce_information.

References

Bolin H.R., and A.D. King. 1980. Fig. *In* S. Nagy and P. Shaw, eds., Tropical and Subtropical Fruits - Composition, Properties, and Uses, pp. 492-505. AVI Publishing Co., Westport, CT.

Chossa, I. 1997. Fig. *In* S. Mitra, ed., Postharvest Physiology and Storage of Tropical and Subtropical Fruits, pp. 245-268. CAB Intl., Wallingford, U.K.

Colelli, G., F.G. Mitchell, and A.A. Kader. 1991. Extension of postharvest life of 'Mission' figs by CO_2-enriched atmospheres. HortScience 26:1193-1195.

Condit, J.J. 1947. The Fig. Chronica Botanica Co., Waltham, MA.

Obenauf, G., M. Gerdts, G. Leavitt, and J. Crane. 1978. Commercial dried fig production. Leaflet 21051, University of California, Division of Agricultural Sciences, Davis, CA.

Garlic

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Scientific Name and Introduction

Garlic, *Allium sativum* L., is a member of the onion family (Alliaceae). It is a bulb comprised of cloves (thickened storage leaves) individually wrapped in dried leaf sheaths or skins attached to a compressed stem plate. The whole bulb is also wrapped in several layers of dried leaf sheaths. In the United States, garlic is grown mostly in California and neighboring States. Garlic is imported principally from Argentina, Chile, China, and Mexico. Garlic is produced as an annual crop for seed, fresh market, and processed (dried) products.

Quality Characteristics and Criteria

High-quality garlic bulbs are clean, white (or other color typical of the variety), and well-cured (dried neck and outer skins). The cloves should be firm to the touch. Cloves from mature bulbs should have a high dry weight and soluble solids content (SSC)—more than 35% in both cases.

Horticultural Maturity Indices

Garlic can be harvested at different stages of development for specialty markets, but most garlic is harvested when the bulbs are mature. Harvest occurs after the tops have fallen and are dried.

Grades, Sizes, and Packaging

Grades include U.S. No. 1 and unclassified and are based primarily on external appearance and freedom from defects. Minimum diameter for fresh market is 38.1 mm (1.5 in). Garlic is usually packed loose in 2.3-, 4.6-, 10-, and 13.6-kg (5-, 10-, 22-, and 30-lb) cartons and may also be packed in smaller-weight net bags or trays for retail.

Cooling

Well-cured garlic has a very low respiration rate and it is typically cooled when placed in storage. High initial airflow may be used to bring pulp temperature down rapidly to storage temperature.

Optimum Storage Conditions

The variety of garlic affects potential storage life, and the recommended conditions for commercial storage depend on the expected storage period. Garlic can be kept in good condition for 1 to 2 mo at ambient temperatures of 20 to 30 °C (68 to 86 °F) under 75% RH (Hardenburg et al. 1986). However, under these conditions, bulbs will eventually become soft, spongy, and shriveled due to water loss. Garlic can be stored for more than 9 mo at -1 to 0 °C (30 to 32 °F) with 60 to 70% RH. Good airflow throughout the vented bins or other storage containers is necessary to prevent any moisture accumulation. Garlic can also be held in common storage for 3 to 4 mo if temperatures are kept cool (cool night air ventilation) with good airflow and low RH. Garlic will eventually lose dormancy, signaled by internal development of the sprout. This occurs most rapidly at intermediate storage temperatures of 5 to 18 °C (41 to 64 °F) (Mann and Lewis 1956, Hardenburg et al. 1986). For long-term storage, garlic should have minimal or no internal sprout growth and should be well cured (see *Special Considerations*).

To control sprout development and lengthen the storage period, garlic may be treated with preharvest applications of sprout inhibitors, such as maleic hydrazide, or be irradiated after harvest (Hardenburg et al. 1986). Garlic odor is easily transferred to other products, so garlic should be stored separately. High RH in storage will favor mold growth and rooting. Mold growth can also be problematic if garlic has not been well cured before storing.

Controlled Atmosphere (CA) Considerations

Atmospheres with high CO_2 (5 to 15%) are beneficial in retarding sprout development and decay during storage at 0 to 5 °C (32 to 41 °F). Low O_2 (0.5%) alone does not retard sprout development of 'California Late' stored up to 6 mo at 0 °C (32 °F). Atmospheres with 15% CO_2 may produce a yellow, translucent discoloration on some cloves after about 6 mo (Cantwell 2006).

Retail Outlet Display Considerations

Garlic should be kept cool and dry.

Chilling Sensitivity

Garlic is not chilling sensitive, and the optimum storage temperature of -1 °C (30 °F) is just above the freezing point of garlic.

Ethylene Production and Sensitivity

Garlic produces very low amounts of ethylene and is not particularly sensitive to ethylene exposure.

Respiration Rates

Temperature	Intact bulbs	Fresh-peeled cloves
	---------mg CO_2 kg^{-1} h^{-1}-------	
0 °C	4 to 12	24
5 °C	8 to 24	30 to 40
10 °C	12 to 36	70 to 100
15 °C	14 to 30	
20 °C	14 to 26	

Data modified from Hardenburg et al. (1986) with data for intact and fresh-peeled cloves from Cantwell (2006).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day. Respiration rates increase when sprouting begins.

Physiological Disorders

Waxy breakdown is a physiological disorder that affects garlic during later stages of growth and is often associated with periods of high temperature near harvest. Early symptoms are small, light-yellow areas in the clove flesh that darken to yellow or amber. Later, the clove becomes translucent, sticky, and waxy, but the outer dry skins are not usually affected. Waxy breakdown is commonly found in stored and shipped garlic, rarely in the field. In addition to its association with high preharvest temperatures and sunscald, low O_2 and inadequate ventilation during handling and storage may also be contributing factors.

Postharvest Pathology

Penicillium rots (*Pencillium corymbiferum* and other spp.) are common problems in stored garlic. Affected garlic bulbs may show little external evidence until decay is advanced. Affected bulbs are light in weight and individual cloves are soft, spongy, and powdery dry. In an advanced stage of decay, the cloves break down in a green or gray powdery mass. Low RH in storage retards rot development. Less common storage decay problems include fusarium basal rot *(Fusarium oxysporum cepae)*, which infects the stem plate and causes cloves to shatter; dry rot due to *Botrytis allii;* and bacterial rots (*Erwinia* spp., *Pseudomonas* spp.).

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Whole-peeled garlic cloves are a popular convenience product processed originally for foodservice but now found in retail food stores. Fresh-peeled garlic cloves are packed in rigid clear plastic containers or in plastic film liners in carton boxes. The mechanical peeling process results in broken and damaged pieces, and damage is the major factor leading to decay and quality loss during storage. Storage at 0 to 5 °C (32 to 41 °F) is imperative to maintain good quality. A 2- to 3-week storage life is expected if garlic is kept at 5 °C (41 °F) or below. Storage temperatures above 5 °C (41 °F) will result in pink and brown discoloration on the damaged areas and favor root and sprout development.

Special Considerations

Outer cloves of bulbs are easily damaged during mechanical harvest and these damaged areas discolor and decay during storage. Therefore, high-quality garlic for the fresh market is usually harvested manually (pulled and trimmed) to avoid mechanical damage.

Curing garlic is the process by which the outer leaf sheaths and neck tissues of the bulb are dried. Warm temperatures, low RH, and good airflow are conditions needed for efficient curing. Under favorable climatic conditions in California, garlic is usually cured in the field. After harvest and trimming, it may remain in bins in the field to cure further. Curing is essential to maximize storage life and minimize decay.

The characteristic odor and flavor of fresh garlic is due to the formation of organosulfur compounds when the main odorless precursor alliin is converted to allicin by the enzyme alliinase. The content of alliin decreases during storage, but the effect of time, storage temperature, and atmosphere has not been well documented. Production of allicin occurs at low rates unless the garlic cloves are crushed or damaged. Allicin is also an important compound since it decomposes into other sulfur-containing molecules that have purported human health benefits.

References

Cantwell, M. 2000. Garlic. Recommendations for maintaining postharvest quality. Perishables handling. *At* http://postharvest.ucdavis.edu/produce_information.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Kwon, J.H., M.W. Byun, and H.O. Cho. 1985. Effects of gamma irradiation dose and timing of treatment after harvest on the storeability of garlic bulbs. J. Food Sci. 50:379-381.

Mann, L.K., and D.A. Lewis. 1956. Rest and dormancy in garlic. Hilgardia 26(3):161-189.

Shaffer, E., ed. 2000. Produce Availability and Merchandising Guide. *In* The Packer. Vance Pub. Corp., Lenexa, KS.

Snowdon, A.L. 1992. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables, pp. 236-262. CRC Press, Boca Raton, FL.

Takagi, H. 1990. Garlic (*Allium sativum* L.). *In* J.L. Brewster and H.D. Rabinowitch, eds., Onions and Allied Crops, vol. 3, Biochemistry, Food Science and Minor Crops, pp. 109-158. CRC Press, Boca Raton, FL.

Yu, T.H., and C.T. Ho. 1993. Chemistry and stability of sulfur-containing compounds in the genus *Allium. In* G. Charalambous, ed., Shelf-life Studies of Food and Beverages. Chemical Biological and Nutritional Aspects, pp. 501-546. Elsevier Science, New York, NY.

Ginger

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Scientific Name and Introduction

The rhizome of ginger *(Zingiber officinale)* is referred to as a "root" and is used as a spice in cooking and as a pickled vegetable. The knobby, fibrous mature root has a light yellowish-brown skin when fresh. The rhizome is also harvested at a very early stage, before fiber development has taken place, for use in pickles and confectionery.

Quality Characteristics and Criteria

Desired quality characteristics include skin color, plumpness of tuber pieces, sheen on skin, and absence of vegetative sprouts, blemishes, soil, and insect injury. Young ginger is bright yellow to brown and has a high sheen with greenish-yellow vegetative buds, but no sprouts.

Horticultural Maturity Indices

Mature ginger rhizomes are harvested when the plant tops begin to wilt and die. These rhizomes should be plump with a dry, bright yellow-brown skin. The sheen is soon lost and the skin darkens after harvest.

Grades, Sizes, and Packaging

Rhizomes are sold in full, telescoping 13.61-kg (30-lb) and 9.06-kg (20-lb) fiberboard cartons or in 2.27-kg (5-lb) cartons with film bags.

Precooling Conditions

Forced-air or room cooling to 12 to 14 °C (54 to 57 °F) should be used.

Optimum Storage Conditions

Mature ginger rhizomes can be stored at 12 to 14 °C (54 to 57 °F) with 85 to 90% RH for 60 to 90 days. Storage at 13 °C (55 °F) with 65% RH leads to extensive dehydration and a wilted appearance (Akamine 1962). Superficial mold growth can occur if condensation occurs on rhizomes.

Controlled Atmosphere (CA) Considerations

There are no published recommendations.

Retail Outlet Display Considerations

Display fresh young ginger with misting and mature ginger at ambient temperature with no misting.

Chilling Sensitivity

Mature ginger is chilling sensitive if held below 12 °C (54 °F). Symptoms include loss of skin color and pitting of the skin. In severe cases there is internal breakdown.

Ethylene Production and Sensitivity

Very low.

Respiration Rates

Rates are about 5.5 to 6.8 mg CO_2 kg^{-1} h^{-1} (3.1 to 3.8 µL kg^{-1} h^{-1}) at 22 °C (72 °F).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and

1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Dehydration is the most common problem. The rhizomes lose their sheen and darken rapidly during handling (Akamine 1962). Shriveling of the pieces becomes pronounced after the loss of about 10% of harvest weight (Paull et al. 1988).

Postharvest Pathology

Fusarium rot (*Fusarium* spp.) can cause serious problems. Symptoms include pale-brown discoloration of the vascular strands (Trujillo 1963) that invades the rest of the rhizome, which then becomes brown and dry (Teakle 1965). Pythium rot (*Pythium* spp.) has also been reported. The rhizome becomes soft and watery (Haware and Joshi 1974). Fungicides are not permitted, but reasonable control is obtained if the rhizomes are adequately cured and held at 12 to 14 °C (54 to 57 °F). Saprophytes, such as *Penicillium* spp., may grow on cut ends and injured areas and, though not parasitic, they give the cut ends and surface an unsightly appearance.

Quarantine Issues

Rhizome pieces free of soil and insect injury require no treatment.

Suitability as Fresh-Cut Product

None at this time.

References

Akamine, E.K. 1962. Storage of fresh ginger rhizomes. Bull. Hawaii Ag. Exp. Sta. no. 130.

Haware, M.P., and L.K. Joshi. 1974. Studies on soft rot of ginger from Madhya Pradesh. Indian Phytopath. 27:158-161.

Paull, R.E., N.J. Chen, and T.T.C. Goo. 1988. Control of weight loss and sprouting of ginger rhizome in storage. HortScience 23:734-736.

Paull, R.E., N.J. Chen, and T.T.C. Goo. 1988. Compositional changes in ginger rhizomes during storage. J. Amer. Soc. Hortic. Sci. 113:584-588.

Teakle, D.S. 1965. Fusarium rhizome rot of ginger in Queensland. Queensland J. Agric. Animal Sci. 22:263-272.

Trujillo, E.E. 1963. Fusarium yellows and rhizome rot of common ginger. Phytopathology 53:1370-1371.

Ginseng

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Scientific Name and Introduction

American ginseng (*Panax quinquefolium* L.), Chinese sanch'i ginseng *(Panax notoginseng)*, Japanese ginseng (chikusetsu-ningin) *(Panax japonica)*, and Korean ginseng (*Panax ginseng* C.A Meyer) are all perennials of the Araliaceae family (Bae 1978). The edible portion is the main root with two to five lateral roots. Ginseng is used as a cure-all medicine in Asia (Proctor 1990). Ginseng is grown primarily between latitudes 30º to 48º N in Canada, China, Korea, and the United States.

Quality Characteristics and Criteria

High-quality ginseng has a firm main root without defects. It should be clearly defined to show a head (rhizome), body (main root), and legs (lateral roots).

Horticultural Maturity Indices

Ginseng is usually harvested 3 to 5 years after transplanting 1-year-old seedlings. The optimum time for harvest in Korea is August to October, when its medicinal value is highest.

Grades, Sizes, and Packaging

Ginseng is first classified by the age of the root and then by external appearance. Size grades are "first"—over 6 cm (2.4 in) long and 60 g (0.13 lb), "second"—4 to 6 cm (1.8 to 2.7 in) long and 40 to 60 g (0.09 to 0.13 lb), and "third"—3 to 4 cm (1.2 to 1.8 in) long and 30 to 40 g (0.07 to 0.09 lb). Packaging varies greatly.

Precooling Conditions

Ginseng roots are commonly hydrocooled or forced-air cooled to below 5 ºC (41 °F). Cooling generally retards subsequent deterioration such as weight loss and decay.

Optimum Storage Conditions

Ginseng should be stored at 0 ºC (32 °F) with 95% RH or higher. Roots retain good quality for 2 mo at 0 ºC (Yun 1998) and 20 days at 25 ºC (77 °F) (Oh et al. 1979).

Controlled Atmosphere (CA) Considerations

Reduced microorganism growth and attenuated cavitation are the major benefits of CA. Optimal CA is 1% O_2 with >5% CO_2 (Lee and Kim 1979, Yun and Lee 1998). Cavitation is significantly reduced at 15% CO_2 (Yun 1998).

Retail Outlet Display Considerations

Ginseng roots are displayed with green leafy vegetables, and water loss is controlled by humidification or packaging.

Chilling Sensitivity

Ginseng is not chilling sensitive and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Ginseng roots produce only minute amounts of ethylene and are not sensitive to ethylene.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	5.5
10 °C	15.0
15 °C	33.0
25 °C	95.0

Data from Lee and Kim (1979).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

The formation of cavities within the root is a common problem caused by cultural conditions and starch breakdown (Park et al. 1986, Yun 1998). Other disorders include discolored skin and flesh and splitting of the main root.

Postharvest Pathology

Gray mold *(Botrytis cinerea)* is common in ginseng (Oh et al. 1981). Lesions frequently begin in wounds and spread to other areas of the roots. Storage at low temperatures or using CA slows the rate of spread of the disease and should be maintained to minimize pathological disorders and prolong shelf-life.

Quarantine Issues

None.

Suitability as Fresh-Cut Product

No current potential.

Special Considerations

Careful handling is mandatory because it is easy to bruise the surface of main roots and break lateral roots. Damaged areas provide a route for entry of microorganisms.

References

Bae, H.W. 1978. Korean Ginseng. Korean Ginseng and Tobacco Research Institute, Taejon, South Korea.

Lee, S.W., and K.S. Kim. 1979. Studies on CA storage of fresh ginseng. Korean J. Food Sci. Technol. 11:131-137.

Oh, H.I., S.D. Kim, J.H. Do, et al. 1979. Studies on storage methods of Korean fresh ginseng. *In* Report of Office of Monopoly, pp. 67-73. Office of Monopoly, Seoul, Korea.

Oh, H.I., H.W. Noh, J.H. Do, et al. 1981. Physico-chemical and microbiological changes during storage of fresh ginseng. Korean J. Ginseng Sci. 5:87-96.

Park, H., J.H. Lee, M.K. Lee, et al. 1986. Study on effect of cultural condition on occurrence of inside cavity and inside white of red ginseng. *In* Report of Study in Korean Ginseng. Korean Ginseng and Tobacco Research Institute, Taejon, South Korea.

Proctor, J.T.A., J.C. Lee, and S.S. Lee. 1990. Ginseng production in Korea. HortScience 25:746-750.

Yun, S.D. 1998. Biochemical Metabolism and Quality Changes of Fresh and Processed Korean Ginseng as Influenced by CA Storage. Dissertation, Seoul National University, Seoul, South Korea.

Yun, S.D., and S.K. Lee. 1998. Quality of red ginseng processed from the stored roots. Acta Hort. 464:534.

Grape (American)

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Scientific Name and Introduction

American grapes (*Vitis labrusca* L.) are grown in areas of the United States where *V. vinifera* has marginal survival, usually because of lack of cold hardiness. Juice, wine, and table grape varieties have been developed from *V. labrusca*. The best known grape cultivars are 'Concord,' 'Catawba,' 'Delaware,' 'Niagara,' 'Venus,' 'Himrod,' and 'Reliance.'

Quality Characteristics and Criteria

High-quality grapes are free of injury, decay, cracking, and sunscald; appear and feel turgid; have a dry stem scar; and are fully colored. The rachis should be green and berries are firmly attached to pedicels. Bunches should be compact, but berries not too tightly packed.

Horticultural Maturity Indices

For fresh market, berries should be harvested when soluble solids content (SSC) is 14 to 18%.

Grades, Sizes, and Packaging

No standard packaging is used with American grapes. Grapes are usually packed as intact or trimmed clusters (rachis and berries) in bulk in lugs, in quart-size vented plastic containers, or in plastic slit bags of 2 lb (0.9 kg).

Precooling Conditions

Forced-air cooling to lower the temperature to below 2 °C (36 °F) within a day of harvest is recommended.

Optimum Storage Conditions

American grapes can be held 4 to 7 weeks at -0.5 to 0 °C (31 to 32 °F) with 85 to 90% RH (Ginsburg et al. 1978). Exposure to temperatures above 0 °C (32 °F) can greatly increase shatter and decay, especially in tightly packed clusters.

Controlled Atmosphere (CA) Considerations

CA is not currently used for American grapes.

Retail Outlet Display Conditions

Store and display grapes at the coldest refrigeration temperature possible. Delays in cooling greatly increase shatter and decay (Lutz 1939).

Chilling Sensitivity

American grapes are not known to be chilling sensitive.

Ethylene Production and Sensitivity

Stimulation of *Botrytis cinerea* (gray mold) growth can occur on berries and stems in the presence of ethylene. Ethylene production from American grapes is less than 0.1 µL kg^{-1} h^{-1}.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 ºC	3
4 to 5 ºC	5
10 ºC	8
15 to 16 ºC	16
20 to 21 ºC	33
25 to 27 ºC	39

Data from Lutz (1939).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Disorders encountered on American grapes include sunburn, shrivel from low-RH storage, and bleaching or stipple near berry pedicels from SO_2 application (Morris et al. 1992).

Postharvest Pathology

American grapes are susceptible to gray mold (*Botrytis cinerea* Pers.), ripe rot (*Colletotrichum gloesporioides* [Penz.] Penz. & Sacc.), macrophoma rot (*Botryosphaeria dothidea* [Moug. Ex Fr.] Ces & de Not.), powdery mildew (*Uncinula necator* [Schw.] Burr.), blue mold *(Penicillium)*, alternaria (*Alternaria alternata* [Fr.] Keissl), and aladosporium rot (*Cladosporium herbarum* Pers.:Fr.) (Hewitt 1988). Undeveloped berries can show infection by black rot (*Guignardia bidwelli* [Ellis] Viala & Ravaz).

Quarantine Issues

None.

Suitability as Fresh-Cut Product

No information at this time.

Special Considerations

Sulfur bisulfite pads used with plastic liners can extend shelf-life by 2 to 4 weeks, but many cultivars are sensitive to SO_2 injury. Handle clusters carefully during and after harvest to prevent cracking or berry loosening at pedicels.

References

Ginsburg, L., J.C. Combrink, and A.B. Truter. 1978. Long and short term storage of table grapes. J. Refrig. 1(3):137-142.

Lutz, J.M. 1938. Factors Influencing the Quality of American Grapes in Storage. Bull. 606, U.S. Department of Agriculture, Washington, DC.

Morris, J.R., O.L. Oswald, G.L. Main, et al. 1992. Storage of new seedless grape cultivar with sulfur dioxide generators. Am. J. Enol. Vitic. 43:230-232.

Hewitt, W.B. 1988. Berry rots and raisin molds. *In* R.C. Pearson and A.C. Goheen, eds., Compendium of Grape Diseases and Insects, pp. 26-27. APS, St. Paul, MN.

Grape (Muscadine)

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Scientific Name and Introduction

Muscadine grapes (*Vitis rotundifolia* Michx.) are grown primarily in the Southern United States (Olien 1990). Unlike *V. lambrusca* and *V. vinifera*, muscadines are borne singly or in small clusters of 3 to 10 berries and detach from their pedicels when ripe. *V. rotundifolia* is more resistant to disease than bunch grapes. Muscadines are often separated into types based on color. Most commercially important fresh or processed grapes are of the bronze type. Several more recent varieties are of the black (dark purple) type. 'Fry,' 'Noble,' and 'Granny Val' are the most common bronze cultivars used for fresh market; 'Carlos' (bronze) is used for juice and some fresh markets. Other promising black cultivars are 'Nesbitt' and 'Black Beauty.'

Quality Characteristics and Criteria

High-quality muscadines are free of injury, decay, and sunscald; appear and feel turgid; have a dry stem scar; and are fully black or bronze in color.

Horticultural Maturity Indices

For fresh market, muscadines are mature when berries can be detached from their stems or when SSC is between 14 and 18% (Smit et al. 1971, Ballinger and McClure 1983).

Grades, Sizes, and Packaging

No standard packaging exists; quart size is most commonly used. Grapes are generally packaged as single or small clusters of berries in plastic, vented clamshells.

Precooling Conditions

Use forced-air to lower the temperature to 2 °C or below within 12 h of harvest.

Optimum Storage Conditions

Muscadine grapes can be held at -0.5 to 0 °C with over 90% RH for 1 to 4 weeks (Lutz 1939, Ballinger and McClure 1983). Temperatures of 20 °C for 2 days after any cold storage interval shortens subsequent shelf-life by less than 1 week (Ballinger and McClure 1983).

Controlled Atmosphere (CA) Considerations

Preliminary data indicate that 'Fry' muscadines have reduced decay when held in 10% O_2 combined with 10 to 15% CO_2 (Perkins-Veazie, unpublished).

Retail Outlet Display Conditions

Muscadines should be stored and displayed at the coldest refrigeration temperature possible without freezing. As little as 2 days at room temperature can stimulate growth of molds, especially ripe rot.

Chilling Sensitivity

Muscadines are not known to be chilling sensitive.

Ethylene Production and Sensitivity

Stimulation of *Botrytis cinerea* (gray mold) growth can occur on grapes and stems in the presence of ethylene. Ethylene production from muscadines is less than 0.1 µL kg^{-1} h^{-1} (Perkins-Veazie, unpublished).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
2 °C	6 to 14
5 °C	8 to 18
20 °C	33 to 68

Data from Perkins-Veazie (2002, unpublished).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Sunburn, bleaching, or stipple from SO_2 (Ballinger and Nesbitt 1982) are possible.

Postharvest Pathology

Muscadine grapes are susceptible to botrytis, yeasts, ripe rot *(Colletotrichum gloesporioides)*, macrophoma rot *(Botryosphaeria dothidea)*, and blue mold *(Penicillium)* (Ballinger and McClure 1983, Pearson and Goheen 1988).

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Unknown. Processing work with juice and jellies indicates that unstable pigments may cause browning problems if used for minimal processing (Flora 1977).

Special Considerations

Sodium metabisulfite pads and generators (12 to 21 µL L^{-1} SO_2) have been used to extend shelf-life of muscadines from 2 to 8 weeks (Smit et al. 1971, Ballinger and Nesbitt 1982, James et al. 1997).

References

Ballinger, W.E., and W.B. Nesbitt. 1982. Quality of muscadine grapes after storage with sulfur dioxide generators. J. Amer. Soc. Hort. Sci. 107:827-830.

Ballinger, W.E., and W.F. McClure. 1983. The effect of ripeness on storage quality of ‘Carlos’ muscadine grapes. Sci. Hort. 18:241-245.

Flora, L.F. 1977. Storage stability of juices and jellies made from muscadine grapes (*Vitis rotundifolia* Michx.). Amer. J. Enol. Vitic. 28:171-173.

James, J., O. Lamikanra, G. Dixon, et al. 1997. Shelf-life study of muscadine grapes for the fresh market. Proc. Fla. State Hort. Soc. 110:234-237.

Lutz, J.M. 1938. Factors Influencing the Quality of American Grapes in Storage. Technical Bull. 606, U.S. Department of Agriculture, Washington, DC.

Olien, W. 1990. The muscadine grape: botany, viticulture, history, and current industry. HortScience 25:732-739.

Pearson, R.C., and A.C. Goheen, eds. 1988. Compendium of Grape Diseases and Insects. APS, St. Paul, MN.

Smit, C.J.B., H.L. Cancel, and T.O.M. Nakayama. 1971. Refrigerated storage of muscadine grapes. Amer. J. Enol. Vitic. 22:227-230.

Grape (Table)

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Scientific Name and Introduction

The table grape (*Vitis vinifera* L.) is a nonclimacteric fruit with a relatively low rate of physiological activity. It is subject to serious water loss following harvest, which can result in stem drying and browning, berry shattering, and even wilting and shriveling of berries. Gray mold, caused by the fungus *Botrytis cinerea*, requires constant attention and treatment during storage and handling. In California, the major cultivars are ‘Thompson Seedless’ (Sultanina) and ‘Flame Seedless,’ marketed mostly during the summer months up to 8 to 10 weeks after harvest. Present interest centers on other introduced seedless ‘Fantasy’ cultivars such as ‘Ruby Seedless’ and ‘Crimson.’ Seeded ‘Red Globe’ is becoming important late in the season.

Quality Characteristics and Criteria

High consumer acceptance is attained for fruit with high soluble solids content (SSC) or a high ratio of SSC to total acidity (TA)—that is, SSC/TA ratio. Berry firmness is also an important factor for consumer acceptance as are lack of defects such as decay, cracked berries, stem browning, shriveling, sunburned, dried berries, and insect damage.

Horticultural Maturity Indices

In California, harvest date is determined by SSC of 14 to 17.5%, depending on cultivar and production area. In early-production areas, an SSC/TA ratio of 20 or higher is used to determine minimum maturity for cultivars that meet a low minimum SSC. For red- and black-colored cultivars, there is also a minimum color requirement.

Grades, Sizes, and Packaging

Most California table grapes are packed in the field. In contrast to South Africa and Chile, few grapes are shed-packed in the United States. The most common field-packing system is the “avenue pack.” Fruit are picked and placed into picking lugs. Usually, the picker also trims the cluster. The picking lug is then transferred a short distance to the packer, who works at a small, portable stand in the avenue between vineyard blocks.

Shed-packed fruit are harvested by pickers and placed in field lugs without trimming. The fruit are then placed in the shade of the vines to await transport to the shed. At the packing shed, the field lugs are distributed to packers who select, trim, and pack the fruit. Often two different grades are packed simultaneously by each packer to facilitate quality selection. In some operations, trimming, color sorting, and a first quality sorting may occur in the field. In all of the systems, grapes are nearly always packed on a scale to facilitate packing to a precise net weight, whether field- or shed-packed. In general, mid- and late-season grapes are packed in plastic bags or wrapped in paper. For early-season grapes, bulk pack is mainly used. In all cases, packed lugs are subject to quality inspection and check weighing.

After packing and lidding, grapes are palletized on disposable or recycled pallets. Some strapping in the field before loading is necessary in grapes packed in shoebox boxes. Often, loaded pallets coming from the field pass through a “pallet squeeze,” a device that straightens and tightens the stacks of containers. These pallet loads are unitized, usually by strapping or netting. Some palletizing glue is used in shed-packing operations. This glue bonds the corrugated containers vertically on the pallet so that only horizontal strapping is required.

Precooling Conditions

Cooling must start as soon as possible, and SO_2 applied, within 12 h of harvest. Many forced-air coolers for grapes in California are designed to achieve seven-eighths cooling in 6 h or less. After cooling is complete, pallets are moved to a storage room to await transport.

Optimum Storage Conditions

Ideally, storage rooms should operate at -1 to 0 ºC (30 to 32 ºF) with 90 to 95% RH and a moderate airflow of 20 to 40 ft^3 min^{-1} ton^{-1} (0.63 to 1.25 kL min^{-1} metric ton^{-1}) of stored grapes. The constant low temperature, high RH, and moderate airflow are important to limit water loss from fruit stems. Fruit should be stored at a pulp temperature of -0.5 to 0 ºC (31 to 32 ºC) throughout their postharvest life.

Optimum Temperature

A storage temperature of -1 to 0 ºC (30 to 32 ºF) is recommended for mature fruit. Freezing damage may occur in less mature grapes. The highest freezing point for berries is -3.0 ºC (27 ºF), but the freezing point varies depending on SSC. A -2 ºC (28 ºF) freezing point for stems has been reported for wine grapes. More recent table grape cultivars are more sensitive to stem freezing damage. An RH of 90 to 95% and an air velocity of approximately 20 to 40 ft^3 min^{-1} (0.63 to 1.25 kL min^{-1}) is suggested during storage.

Controlled Atmosphere (CA) Considerations

CA of 2 to 5% O_2 combined with 1 to 5% CO_2 during storage or shipment is not currently recommended for table grapes, because it is only slightly beneficial. SO_2 is used for decay control. CO_2 at 10 to 15% in air can be used to control grey mold for 2 to 4 weeks depending on cultivar.

Retail Outlet Display Considerations

Use of a cold table for display is recommended.

Chilling Sensitivity

Table grapes are not chilling sensitive.

Ethylene Production and Sensitivity

Table grapes produce less than 0.1 µL kg^{-1} h^{-1} at 20 ºC (68 ºF) ethylene. They are not very sensitive to ethylene.

Respiration Rates

For grape clusters; that is, berries and stems:

Temperature	mg CO_2 kg^{-1} h^{-1}
0 ºC	2 to 4
5 ºC	6 to 8
10 ºC	10 to 16
20 ºC	24 to 30

Stem respiration is approximately 15-fold higher than berry respiration.

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Shatter is a loss of berries from the cap stem. In general, shatter increases in severity with increasing maturity (that is, the longer fruit remain on the vine). Berries of seedless cultivars are usually less well attached to the cap stem than seeded cultivars. Shatter varies considerably from season to season, and there is a large variation among varieties. Gibberellin applied at fruit set weakens berry attachment. Shatter is mainly due to rough handling during field packing with additional shatter occurring all the way to final retail sale. Shatter incidence can be reduced by controlling pack depth and packing density ($in^3\ lb^{-1}$), using cluster bagging, practicing gentle handling, and maintaining recommended temperature and RH. Cane-girdling reduces shattering incidence.

Waterberry is associated with fruit ripening and most often begins to develop shortly after veraison (berry softening). The earliest symptom is the development of small (1- to 2-mm) dark spots on the cap stems (pedicles) and/or other parts of the cluster framework. These spots become necrotic and slightly sunken, and they expand to affect more areas. The affected berries become watery, soft, and flabby when ripe. In California, this disorder has been associated with a high-nitrogen-status vine, canopy shading, or cool weather during veraison and fruit ripening. Avoid overfertilization with nitrogen. Foliar nutrient sprays of nitrogen should be avoided in waterberry-prone vineyards. Removing affected berries during harvest and packing is a common, though labor-intensive, practice.

Postharvest Pathology

Gray mold. The most destructive of the postharvest diseases of table grapes is gray mold *(Botrytis cinerea)*, primarily because it develops at temperatures as low as 31 ^{o}F (-0.5 ^{o}C) and grows from berry to berry. Gray mold first turns berries brown, then loosens the skin of the berry. Its white, threadlike hyphal filaments erupt through the berry surface, and finally masses of gray-colored spores develop. Wounds on the berry surface near harvest provide opportunities for infection, though no wound is required for infection under wet conditions. Removing desiccated, infected grapes from the previous season can reduce gray mold infection. Leaf-removal canopy management, preharvest fungicides, and trimming visibly infected, split, cracked, or otherwise damaged grapes before packing is recommended. Prompt cooling and fumigation with SO_2 (100 µL L^{-1} for 1 h) are essential to control gray mold during cold storage. Because of increased interest in the export market, there is a need to use SO_2-generating pads, especially for long-distance export marketing in which grapes are in ocean transport for extended periods. These pads have sodium metabisulfite incorporated into them that releases SO_2 during transit and marketing.

Other pathogens. Black rot, caused by *Aspergillus niger;* blue rot, caused by *Penicillium* spp.; and rhizopus rot, caused by *Rhizopus stolonifer* or *R. oryzae*, become important at warmer temperatures, and they commonly appear sometime during transport or marketing after grapes are removed from cold storage. They are at least partially controlled by SO_2 fumigation, though little research has been done to show this (Snowdon 1990).

Sulfur dioxide use. Botrytis rot of grapes is not sufficiently reduced by fast cooling alone. It is standard practice in California to fumigate with SO_2 immediately after packing and follow with lower-dose treatments weekly during storage. Formulas for calculating initial and subsequent weekly SO_2 fumigation dosages using the traditional system are available (Luvisi et al. 1995, Nelson 1985). It was demonstrated that the amount of SO_2 gas needed to kill *Botrytis* spores or to inactivate exposed mycelium depends on the concentration and length of time the fungus is exposed to the fumigant. A cumulative concentration, calculated as the product of concentration and time, called “CT product,” describes the SO_2 exposure needed to kill the decay organism. A CT of at least 100 µL L^{-1} h^{-1} is the minimum required to kill spores and mycelia of *Botrytis* at 0 °C (32 °F). This finding was the basis for the development of the total utilization system (Luvisi et al. 1992). Total utilization often uses about half as much SO_2 as the traditional method and improves uniformity and effectiveness of SO_2 fumigant. In this total utilization system, the first fumigation is done in conjunction with forced-air cooling. The forced air flows through boxes and ensures good penetration of SO_2 even to the center boxes on a pallet. In most combinations of boxes and packs, this system produces over 80% penetration, measured as a percentage of the room air CT product. Storage fumigation is done every 7 to 10 days.

During ocean shipment for periods longer than 10 days or long retail handling in which SO_2 fumigation cannot be applied, the use of SO_2-generating pads in combination with a box liner is advised. These SO_2-generating pads have sodium metabisulfite incorporated into them to allow a constant and slow release of SO_2 during shipping and marketing. In California, a slow-release SO_2-generating pad, combined with a perforated polyethylene box liner with 1/4-in (6.4-mm) holes at 3- to 4-in (7.6- to 10.2-cm) center, reduces water loss and assures gray mold control without enhancing SO_2 phytotoxicity (Crisosto et al. 1994).

Quarantine Issues

Issues associated with exotic pest quarantines, addressing either imported or exported table grapes, can change rapidly. Rules regarding import requirements are issued by USDA Animal and Plant Health Inspection Service (APHIS). This agency provides information to assist exporters in targeting markets and defining what entry requirements a particular country might have for table grapes. APHIS, in cooperation with State plant boards, developed a database called "Excerpt" to track the phytosanitary requirements for each country. APHIS also provides phytosanitary inspections and certifications declaring grapes are free of pests to facilitate compliance with foreign regulatory requirements.

Grapes imported into the United States are fumigated with methyl bromide, following treatment schedules issued by APHIS, to prevent entry of insect pests. Cold treatments are also accepted by APHIS for the control of fruit flies. Of primary concern are the vine moth, *Lobesia botrana;* the Mediterranean fruit fly, *Ceratitis capitata;* and miscellaneous external-feeding insects.

Grapes exported from the United States may harbor pests of concern elsewhere, but they rarely require treatment, though this situation can change rapidly. Black widow spiders are occasional hitchhikers within grape clusters or within grape boxes. SO_2 fumigation, alone or combined with CO_2, has been used successfully to kill spiders before export. Omnivorous leafroller, *Platnota stultana*, is found on grapes in California and has the potential to be a pest of regulatory concern on table grapes exported to counties where this pest is not found. Two methods of control are insecticidal CA treatment (Ahumada et al. 1996) and low-temperature storage combined with SO_2 slow-release generators (Yokoyama et al. 1999).

Suitability as Fresh-Cut Product

Grapes are well-adapted to a stemless packaging system.

Special Considerations

Market life varies among table grape cultivars grown in California and is also strongly affected by temperature management and decay susceptibility.

Acknowledgments

Some of the information in this chapter is from the University of California, Davis, website on "Fresh Produce Facts" at http://postharvest.ucdavis.edu/produce_information.

References

Ahumada, M.H., E.J. Mitcham, and D.G. Moore. 1996. Postharvest quality of 'Thompson Seedless' grapes after insecticidal controlled-atmosphere treatments. HortScience 31:833-836.

Cappellini, R.A., M.J. Ceponis, and G.W. Lightner. 1986. Disorders in table grape shipments to the New York market, 1972-1984. Plant Dis. 70:1075-1079.

Crisosto, C.H., J.L. Smilanick, N.K. Dokoozlian, and D.A. Luvisi. 1994. Maintaining table grape postharvest quality for long distant markets. *In* Proceedings of the International Symposium on Table Grape Production, Anaheim, California, June 28-29,1994, pp. 195-199. American Society for Enology and Viticulture, Davis, CA.

Harvey, J.M., and W.T. Pentzer. 1960. Market Diseases of Grapes and Other Small Fruits. Agriculture Handbook 189, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Kanellis, A.K., and K.A. Roubelakis-Angelakis. 1993. Grape. *In* G.B. Seymour et al., eds., Biochemistry of Fruit Ripening, pp. 189-234. Chapman and Hall, London, U.K.

Lindsey, P.J., S.S. Briggs, K. Moulton, and A.A. Kader. 1989. Sulfites on grapes: issues and alternatives. Chemical Use in Food Processing and Postharvest Handling: Issues and Alternatives, pp. 5-19. University of California, Agricultural Issues Center, Davis, CA.

Luvisi, D.A., H. Shorey, J. Smilanick, et al. 1995. Packaging California Table Grapes. DANR Pub. no. 1934, University of California, Oakland, CA.

Luvisi, D.A., H.H. Shorey, J.L. Smilanick, et al. 1992. Sulfur Dioxide Fumigation of Table Grapes. DANR Pub. no. 1932, University of California, Oakland, CA.

Nelson, K.E. 1985. Harvesting and Handling California Table Grapes for Market. DANR Pub. no. 1913, University of California, Oakland, CA.

Nelson, K.E. 1978. Precooling—its significance to the market quality of table grapes. Int. J. Refrig. 1:207-215.

Ryall, A.L., and J.M. Harvey. 1959. The Cold Storage of Vinifera Table Grapes. Agriculture Handbook 159, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Snowdon, A.L. 1990. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 1, General Introduction and Fruits. CRC Press, Boca Raton, FL.

Yahia, E.M., K.E. Nelson, and A.A. Kader. 1983. Postharvest quality and storage-life of grapes as influenced by adding carbon monoxide to air or controlled atmospheres. J. Amer. Soc. Hort. Sci. 108:1067-1071.

Yokoyama, V.Y., G.T. Miller, and C.H. Crisosto. 1999. Low temperature storage combined with sulfur dioxide slow release pads for quarantine control of omnivorous leafroller *Platynota stultana* (Lepidoptera: Tortricidae). J. Econ. Entom. 92(1):235-238.

Grapefruit

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Scientific Name and Introduction

Citrus paradisi Macf., a member of the Rutaceae family, originated in the Caribbean and was introduced in Florida in the early 19th century (Gmitter 1995). The grapefruit is classified as a hesperidium, a kind of berry with a leathery rind that is divided into segments. Each segment contains hundreds of individual juice vesicles that compose the majority of the edible portion of the fruit. Florida is the largest producer of grapefruit in the United States, followed by Texas, California, and Arizona. White- and red-pigmented cultivars are grown. 'Marsh' is the dominant white cultivar. 'Ruby Red,' 'Star Ruby,' 'Henderson,' 'Ray Ruby,' and 'Flame' are the most popular red-pigmented cultivars (Saunt 2000).

Quality Characteristics

A high-quality fresh-market grapefruit will have a turgid, smooth peel and be relatively blemish-free. The fruit should be elliptical and firm. SSC:TA balance within the edible portion should be appropriate, and bitterness should be at a minimum.

Horticultural Maturity Indices

In markets that emphasize processing, grapefruit must achieve a minimum juice content and SSC:TA ratio before harvest.

Grades, Sizes, and Packaging

Marketable fresh grapefruit generally range from size 23 (23 fruit/carton) to 56 (56 fruit/carton). Grade standards for fresh grapefruit rely on color-break, texture, peel blemishes, shape, and firmness. Grapefruit are commonly packed, stored, and shipped in $^{4}/_{5}$-bushel cardboard cartons (Soule and Grierson 1986).

Optimum Storage Conditions

Grapefruit are typically stored at 12 to 15 °C (54 to 59 °F) with 95% RH. Coatings are applied in the packinghouse to reduce water loss from the peel. However, to minimize postharvest pitting, grapefruit should be cooled immediately to <10 °C (50 °F) with 95% RH after harvest and maintained at 5 to 8 °C (41 to 46 °F) during transit and storage until distribution at retail outlets. High-shine water waxes will minimize chilling injury, and incorporated fungicides should control decay at these temperatures. At optimum storage temperatures, fruit respiration rates will be reduced and quality will be maintained up to 6 weeks (ASHRAE 1998).

Controlled Atmosphere (CA) Considerations

Though some benefit of increased firmness and delayed senescence can be gained from CA storage, commercial use of CA storage for grapefruit is very limited or nonexistent (Arpaia and Kader 2000).

Chilling Sensitivity

Chilling injury can occur with low-temperature storage, typically 5 °C (41 °F) or below. Chilling injury is characterized by peel pitting. Pitting associated with postharvest pitting is targeted to areas of the peel surrounding oil glands, whereas pitting associated with chilling injury is not targeted to oil glands (Petracek et al. 1995). Coating grapefruit with high-shine water waxes reduces the incidence of chilling injury. Conditioning fruit by intermittent warming or stepwise lowering of temperature can also reduce chilling injury.

Ethylene Production and Sensitivity

The grapefruit is a nonclimacteric fruit and does not exhibit a classic ripening pattern of increased respiration and ethylene production. The rate of ethylene production is typically <0.1 $\mu L\ kg^{-1}\ h^{-1}$ at 20 °C.

Degreening is necessary for marketing early-season fresh grapefruit in areas where night temperatures remain high. In these cases, 1 to 5 $\mu L\ L^{-1}$ ethylene for periods of 12 h to 3 days is used to cause the destruction of peel chlorophyll. The recommended temperature for degreening is 28 to 29 °C (82 to 84 °F) in Florida and 21 to 22 °C (70 to 72 °F) in California, each reflecting the physiological state of the fruit grown under different climactic conditions. High RH of 90 to 95% must be maintained to avoid softening and accentuation of existing peel injuries or blemishes. One complete air change per hour should enter the degreening room to avoid unnecessary buildup of CO_2 and to assist in uniform temperature and ethylene distribution (Wardowski 1996).

Respiration Rates

Respiration rates at optimum storage temperature are generally <10 mg $CO_2\ kg^{-1}\ h^{-1}$ (Arpaia and Kader 2000).

Physiological Disorders

Granulation, or section-drying, affects late-season grapefruit dominantly on the stem or stylar end of the segment. Granulation can be severe in larger fruit stored for extended durations (Burns and Albrigo 1998). Granulation can be avoided by harvesting large fruit early in the season.

Oleocellosis can occur during harvest when excessive squeezing force is used to remove fruit from the stem. Grapefruit harvested in the morning, when RH is high, are most susceptible because oil glands are easily broken in turgid peel. Symptoms of oleocellosis appear in the packinghouse or in storage, and can be exacerbated by degreening.

Stem-end rind breakdown (SERB) is characterized by collapse and sinking of the peel in irregularly shaped regions near the stem end. SERB is closely associated with excessive water loss. Late-season grapefruit are most susceptible to SERB.

Blossom-end clearing is most commonly found in late harvested, thin-peeled red-pigmented grapefruit. The wet, translucent area that develops dominantly on the blossom end results from the leaking of juice from the segments to the peel. Blossom-end clearing can be reduced by reducing pulp temperatures to <21 °C (70 °F) after harvest and eliminated by avoiding high-impact handling procedures (Echeverria et al. 1999).

Green ring is a physiological disorder that appears on early-season grapefruit in Florida. The disorder is characterized by failure of the peel to degreen in circular areas around fruit-to-fruit contact points. The remaining green ring can become necrotic as fruit remain in storage. The incidence of green ring disappears as the fruit peel matures.

Interest in long-term storage of grapefruit has developed for the purposes of extending market availability. Grapefruit stored longer than 6 weeks at 3 °C (37 °F) may develop physiological collapse of juice vesicles (Brown et al. 1998).

Postharvest Pathology

Postharvest pitting is a peel disorder that affects waxed grapefruit stored at higher temperatures. Postharvest pitting can be reduced or eliminated by reducing fruit pulp temperature to 10 °C (50 °F) or less and coating fruit with highly gas-permeable coatings (Petracek et al. 1995, Florida Department of Citrus 1996).

Postharvest decay can result in significant losses of grapefruit. Postharvest grapefruit decays generally fall into two categories: those that develop as a result of colonization or infection on the fruit before harvest (stem end rots, anthracnose, and brown rot) and those that develop by inoculations made through wounds made during harvest or subsequent handling (blue and green mold and sour rot). Stem end rots develop as latent infections on the fruit button (calyx and disc) and begin growth through the core after harvest. The decay develops unevenly at the stem and stylar ends resulting in wavy margins. Stem-end rots are a problem with grapefruit grown in warm humid climates such as Florida but are rare in Mediterranean climates.

Diplodia natalensis is prevalent in early-season fruit if temperatures are high and degreening is used. Development of *Phomopsis citri* is favored during the winter months when temperatures are low and degreening is no longer necessary. *Alternaria citri* is a less aggressive fungus that can be problematic in overmature grapefruit and those in extended storage. Often the symptoms of alternaria, internal black discoloration generally towards the stem end, are not visible until the fruit are cut.

Anthracnose, *Colletotrichum gloesporioides*, is a minor problem that can appear on late-season fruit. Brown rot, caused by *Phytophthora citrophthora*, appears more frequently in mature fruit and fruit stored for longer durations at low temperatures. Green and blue mold, caused by *Penicillium digitatum* and *italicum*, respectively, invade fruit through wounds made during harvest handling. Growth of *P. digitatum* is more favorable at temperatures above 10 °C (50 °F), whereas growth of *P. italicum* occurs more readily at lower temperatures. Immature fruit are resistant to sour rot *(Geotrichum candidum)* infection, but as the fruit mature, the disease can become a problem. Consequently, late-season grapefruit can become infected, especially since the disease develops more readily at temperatures above 15 °C (59 °F) (Eckert and Brown 1986, Whiteside 1988, Florida Department of Citrus 1996).

Drenching harvested grapefruit with thiabendazole (TBZ) before packinghouse arrival is recommended for *Diplodia*, *Phomopsis*, anthracnose, and *Penicillium* control. In addition, application of aqueous imazalil or TBZ in the wax treatment aids in control. Minimizing degreening time by delaying harvest will assist in controlling stem-end rot caused by *Diplodia* and anthracnose. Careful harvesting and handling can reduce injuries that allow wound pathogens to enter grapefruit. Good sanitation of packinghouse equipment and storage areas will help control diseases that have no effective chemical control, such as sour rot. Generally, precooling or storing fruit after packing at temperaturesof 10 °C (50 ºF) or below will help control growth of postharvest pathogens.

Quarantine Issues

In areas infested with tropical fruit flies, cold treatment is an approved quarantine treatment. However, grapefruit must first be preconditioned at 10 to 15 °C (50 to 59 °F) to increase resistance to chilling injury. After 1 week, temperatures can be reduced to 0.6 to 2.2 °C (33 to 36 °F) for 14 to 24 days. In areas of low fly infestation, a less stringent temperature-duration schedule can be used (Florida Department of Citrus 1996). The appearance of citrus canker (*Xanthomonas axonopodis* pv. citri) has restricted movement of grapefruit grown in affected areas in Florida. Compliance with the Citrus Canker Eradication Program (2000) is required for harvesting, packing, and shipping fruit from quarantined areas.

Suitability as Fresh-Cut Product

The potential for grapefruit as a fresh-cut product is great. Peeled and sectioned grapefruit packaged in hard plastic containers is displayed on refrigerated shelves of Southeastern U.S. retail markets. Technological developments have overcome various postharvest problems with fresh-cut citrus. However, further development of automated systems for efficient and economical peeling is essential (Pao et al. 1997).

References

ASHRAE [American Society of Heating, Refrigerating and Air-Conditioning Engineers]. 1998. Citrus fruit, bananas, and subtropical fruit. *In* 1998 ASHRAE Handbook on Refrigeration. American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, GA.

Arpaia, M.L., and A.A. Kader. 2000. Grapefruit. Recommendations for Maintaining Postharvest Quality. *At* http://postharvest.ucdavis.edu/produce_information.

Brown, G.E., P.D. Petracek, M. Chambers, et al. 1998. Attempts to extend the market availability of 'Marsh' grapefruit with storage at 2 to 3 ºC. Proc. Fla. State Hort. Soc. 111:268-273.

Burns, J.K., and L.G. Albrigo. 1998. Time of harvest and method of storage affect granulation in grapefruit. HortScience 33:728-730.

Echeverria, E., J.K. Burns, and W.M. Miller. 1999. Fruit temperature and maturity affect development of blossom end clearing in grapefruit. HortScience 34:1249-1250.

Eckert, J.W., and G.E. Brown. 1986. Postharvest diseases and their control. *In* W.F Wardowski, S. Nagy, and W. Grierson, eds., Fresh Citrus Fruits, pp. 315-360. AVI Publishing Co., Westport, CT.

Florida Department of Agriculture and Consumer Services. 2000. Citrus Canker Eradication Program. *At* http://www.freshfromflorida.com.

Florida Department of Citrus. 1996. Fact Sheets on Postharvest Diseases of Citrus. *At* http://www.crec.ifas.ufl.edu/extension.

Gmitter, F.G. 1995. Origin, evolution, and breeding of the grapefruit. *In* J. Janick, ed., Plant Breeding Reviews, vol. 13, pp. 345-363. John Wiley & Sons, New York, NY.

Pao, S., P.D. Petracek, and M.A Ismail. 1997. Advances in preparing peeled fresh-cut citrus. Food Tech. Intl. 42:39-40.

Petracek, P.D., W.F. Wardowski, and G.E. Brown. 1995. Pitting of grapefruit that resembles chilling injury. HortScience 30:1422-1426.

Saunt, J. 2000. Citrus Varieties of the World. Sinclair Intl. Ltd., Norwich, U.K.

Soule, J., and W. Grierson. 1986. Maturity and grade standards. *In* W.F. Wardowski, S. Nagy, and W. Grierson, eds., Fresh Citrus Fruits, pp. 23-48. AVI Publishing Co., Westport, CT.

Wardowski, W.F. 1996. Recommendations for Degreening Florida Fresh Citrus Fruit. Circular 1170, pp. 1-3. Florida Cooperative Extension Service, University of Florida, Gainesville, FL.

Whiteside, J., S. Garnsey, and L. Timmer, eds. 1988. Compendium of Citrus Diseases. APS Press, St. Paul, MN.

Greens for Cooking

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Scientific Name and Introduction

Leafy greens that are normally eaten cooked include collards and kale (*Brassica oleraceae* L. var. Acephala DC.), rape (*Brassica napus* L. var. *napus*), spinach (*Spinacia oleraceae* L.), mustard (*Brassica juncea* [L.] Czerniak), and turnip (*Brassica rapa* L. var. [DC.] Metzg. *utilis*) (Maynard and Hochmuth 1997). Since the intended use is either cooking at a later date or immediate processing (canning or freezing) for later sale, some handlers do not give the attention to quality maintenance that would normally be given to fresh salad greens. However, managers should recognize that quality at the point of sale is of primary concern for all vegetables, whether they are to be cooked or eaten raw.

Quality Characteristics and Criteria

Leaves should be of similar varietal characteristics, fresh, fairly tender and clean, well-trimmed, of characteristic color for the variety or type of greens, and free from decay, discoloration, freezing injury, foreign material, disease, insects, and damage caused by coarse stalks or other mechanical means (AMS 1953a,b, Hurst 2000)

Horticultural Maturity Indices

Spinach leaves are typically harvested at about mid maturity, while other types of greens may be allowed to grow until the leaves have reached nearly full size but have not begun to senesce. Hand-harvesting allows a greater degree of selection of leaf size, whereas in mechanical harvesting every leaf large enough to reach the cutting blade is taken.

Grades, Sizes, and Packaging

All greens for cooking, except spinach, are classified as either U.S. No. 1 or unclassified. The term “unclassified” is not an official U.S. standard; it simply means that no specific grade has been assigned (AMS 1953a,b). Since spinach is often consumed uncooked, greater flexibility is included in its classification than for other leafy greens. Thus, the grades for spinach are U.S. Extra No. 1, U.S. No. 1, and U.S. Commercial (AMS 1946). The leaf size of the various types of greens offered for sale depends primarily on the requirements of the buyer and the physiological condition of the product. Obviously, large, overmature leaves would not be marketed.

Leaf collards, kale, turnip greens, and mustard are commonly bunched using rubberbands or twist ties. The size of the bunch may vary but is generally approximately 0.5 kg (1 lb). Direct packing of loose leaves may be done at the request of the buyer. Head collards are packed loose into cartons with 8 to 16 bunches per container. Waxed fiberboard cartons or wire-bound crates are commonly used (Hurst 1999, Sanders et al. 1999). Spinach leaves, which are smaller and more tender, may be packed loose or bunched, but they require greater care to avoid handling injury (Suslow and Cantwell 2002).

Precooling Conditions

Field heat should be removed from greens as quickly as possible. Hydrocooling, hydrovac-cooling, liquid-icing, package-icing, and top-icing all have been used. Water that is used for washing or cooling should contain approximately 200 µL L^{-1} chlorine (Kasmire and Cantwell 1999). When package-iced, approximately 1 kg (2.2 lb) of ice is recommended per 1.8 kg (4 lb) of product (Hurst 2000; Boyhan et al. 2004).

Optimum Storage Conditions

Greens should be stored near 0 °C (32 °F) with 95 to 98% RH. Crushed ice may be placed in baskets or boxes to help maintain low temperature and high RH. When properly handled, greens in general may be kept for about 2 weeks (Hardenburg et al. 1986, Sanders et al. 1999, Suslow and Cantwell 2002). Turnip greens are particularly perishable, in contrast to kale, which has been kept in excellent condition for up to 3 weeks under ideal storage conditions (Hardenburg et al. 1986).

Controlled Atmosphere (CA) Considerations

Spinach benefits slightly from storage at 7 to 10% O_2 combined with 5 to 10% CO_2 (Saltveit 1997). When prepackaged in plastic bags, films should allow the generation of 1 to 3% O_2 and 8 to 10% CO_2 (Suslow and Cantwell 2002). Neither CA nor modified atmosphere packaging (MAP) is commonly used commercially for leafy greens other than spinach.

Retail Outlet Display Considerations

Though greens are sometimes displayed on unrefrigerated counters, they should be placed on ice or on refrigerated counters. Intermittent misting minimizes water loss and wilting.

Chilling Sensitivity

Leafy greens are not sensitive to chilling temperatures and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

The ethylene production rate for fresh spinach is <0.1 µL kg^{-1} h^{-1} at 20 ºC (68 °F) (Suslow and Cantwell 2002). Similar data are not available for other greens, but their ethylene production rates could reasonably be expected to be in the same general range as that of spinach (Kader 1992). All leafy greens are sensitive to ethylene in the postharvest environment, which accelerates senescence and leaf yellowing (Suslow and Cantwell 2002).

Respiration Rates

The data provided below are for spinach. Similar data are not available for other types of leafy greens.

Temperature	mg CO_2 kg^{-1} h^{-1}
0 ºC	19 to 22
5 ºC	32 to 58
10 ºC	82 to 138
15 ºC	134 to 223
20 ºC	172 to 287

Data from Hardenburg et al. (1986).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Freezing injury, which results in water-soaked tissue and decay, is the most common physiological disorder. Temperatures slightly below 0 °C (32 °F) can result in freezing (Suslow and Cantwell 2002).

Postharvest Pathology

Bacterial soft rots, primarily caused by *Erwinina* and *Pseudomonas*, are the most common types of postharvest decay (Suslow and Cantwell 2002). Other market diseases may be found, but in general these are not of serious concern if appropriate disease control has been implemented during production and if greens are properly handled.

Quarantine Issues

There are no current issues. However, anyone exporting fresh produce should check with the appropriate agency in the importing country to ensure that all regulations are met.

Suitability as Fresh-Cut Product

All leafy greens have potential for fresh-cut marketing.

Special Considerations

Harvest workers should sanitize cutting tools periodically to avoid the spread of decay-causing microorganisms.

References

AMS [USDA Agricultural Marketing Service]. 1946. United States Standards for Grades of Spinach Leaves (Fresh). U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

AMS [USDA Agricultural Marketing Service]. 1953a. United States Standards for Grades of Collard Greens or Broccoli Greens. U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

AMS [USDA Agricultural Marketing Service]. 1953b. United States Standards for Grades of Mustard Greens and Turnip Greens. U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Boyhan, G.E., William C. Hurst, W. Terry Kelley, et al. 2004. Postharvest handling and transportation of fruits and vegetables. University of Georgia Fact Sheet 100. *At* http://pubs.caes.uga.edu/caespubs/pubcd/FS-100.

Boyette, M.D., D.C. Sanders, and E.A. Estes. 1999. Postharvest cooling and handling of cabbage and leafy greens. North Carolina State University Cooperative Extension Service. *At* http://www.bae.ncsu.edu/programs/extension/publicat/postharv/ag-413-5/index.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Hurst, William C. 2000. Commercial production and management of cabbage and leafy greens. University of Georgia Bull. 1181. *At* http://pubs.caes.uga.edu/caespubs/pubcd/B1181.

Kader, A.A. 1992. Postharvest biology and technology: an overview. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, pp. 15-20. DANR Pub. no. 3311, University of California, Davis, CA.

Maynard, D.N., and G.J. Hochmuth. 1997. Knott's Handbook for Vegetable Growers. 4th ed. John Wiley & Sons, New York, NY.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California Davis, CA.

Seelig, R.A. 1974. Collards—Fruit and Vegetable Facts and Pointers. United Fresh Fruit and Vegetable Association, Alexandra, VA.

Suslow, T.V., and Marita Cantwell. 2002. Spinach, recommendations for maintaining postharvest quality. Produce Facts. University of California, Davis, CA. *At* http://postharvest.ucdavis.edu/produce_information.

Guava

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Scientific Name and Introduction

The guava (*Psidium guajava* L.) is round or oval and can be eaten as a fresh fruit at two stages: mature green when it has white flesh and tastes like a sweet apple, or fully ripe when it has white to bright-red flesh, light-yellow skin, tastes very sweet, and is quite fragrant.

Quality Characteristics and Criteria

Skin color is used to measure maturity and ripeness. Size and shape are other important quality criteria. Fruit should be free of defects, decay, and insect damage. Some varieties have only a few seeds, while others have a large cavity full of seeds. Fruit range from 9 to 12 cm (3.5 to 4.7 in) in size.

Horticultural Maturity Indices

Harvest stage depends on variety and the stage at which the fruit are to be eaten. If eaten green, guava fruit should be harvested at the mature, firm stage without any signs of ripening. Fruit to be consumed soft and ripe are harvested when they show some sign of color change from green to yellow, as well as initial softening. Later harvesting, when fruit are riper, can lead to a high number of fruit fly stings and, later, larvae in the flesh. Soluble solids content (SSC) can vary from 3% in green fruit to over 10% in ripe fruit, and total acidity (TA) from 0.2 to 1.5%; cultivars vary greatly in sweetness and acidity. There is also seasonal variation in acidity in some cultivars.

Grades, Sizes, and Packaging

Guava fruit are commonly shipped in 4.5-kg (10-lb) single-layer cartons with foam sleeves or wrapping to prevent injury.

Precooling Conditions

Room, forced-air, or hydrocooling should be used to about 10 °C (50 °F).

Optimum Storage Conditions

Mature green and partially ripe fruit can be held for 2 to 3 weeks at 8 to 10 °C (46 to 50 °F). Ripe, soft fruit can be held about 1 week at 5 to 8 °C (41 to 46 °F). RH of 90 to 95% is recommended (Kader 1999). Shelf-life is about 7 days when stored at 20 °C (68 °F).

Controlled Atmosphere (CA) Considerations

Short-term treatment (24 h) with 10% O_2 in combination with 5% CO_2 before storage in air at 4 °C (39 °F) for 2 weeks delays color development and reduces chilling injury compared with fruit held in air (Bautista and Silva 1997). Modified atmosphere packaging (MAP) in polyethylene bags and use of wax coatings delay ripening and softening. Skin blackening is a problem when some wax coatings are applied (McGuire and Hallman 1995).

Retail Outlet Display Considerations

Display guava fruit chilled if fruit are fully ripe. Display guava fruit at 8 to 10 °C (46 to 50 °F) if fruit are green and if ripening is to be avoided.

Chilling Sensitivity

Symptoms include skin scald, pitting, and a failure to ripen if fruit are mature green or partially ripe when chilled. Browning of the flesh can occur. Decay incidence and severity increase with chilling injury. Ripe, soft fruit can be held at 5 °C (41 °F), as they are less sensitive to chilling injury.

Ethylene Production and Sensitivity

Production rates vary from 1 to 20 µL kg^{-1} h^{-1} at 20 °C and show a climacteric pattern of respiration. Rates vary with variety and stage of ripeness. Ripening is accelerated by exposure to ethylene (100 µL L^{-1}, 24 h). Immature fruit do not ripen properly and develop a "gummy" texture (Reyes and Paull 1995).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
10 ºC	8 to 60
20 ºC	18 to 130

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Postharvest desiccation is a major problem, along with mechanical injury. Desiccation leads to a dull yellow, sometimes wrinkled, skin, while mechanical injury leads to browning that can extend into the flesh. Mechanically injured areas of the skin and flesh are very susceptible to decay.

Postharvest Pathology

Most diseases have preharvest origins and are sometimes latent infections such as anthracnose *(Colletrotrichium gloeosporioides)*. Other diseases are associated with entry of pathoges via wounds from insect stings or mechanical damage; for example, aspergillus rot *(Aspergillus niger)*, mucor rot *(Mucor hyemalis)*, phomopsis rot *(Phomopsis destructum)*, and rhizopus rot *(Rhizopus stolonifer)*. Orchard sanitation and effective postharvest management, such as avoiding mechanical injury and prompt cooling, can reduce disease incidence.

Quarantine Issues

Guava is a preferred host for fruit flies. Flies begin to sting fruit at the mature green color break stage, but infestation is a problem as softening begins to occur. Heat treatments and irradiation are both potential disinfestation procedures.

Suitability as Fresh-Cut Product

Sliced mature green fruit are available in many Southeast Asian countries and are eaten like apple slices. Ripe fruit are also prepared as slices with both the skin and seeds removed. Both types are sold in trays with an overwrap.

References

Bautista, P.B., and M.E. Silva. 1997. Effects of CA treatments on guava fruit quality. *In* A.A. Kader, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, Abstract 113. University of California, Davis, CA.

Kader, A.A. 1999. Guava—produce facts. University of California, Davis, Perishables Handling Quarterly 97:19-20.

McGuire, R.G., and G.J. Hallman. 1995. Coating guavas with cellulose- or carnaba-based emulsions interferes with postharvest ripening. HortScience 30:294-295.

Reyes M.U., and R.E. Paull. 1995. Effect of storage temperatures and ethylene treatment on guava (*Psidium guajava L.*) fruit ripening. Postharv. Biol. Technol. 6:357-365.

Honeydew Melon

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Scientific Name and Introduction

Cucumis melo L. (Inodorus Group), called winter melons even though they are mainly grown in the spring in Texas and summer elsewhere, include honeydew, casaba, crenshaw, and canary melons (Bailey 1976). This melon group is an annual, tender, running herb of the Cucurbitaceae (gourd) family that is grown for its sweet, flavorful fruits with light-green, white, or pink flesh. Honeydew melons are the dominantly grown and shipped melon of this group and are primarily produced in Arizona, California, and Texas.

Quality Characteristics and Criteria

Minimum quality standards for honeydew melons are good internal quality of 8% soluble solids content (SSC) (10% in California); firm; well-formed; mature; and free of aphid stain, rust spot, bruises, broken skin, solar injury (sunscald and sunburn), hail damage, moisture loss, insect damage, or growth cracks (AMS 1981). Nonhybrid honeydew melons are ready for harvest (cutting) when the rind is slightly waxy and the color is mostly whitish with a light-green tinge. These fruit should be well filled out and covered by a fine fuzz of hairs. Superior honeydew melon quality at harvest is associated with a whitish peel, high SSC, and round fruit shape (Lester and Shellie 1992). Hybrid honeydew melons will abscise (slip) when mature and are mostly creamy white, slightly waxy, and may have very sparse netting. Full-slip hybrid honeydew melons, versus honeydew melons cut at harvest, are perceived by consumers to have superior flavor, texture, and sweetness.

Horticultural Maturity Indices

Honeydew melons**,** hybrids and nonhybrids, are ready to eat when the peel turns pale green to cream colored and the surface feels waxy. The blossom end gives when pressed with the thumb, and the melon has a pleasant aroma. Less ripe and cold melons have little aroma. The majority of honeydew melons have green flesh, but specialty fruit can have gold, orange, or pink flesh.

Casaba melons are ready to eat when the very furrowed or wrinkled peel is yellow and the blossom end is springy. The flesh should be soft, almost white, with a slight salmon cast around the seed cavity and subtly sweet. No aroma is produced except for a hint of cucumber.

Crenshaw melons are a cross between casaba and persian (see “Netted Melons”). Crenshaw melons are ready to eat when half the dark-green peel turns yellow, the blossom end is springy, and a pleasant spicy aroma is emitted at room temperature. The very sweet and juicy flesh should be salmon color and soft. Entirely yellow and soft fruit are overripe and unpleasant to eat.

Canary melons are ready to eat when the peel, generally smooth but sometimes furrowed, is bright canary yellow (the brighter the peel, the riper the melon) and the oval-shaped fruit is springy at the blossom end. The flesh should be crisp, flavorful, and white, with a hint of pink around the seed cavity. A fragrant aroma is emitted at room temperature.

Grades, Sizes, and Packaging

Grades include U.S. No. 1, U.S. Commercial, and U.S. No. 2, based primarily on percentage of honeydew fruit that meet decay, damage, and disease tolerance guidelines (AMS 1981).

Honeydew fruit have no Federal marketing standard for SSC except for May 1 through June 20, when all honeydew melons regardless of grade must be at 8% SSC minimum (AMS 1981). Size classification is the number of fruit (based on a uniform fruit diameter and fruit weight) per box to achieve a standard weight of 13.6 kg (30 lb). The distinct size classes are 4, 5, 6, 8, and 9.

Precooling Conditions

Honeydew melons harvested cut from the vine need not be precooled. Full-slip melons should be precooled to 10 to 15 ºC (50 to 60 ºF) soon after harvest to reduce the rate of ripening and sugar loss. Hydrocooling and forced-air cooling are acceptable methods of precooling. Hydrocooling is the most efficient and can reduce a 35 ºC (95 ºF) melon to at least 15 ºC at the center of the flesh within 20 min. The larger fruit sizes take longer.

Optimum Storage Conditions

Prolonged holding (3 weeks) of fruit harvested cut from the vine, as well as casaba, crenshaw, and canary melons, should be stored at 10 ºC (50 ºF) with 90 to 95% RH. Honeydew melons cut from the vine that have been induced to ripen with ethylene, as well as full-slip honeydew melons, should be stored at 7 ºC with 95% RH; they can be held for 7 to 10 days.

Controlled Atmosphere (CA) Considerations

CA storage of honeydew melons harvested cut from the vine has limited commercial use. CA conditions for full-slip melons are not known.

Retail Outlet Display Considerations

Honeydew melons are less perishable then netted melons (see “Netted Melons”), while those fully abscised (full-slip) are highly perishable and should therefore be displayed promptly on arrival.

Chilling Sensitivity

Chilling injury can occur at temperatures below 7 ºC (45 °F), but the riper the melon the more tolerant to chilling injury. Injury is expressed as pitting and darkened, elongated patchy surface lesions.

Ethylene Production and Sensitivity

Honeydew melons harvested cut from the vine, as well as casabas, crenshaw, and canary melons, produce very low amounts of ethylene. However, they benefit at the time of shipping, soon after harvest, by exposure to 100 µL L^{-1} ethylene at 12.5 to 25 ºC (55 to 77 ºF) for up to 24 h (Kader 1992). Full-slip honeydew melons should not be gassed with ethylene.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
5 ºC	8
10 ºC	14
15 ºC	24
20 ºC	30
25 ºC	33

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Compression, bruising, scuffing, and cutting may occur during harvest and at packing sheds and may lead to desiccation, water-soaking, internal breakdown, and discoloration of the peel. Honeydew melons should never be dropped more than 60 cm (2 ft), and all harvesting and packing line equipment should be well-padded to reduce bruising, scuffing, and cuts (Ryall and Lipton 1979). To reduce fruit crushing and bruising at harvest, replace the traditional deep 180-cm-bed

(6-ft-bed) hauling trucks with stackable, ventilated plastic field boxes measuring 1.2 m × 1.2 m × 0.6 m (48 in × 48 in × 26 in deep), and load them onto a flatbed truck (Kader 1992).

Postharvest Pathology

Honeydew melons produced in the Western United States occasionally develop bacterial brown spot, infested by *Pantoea ananatis* (formerly called *Erwinia ananas*). *Alternaria alternata* and *Cladosporium cucumerinum* rots can be found on honeydew as a result of chilling injury, cuts, punctures, or holding fruit too long in storage (Bruton 1995, Zitter et al. 1996).

Quarantine Issues

Honeydew melons entering the United States must be disinfested of external feeders (noctuid moths, thrips, and *Copitarisa* species) by fumigation with methyl bromide (APHIS 1998). Methyl bromide was identified as causing significant damage to the Earth's protective ozone layer and was scheduled for global phaseout under the Montreal Protocol, an international treaty developed to protect the Earth from the detrimental effects of ozone depletion. Title VII of the U.S. Clean Air Act (Amendments of 1990) requires that production and importation of "Class I" substances (ozone depletion potential of 0.2 or greater) be phased out in the United States by the year 2005. Use of methyl bromide for preshipment and quarantine purposes has been declared exempt from these restrictions, but the limited supply and increasing cost of methyl bromide may make it undesirable for commercial use in the future.

Suitability as Fresh-Cut Product

Honeydew fruit harvested cut from the vine or hybrid honeydew fruit harvested at half-slip with 11 to 12% SSC have crisp pulp and are appropriate for fresh-cut processing. Cultivar selection is essential as there is considerable variation among cultivars for sugar, firmness, and flesh thickness—that is, piece yield. Fruit should be well washed and sanitized by rinsing in 200 µL L^{-1} of a 5.25% sodium hypochlorite solution at 5 ºC (41 °F), pH 6.5 to 7.0, for 5 min, and cut into cubed pieces with very sharp blades. Cubed pieces should be rinsed with 150 µL L^{-1} of 5.25% NaOCl at 5 ºC (41 °F) for 30 sec. Shelf-life of honeydew fruit cubes, with good eating quality, can be expected for 6 to 10 days when stored at 5 ºC (41 °F). Modified atmospheres of 5% O_2 combined with 5% CO_2 are beneficial in retarding microbial growth and reducing loss in firmness and other quality degradations. Shelf-life of honeydew fruit cubes is not reduced by taking pieces from defective areas such as the ground spot or sunburned regions, but eating quality is reduced due to lower sugar content, green color, and firmness (Wu and Watada 1999).

Special Considerations

Product quality and shelf-life of full-slip, hybrid honeydew can be extended by applying an amino acid-chelated calcium (80 mM) rinse or soak prior to sizing and storage (Lester and Grusak 1999).

References

AMS [USDA Agricultural Marketing Service]. 1981. U.S. Standards for Grades of Honey Dew and Honey Ball Type Melons. U.S. Department of Agriculture, Washington, DC.

APHIS [USDA Animal and Plant Health Inspection Service]. 1998. T101-o-2 MB Methyl bromide fumigation of melons for external feeders. *In* APHIS Plant Protection and Quarantine Treatment Manual, pp. 5-2-23. U.S. Department of Agriculture, Hyattsville, MD.

Bailey, L.H., and E.Z. Bailey. 1976. Hortus Third: A Concise Dictionary of Plants Cultivated in the United States and Canada. Macmillan Publishing Company, New York, NY.

Bruton, B.D. 1995. Etiology, epidemiology, and control of muskmelon fruit rots. *In* G.E. Lester and J.R. Dunlap, eds., Cucurbitaceae ’94, pp. 48-54. Gateway Printing Co., Edinburg, TX.

Kader, A.A. 1992. Postharvest Technology of Horticultural Crops. University of California, Davis, CA.

Lester, G., and K.C. Shellie. 1992. Postharvest sensory and physicochemical attributes of honey dew melon fruits. HortScience 27:1012-1014.

Lester, G.E., and M.A. Grusak. 1999. Postharvest application of calcium and magnesium to honeydew and netted muskmelons: effects on tissue ion concentrations, quality, and senescence. J. Amer. Soc. Hort. Sci. 124:545-552.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation and Storage of Fruits and Vegetables, vol. 1, Vegetables and Melons. AVI Pub. Co., Westport, CT.

Sholtz, W.W., H.B. Johnson, and W.R. Buford. 1963. Heat evolution rates of some Texas-grown fruits and vegetables. J. Rio Grande Valley Hort. Soc. 17:170-175.

Wu, T.Z., and A.E. Watada. 1999. Quality changes of fresh-cut honeydew melons during controlled atmosphere storage. J. Food Qual. 22:513-521.

Zitter, T.A, D.L. Hopkins, and C.E. Thomas. 1996. Compendium of Cucurbit Diseases. APS Press, St. Paul, MN.

Horseradish

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Scientific Name and Introduction

Horseradish (*Armoracia rusticana*, syn. *Cochlearia armoracia* Gaertn., Mey., Scherb.) is a perennial of the Cruciferae family. The plant is native to southeastern Europe, where the roots and leaves are used for food, condiments, and medicinal purposes. Horseradish is grown for its enlarged taproot, which is used as an appetizing condiment for meats and fish. The characteristic pungent aroma and taste come from sulfur compounds. Horseradish is grown worldwide, but especially in Europe, the United States (mainly southwestern Illinois), and Russia.

Quality Characteristics and Criteria

Several criteria are used for quality evaluation of horseradish, such as uniformity of shape and size, firmness, smoothness, freedom from hollow heart, internal color of the roots, other defects, and decay. The most important quality criteria are long, uniform roots with white flesh and pungent flavor.

Horticultural Maturity Indices

Horseradish is ready to harvest after the leaves have been killed by frost. Sometimes it is harvested at an early stage of development and the roots used for processing. Horseradish that is harvested when roots are actively growing does not store as well as roots that are conditioned by cold before harvest.

Grades, Sizes, and Packaging

Horseradish roots Grade I should be at least 25 cm (10 in) long and 2.5 cm (1 in) in diameter measured one-third of the distance from the top. Grade II horseradish roots are 15 cm (6 in) long and 1.5 cm (0.6 in) in diameter. Smaller roots may be acceptable for processing. Horseradish for fresh harvest is commonly packed in 20- to 25-kg (44- to 55-lb) sacks or in small retail packages about 1 kg (2.2 lb). Roots intended for storage are packed in 15-kg (33-lb) polyethylene-lined crates or large containers with a capacity 300 to 500 kg (660 to 1,100 lb).

Precooling Conditions

Horseradish roots are very sensitive to wilting. Roots should be precooled to 4 to 5 °C (39 to 41 °F) immediately after harvest using forced air at 0 °C (32 °F) with 90 to 98% RH.

Optimum Storage Conditions

Roots can be stored for 8 to 12 mo at 0 °C (32 °F) with 98 to 100% RH (Adamicki et al. 1999). Pungency is rapidly lost at higher temperatures, and roots dry out at lower RH. Perforated polyethylene bags and lined crates or bins can maintain a high RH during storage. Roots can also be stored at -1 to -2 °C (28 to 30 °F). Freshly harvested and washed roots can be stored for several months in polyethylene bags or lined polyethylene crates. In areas with mild winters, horseradish may be left in the ground and harvested in early spring. Horseradish can also be stored over winter in cool cellars or in outdoor pits (clamps) or trenches.

Controlled Atmosphere (CA) Considerations

There is no or only slight benefit from CA. High levels of CO_2 increase respiration but do not cause greater loss of weight, dry matter, or sugar content during storage. An increase in sucrose occurs as CO_2 increases up to 7.5% (Weichmann 1980).

Retail Outlet Display Considerations

Washed horseradish roots packed in polyethylene bags can be placed on refrigerated shelves for several days at temperatures below 10 °C (50 °F).

Chilling Sensitivity

Horseradish roots are not chilling sensitive and can survive temperatures as low as -8 °C (18 °F) (Bohling and Hansen 1980).

Ethylene Production and Sensitivity

Horseradish roots produce a very low amount of ethylene, <1 μL kg^{-1} h^{-1}, and are not particularly sensitive to ethylene exposure.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	8
5 °C	14
10 °C	25
15 °C	32
20 °C	40

Data from Ryall and Lipton 1983.

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

There are no important physiological disorders of horseradish root.

Postharvest Pathology

The soilborne fungus *Verticilium dahliae* Kleb. infects the vascular tissue of the horseradish plant, resulting in discoloration (Eastburn and Weizierl 1995). The discoloration often appears as black specks in cross section or as streaks along the root when the root is cut lengthwise. It is the major reason for loss in market quality of horseradish roots.

Quarantine Issues

None.

Suitability as Fresh-Cut Product

There is no current potential.

References

Adamicki, F., W. Macias, and E. Badełek. 1999. Effect of temperature on the quality and storage ability of two cultivars of horseradish. Unpublished.

Bohling, H., and H. Hansen. 1980. Influence of controlled atmosphere on the respiration activity of achlorophyllous vegetable kinds. Acta Hort. 116:165-170.

Dobrzański, A., J. Pałczyński, and F. Adamicki. 1994. The influence and soil applied herbicides on weed control, yield and storage-life of horseradish (*Cochlearia armoracia* L.). Biul. Warzywniczy 42:53-63.

Eastburn, D., and R. Weizierl. 1995. Horseradish. A Guide to Major Insect and Disease Problems. University of Illinois Cooperative Extension Service, Urbana, IL.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Ryall, A.L., and W.J. Lipton. 1983. Handling, Transportation and Storage of Fruits and Vegetables, vol. 1, 2nd ed. AVI Publishing Co., Westport, CT.

Schirmer, H., and B. Tauscher. 1999. Langzeitlagerung von Meerretich bei unterschiedlichen Temperaturen. Gemüse 7:449-450.

Weichmann, J. 1980. CA storage of horseradish (*Armoracia rusticana* Ph.Gärtn., B.May. et Scherb.). Acta Hort. 116:171-178.

Jerusalem Artichoke

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Scientific Name and Introduction

Helianthus tuberosus L., the Jerusalem artichoke, is a perennial of the Asteraceae family (Compositae) that is grown as an annual. The tops die in the early winter, at which time the tubers are harvested. There are many cultivars, and the cultivar selected depends on the production location. Commercial production in the United States is limited and found mostly in the Northeast and North Central States and California. In the Deep South, soilborne diseases largely prevent commercial production (McCarter and Kays 1984).

Interest in the crop has stemmed from the fact that the storage form of carbon in the Jerusalem artichoke is inulin, a straight chain fructan that is poorly digested by humans. Inulin can be used as a bulking agent in foods when sugar is replaced with an artificial sweetener. The volume previously occupied by sugar is replaced by the low-calorie inulin, allowing the total caloric content of the processed product to be greatly reduced. With little reformulation, inulin, though not sweet, has functions similar to sugar in many foods; that is, browning reactions, aroma synthesis, and textural properties. Likewise, inulin, whether ingested as Jerusalem artichoke tubers or as a bulking agent, is a dietary fiber and confers a number of health advantages. For example, it lowers blood cholesterol level; promotes *Bifido* bacteria in the large intestine; reduces blood sugar level, low-density lipoproteins, and triglycerides; and helps prevent certain heart diseases (Varlamova et al. 1996).

Quality Characteristics and Criteria

Tuber size and shape are critical quality attributes and are strongly modulated by cultivar and production conditions. Many clones have an irregular tuber surface topography due to branching, an undesirable trait.

Horticultural Maturity Indices

The tubers are harvested in the late fall, generally after the first frost. In production areas where harvest can be accomplished throughout winter (see *Storage Options* section below), the crop can be field stored and harvested as needed. Elsewhere, harvest is followed by cold storage.

Grades, Sizes, and Packaging

There are no existing standard grades. Generally, larger tubers with smooth surfaces are preferred. Polyethylene bags are the typical packaging used, though precise recommendations are not established. Package physical parameters vary with storage temperature, product volume, and other factors.

Precooling Conditions

Generally, precooling is not required, though placing the tubers under favorable low temperature conditions as soon as possible after harvest is recommended.

Storage Options

The three primary storage options are refrigerated storage, common storage in root cellars, and in situ field storage. In common storage in root cellars, champs, or pits, cooling is obtained from the natural low temperatures of the outdoor air and soil (Shoemaker 1927). In the first two options (refrigerated and common storage), tubers are harvested in fall and placed in storage. With field storage, however, tubers are left in the ground and harvested as needed. Cold storage is highly effective, but costly. Regardless, refrigerated storage is routinely used for seed and fresh market tubers, especially in situations where field storage is not a viable alternative. Root cellars, champs, and pits are used when the tubers must be harvested in the fall, prior to the ground freezing or other adverse conditions occurring, and refrigeration is not available or is prohibitively expensive.

The selection of in situ field storage depends on several factors. Location is the primary determinant in the potential success of in situ field storage. Field storage is a viable option in northern hemisphere production areas where cold soil temperatures prevail throughout the winter, but freezing of the soil surface is uncommon. Sandy, well-drained soils are preferred because they allow harvest throughout the winter. Locations that do not meet these criteria generally require the use of refrigeration or some form of common storage.

Optimum Storage Conditions

Tubers can be stored for 6 to 12 mo at 0 to 2 °C (32 to 34 °F) and 90 to 95% RH. Some cultivars are much more susceptible to storage losses than others (Steinbauer 1932). Tubers shrivel readily and are more likely to decay at low RH. Rates of dry matter loss during storage at various temperatures is shown in the section on *Respiration Rates* below.

Controlled Atmosphere (CA) Considerations

The benefit of CA storage has not been adequately assessed. Storage of tubers in 22.5% CO_2 with 20% O_2 significantly retarded the rate of inulin degradation, apparently through an effect on enzyme activity (Denny et al. 1944).

Retail Outlet Display Considerations

Water loss accounts for the majority of postharvest weight loss during retail sales. Product should be displayed in refrigerated display cases and, when not packaged, under high RH conditions such as that afforded by mist systems.

Chilling Sensitivity

Tubers can withstand low temperatures without damage but freeze at -2.2 °C (28 °F) (Whiteman 1957). Freezing at -10 °C (14 °F), whether in the field or in storage, causes rapid deterioration, but nonlethal freezing at -5 °C (23 °F) causes little damage. As with most fleshy plant products, temperature at which freezing damage occurs and extent of damage vary with cultivar, season, preconditioning, rate of freezing, and other factors (Kays 1997).

Ethylene Production and Sensitivity

Tubers are not sensitive to ethylene.

Respiration Rates

Temperature	Respiration	Rate of dry matter loss
	mg CO_2 kg^{-1} h^{-1}	g kg^{-1} day^{-1}
0 °C	10.2	0.162
5 °C	12.3	0.201
10 °C	19.4	0.317
20 °C	49.5	0.801

Data from Peiris et al. (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Storage losses are due primarily to desiccation, rotting, sprouting, freezing, and inulin degradation. Desiccation remains a significant storage problem even though losses can be fairly easily circumvented with proper storage conditions. Storage at high RH is essential (Shoemaker 1927, Steinbauer 1932) because tubers lack a corky surface layer similar to that found on potatoes to reduce water loss; their thin, easily damaged surface permits rapid water loss. While beneficial for some produce (Kays 1997), γ-irradiation greatly accelerates inulin degradation (Salunkhe 1959) and is of little storage value.

Postharvest Pathology

Storage rots are a serious problem (McCarter and Kays 1984, Barloy 1988), and higher storage temperatures result in greater loss. Approximately 20 organisms causing storage rots have been isolated from Jerusalem artichoke tubers. The organisms most frequently isolated were *Botrytis cinerea* Pers. and *Rhizopus stolonifer* (Ehrenb.: Fr.) Vuill., though *R. stolonifer* and *Sclerotinia sclerotiorum* (Lib.) de Bary are the most serious organisms causing rots at low storage temperatures. *Sclerotium rolfsii* Sacc. and *Erwinia carotovora* spp. *carotovora* (Jones) Bergey et al., in contrast, are not significant pathogens at temperatures below 20 °C (68 °F). Storage rots are controlled by storage at 0 to 2 °C (32 to 34 °F), removal of diseased tubers, minimizing mechanical damage, and proper RH control.

Quarantine Issues

None.

Suitability as Fresh-Cut Product

No current potential.

Special Considerations

During storage, tubers undergo significant alterations in carbohydrate chemistry, which, depending on the intended use, can have a pronounced effect on quality. Inulin is not one compound, but a series of molecules of varying chain length that begin to depolymerize during storage (Jefford and Edelman 1963, Schorr-Galindo and Guiraud 1997), whether harvested or left in situ. The degree of polymerization is critical for uses such as fat replacement or high-fructose syrups. With the former, as the chain length decreases the ability of inulin to mimic a lipid diminishes. Likewise, with progressive depolymerization, the ratio of fructose:glucose decreases and, upon hydrolysis, yields a progressively less pure fructose syrup. For example, during winter storage the fructose:glucose ratio decreases from 11 to 3 (Schorr-Galindo and Guiraud 1997). Thus, syrups derived from stored tubers contain a lot more glucose than fructose.

References

Barloy, J. 1988. Jerusalem artichoke tuber diseases during storage. *In* G. Grassi and G. Gosse, eds., Topinambour (Jerusalem Artichoke). Proceedings of a Workshop Held in Madrid, 30 September and 1 October 1987, pp. 145-149. Office for Official Publications of the European Communities, Luxembourg, Luxembourg.

Denny, F.E., N.C. Thornton, and E.M. Schroeder. 1944. The effect of carbon dioxide upon the changes in the sugar content of certain vegetables in cold storage. Cont. Boyce Thompson Inst. 13:295-311.

Jefford, T.G., and J. Edelman. 1963. The metabolism of fructose polymers in plants. II. Effect of temperature on the carbohydrate changes and morphology of stored tubers of *Helianthus tuberosus* L. J. Exp. Bot. 14:56-62.

Kays, S.J. 1997. Postharvest Physiology of Perishable Plant Products. Exon Press, Athens, GA.

McCarter, S.M., and S.J. Kays. 1984. Diseases limiting production of Jerusalem artichokes in Georgia. Plant Dis. 64:299-302.

Peiris, K.J.S., J.L. Mallon, and S.J. Kays. 1997. Respiratory rate and vital heat of some specialty vegetables at various storage temperatures. HortTechnology 7:46-48.

Salunkhe, D.K. 1959. Physiological and biochemical effects of gamma radiation on tubers of Jerusalem artichoke. Bot. Gaz. 120:180-183.

Schorr-Galindo, S., and J.P. Guiraud. 1997. Sugar potential of different Jerusalem artichoke cultivars according to harvest. Biores. Tech. 60:15-20.

Shoemaker, D.N. 1927. The Jerusalem Artichoke as a Crop Plant. Technical Bull. 33, U.S. Department of Agriculture, Washington, DC.

Steinbauer, C.E. 1932. Effects of temperature and humidity upon length of rest period of tubers of Jerusalem artichoke *(Helianthus tuberosus).* Proc. Amer. Soc. Hort. Sci. 29:403-408.

Varlamova, C., E. Partskhaladze, V. Oldhamovsky, and E. Danilova. 1996. Potential uses of Jerusalem artichoke tuber concentrates as food additives and prophylactics. *In* A. Fuchs, S.Schhittenhelm, and L. Frese, eds., Proceedings of the 6th Seminar on Inulin, Braunschweig, Germany, pp. 141-144. Carbohydrate Research Foundation, The Hague, Netherlands.

Whiteman, T.M. 1957. Freezing Points of Fruits, Vegetables and Florist Stocks. Marketing Research Report 196, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Jicama

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Scientific Name and Introduction

Jicama (*Pachyrhizus erosus* [L.] Urban) is a root crop of the Legume family (Leguminosae). It is also called “yam bean” and is a brown-skinned, turnip-shaped root eaten raw or cooked as a substitute for water chestnut. The root only forms under warm, short days. Therefore, most jicama in U.S. markets is imported from Mexico, where it is a native crop. Jicama is also produced, to a limited extent, in Hawaii. Roots are about 85% water, less than 1% fiber, less than 1.5% protein, less than 0.5% ash, and about 10% carbohydrate, of which about 10% is sucrose.

Quality Characteristics and Criteria

Good quality jicama roots should be smooth and firm, be uniform in shape and size, be free from mechanical damage, and have a crisp, succulent, white, sweet-starchy flesh.

Horticultural Maturity Indices

Jicama roots can be harvested at various stages of development. Young, tender roots harvested from green plants (100 to 150 g; 3.5 to 5.3 oz) are found in specialty markets. Fully mature roots, however, weigh from 250 to 1,500 g (0.55 to 3.3 lb). Mature roots are characterized by size and well-developed periderm as well as their starchy-sweet flavor. To promote hardening of the periderm, plant tops are removed mechanically or irrigation is stopped.

Grades, Sizes, and Packaging

There are no U.S. grades for jicama. In Hawaii, however, two grades are recognized based on size and freedom from defects (dirt, discoloration, growth cracks, roughness, insect damage, and mechanical injury).

After transport in bulk, jicama roots are typically packed in wooden crates of 9 kg (20 lb) or more or in carton boxes of about 4.5 kg (10 lb) for export to the United States.

Optimum Storage Conditions

Jicama can be stored for 2 to 4 mo at 12.5 to 15 °C (54 to 59 °F) with 80 to 90% RH. However, leaf and stem sprouts develop after 2 mo with loss of weight and diminished juiciness of the pulp. Minimizing mechanical damage to the periderm during harvest will reduce decay incidence during storage.

Controlled Atmosphere (CA) Considerations

No information is available on the potential benefits of CA storage of intact jicama roots. Based on work with other root crops, however, it would not be expected to provide much benefit. Decay development and discoloration of fresh-cut pieces was reduced by a modified atmosphere containing 5 to 10% CO_2 (Aquino-Bolaños et al. 2000).

Retail Outlet Display Considerations

Keep roots cool and dry to reduce water loss and superficial decay.

Chilling Sensitivity

Depending on variety and production area, jicama may develop symptoms of chilling injury after 1 to 3 weeks of storage at 10 °C (50 °F) (Cantwell et al. 1992, Mercado and Cantwell 1998). No chilling injury is observed on roots stored at 12.5 °C (55 °F). Decay is the main external symptom of chilling injury, and discoloration and loss of crisp texture are the main internal symptoms. The roots eventually become "rubbery" in texture when severely chilled. Internal discoloration typically occurs from the skin inwards and is more common and more severe in moderately chilled roots stored at 10 °C (50 °F). At lower temperatures, the pulp will take on a translucent appearance but not necessarily develop brown discoloration; these roots also exhibit external decay.

Ethylene Production and Sensitivity

Jicama produces only very low amounts of ethylene, <0.1 µL kg^{-1} h^{-1}, though higher rates may be observed after chilling at 10 °C (50 °F), about 0.5 µL kg^{-1} h^{-1}. Jicama is not sensitive to ethylene exposure (Cantwell 2006).

Respiration Rates

Temperature	Intact roots	Fresh-cut pieces
	----------mg CO_2 kg^{-1} h^{-1}----------	
0 °C	4 to 8	4 to 8
5 °C	10 to 12	8 to 12
10 °C	9.5 to 19	11 to 19
12.5 °C	4 to 8	-
20 °C	5 to 7	-

Data for intact commercial size roots from Cantwell et al. (1992).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

At 5 °C and 10 °C, respiration rates increase during storage; rates decrease during storage at temperatures above 10 °C. Less mature roots may have higher rates (Bergsma and Brecht 1992). Respiration rates for fresh-cut pieces were from 2-by-3 cm cylinders (Aquino-Bolaños et al. 2000).

Physiological Disorders

See C*hilling Sensitivity* section above.

Postharvest Pathology

The most common decay organisms found externally on jicama roots are species of *Penicillium*, *Rhizopus*, and *Cladosporium* (Bruton 1983, Cantwell et al. 1992). Most postharvest decay of jicama is a consequence of mechanical or chilling injury.

Quarantine Issues

None.

Suitability as Fresh-Cut Product

Fresh-cut jicama is incorporated in mixed vegetable snack trays because of its crisp texture and sweet-starchy flavor. Fresh-cut jicama should be stored below 5 °C (41 °F) to reduce microbial growth and discoloration. A shelf-life of 4 to 8 days can be expected at 5 °C (41 °F) in air. Modified atmosphere with 5 to 10% CO_2 maintains quality and extends shelf-life of fresh-cut jicama (Aquino-Bolaños et al. 2000).

Special Considerations

Curing. The periderm of jicama roots is easily damaged during harvest and transport, and this leads to an unsightly appearance, high rates of water loss, and increased susceptibility to decay. Wound healing or curing can be achieved by holding jicama roots at 20 to 25 °C (68 to 77 °F) under 95 to 100% RH for at least 1 week. These conditions are similar to those described for curing sweetpotatoes and other tropical root and tuber crops.

References

Aquino-Bolaños, E.N., M.I. Cantwell, G. Peiser, and E. Mercado-Silva. 2000. Changes in the quality of fresh-cut jicama in relation to storage temperatures and controlled atmospheres. J. Food Sci. 65(7):1238-1243.

Bergsma, K.A., and J.K. Brecht. 1992. Postharvest respiration, moisture loss, sensory analysis and compositional changes in jicama *(Pachyrhrizus erosus)* roots. Acta Hort. 318:325-332.

Bruton, B.D. 1983. Market and storage diseases of jicama. J. Rio Grande Valley Hort. Soc. 36:29-34.

Cantwell, M. 2006. Jicama Recommendations for Maintaining Postharvest Quality. Perishables Handling. *At* http://postharvest.ucdavis.edu/produce_information.

Cantwell, M., W. Orozco, V. Rubatzky, and L. Hernández. 1992. Postharvest handling and storage of jicama roots. Acta Hort. 318:333-343.

Mercado-Silva, E., and M. Cantwell. 1998. Quality changes in jicama roots stored at chilling and nonchilling temperatures. J. Food Qual. 21:211-221.

Paull, R.E., and N.J. Chen. 1988. Compositional changes in yam bean during storage. HortScience 23(1):194-196.

Kiwifruit

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Scientific Name and Introduction

The most common of the edible kiwifruit in the Western world is *Actinidia deliciosa*, a perennial of the Actinidiaceae. The fruit, produced on climbing or straggling plants, is a berry containing hundreds of small, dark seeds embedded in green flesh. Its skin is hairy and light brown. Different species exhibit variability in numerous attributes; for example, skin color (green to brown), flesh color (yellow to green), degree of hairiness, and taste (Ferguson 1990a,b). The guidelines presented here are based on information published for the 'Hayward' cultivar and similar types of *A. deliciosa*. A yellow-fleshed fruit of *A. chinensis* is rapidly gaining favor in the market, but little information is available.

It is important to note that most of the following information, especially that related to grades, sizes, and packaging, is derived from U.S. and California literature. In order of importance in the world market, Italy is the leading producer followed by New Zealand, Chile, and California. Therefore, the guidelines used by the European Union should be considered as well.

Quality Characteristics and Criteria

High-quality kiwifruit should not be shriveled and should be free from sunscald, scars, growth cracks, insect injury, bruises, internal breakdown, and decay. At table ripeness, fruit should have at least 14% SSC (soluble solids content) with flesh firmness of 2 to 3 lb (0.9 to 1.35 kg) penetration force, measured with a 5/16 in (8 mm) tip (Crisosto et al. 1999).

Horticultural Maturity Indices

Harvest maturity for kiwifruit produced in California is defined as a minimum of 6.5% SSC and flesh firmness of 14 lb (6.3 kg) force (Crisosto et al. 1999). In New Zealand, the index used for fruit destined for export is a minimum average SSC of 6.2% measured in 10 fruit. A general practice is that if 2 of the 10 fruit measured have below 5.8% SSC, the orchard is not considered acceptable for export picking. Fruit that are to be marketed locally with a minimum of handling may be held on the vine until the SSC reaches 10 to 12% (Beevers and Hopkirk 1990).

Grades, Sizes, and Packaging

Grades include U.S. Fancy, U.S. No. 1, and U.S. No. 2. Criteria that define grades are subjective and are based primarily on the quality characteristics described above (AMS 1986). Because of the irregular shape of kiwifruit, it is difficult to define fruit size in terms of length or diameter. Since California is the most significant producer of kiwifruit in the United States, the size criteria defined by the Kiwifruit Administrative Committee (KAC) are generally adhered to throughout the United States. Size designations are based on number of fruit that can be placed on a single tray. Actual fruit size is based on weight and is defined as the number of uniformly sized fruit required to constitute an 8-lb sample. Current designations from the KAC (1999) are summarized in table 1. Handlers should note this information is subject to change, and the most recent information should be reviewed by anyone packing kiwifruit.

Table 1. 1999/2000 Kiwifruit size designation chart

Tray equivalency size designation	Maximum no. of fruit in 8-lb sample[1]	Fairly uniform size variation[2]
		in
21	22	1/2
25	27	1/2
27/28	30	1/2
30	33	1/2
33	36	3/8
36	42	3/8
39	48	3/8
42	53	3/8
45	55	1/4

[1]Tolerance: Average weight of all sample units must be at least 8 lb (3.63 kg) and no individual sample unit may weigh less than 7 lb 12 oz (3.52 kg).
[2]Tolerance: Not more than 10% of the containers in any lot and not more than 5%, by count, of the fruit in any container may fail to meet the diameter range, except for sizes 42 and 45 in which the tolerance, by fruit count, may not be more than 25%.

A variety of packages are used for kiwifruit. Tray-packed fruit may be placed in cartons of wood or fiberboard that contain one, two, or three trays. Appropriate padding should be placed between trays. Alternatively, volume-filled (typically 23 lb; 10.4 kg) or count-filled cartons are available. Bagged fruit are generally placed in master cartons, a common arrangement being a master container containing twenty 1-lb (0.45 kg) bags. At the retail level, fruit are sometimes sold in lots of 6 to 10 fruit per bag with no size specifications. Mini wooden bins containing about 125 lb (56 kg) of fruit are used for some markets (KAC 1999). Any size carton or configuration may be used in the United States provided it is appropriately labeled.

Precooling Conditions

Early literature recommends that kiwifruit should be cooled to near 0 °C (32 °F) as soon as possible after harvest for maximum storage potential. Forced-air cooling is preferred. Hydrocooling has been used successfully but is not generally recommended because the hairs on the fruit surface tend to retain an excessive amount of water, which can promote the growth of decay-causing microorganisms (McDonald 1990). The decision to precool remains a matter of choice for the packer, and the process of curing (see *Curing*) is gaining acceptance. Lallu (1997) reports that rapid precooling may exacerbate internal breakdown associated with chilling injury.

Curing

Curing occurs during the delay between harvest and cooling and is characterized by some water loss from fruit and drying of the stem scar. In New Zealand, curing for at least 48 h has been reported to reduce the incidence of *Botrytis* decay (Lallu et al. 1997) and development of internal breakdown (Lallu 1997) during subsequent cold storage. In Chile, Retamales et al. (1997) reported that curing up to 72 h did not increase softening during cold storage.

Optimum Storage Conditions

The recommended condition for commercial storage of kiwifruit is 0 °C (32 °F) with 90 to 95% RH. Fruit that are properly handled before storage may be held in good condition for 4 to 5 mo. (See *Ethylene Production and Sensitivity*).

Controlled Atmosphere (CA) Conditions

Kiwifruit respond favorably to CA. The potential for benefit is excellent, with extension of storage life up to about 6 mo. The recommended conditions are 1 to 2% O_2 with 3 to 5% CO_2 at 0 °C. Less than 1% O_2 may induce off flavors, and greater than 7% CO_2 can cause internal breakdown of the flesh. However, the risk of such injuries is moderate as long as management of the atmosphere is given reasonable attention (see *Physiological Disorders*). There is increasing commercial use of CA during both storage and transport. Refer to Kader (1997) for selected references on kiwifruit CA research.

Retail Outlet Display Considerations

Kiwifruit may be displayed on unrefrigerated counters since it is desirable to have the fruit near eating ripeness at the time of sale.

Chilling Sensitivity

Lallu (1997) reports that the fruit of *A. deliciosa* cv. 'Hayward' are chilling sensitive at temperatures near 0 °C with symptoms appearing as a ring or zone of granular, water-soaked tissue in the outer pericarp at the stylar end of the fruit. Other symptoms may include the development of diffuse pitting and a dark, scaldlike appearance on the skin. Curing alleviated symptoms of chilling injury (see *Curing*). The terms "low temperature breakdown," "senescent breakdown," and "physiological pitting" all appear in the literature, but the differences among these disorders are difficult to define in fruit stored for an extended period.

Ethylene Production and Sensitivity

At harvest maturity, kiwifruit are low ethylene producers with rates of approximately 0.1 µL kg^{-1} h^{-1} at 0 °C (32 °F) and about 0.1 to 0.5 µL kg^{-1} h^{-1} at 20 °C (68 °F). Fruit that are ripe at less than 4 lb (1.8 kg) force produce 50 to 100 µL kg^{-1} h^{-1}. Kiwifruit in storage are extremely sensitive to the presence of ethylene and should not be stored with commodities that produce significant amounts. As little as 5 to 10 ppb (0.005 to 0.010 µL L^{-1}) ethylene in the storage atmosphere can accelerate softening without affecting other ripening processes, resulting in unripe fruit that are excessively soft (McDonald 1990, Crisosto et al. 1999).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 ºC	3
4 to 5 ºC	5 to 7
10 ºC	12
20 to 21 ºC	16 to 22

Data from Hardenburg et al. (1986).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

In storage or transit, the flesh of immature fruit may soften rapidly and have a water-soaked appearance while the core remains hard and tough (Beevers and Hopkirk 1990). A similar type of hard-core disorder also has been attributed to exposure of the fruit to damaging levels of ethylene in combination with CO_2 of 8% or higher (Crisosto et al. 1999).

Inadvertent freezing results in flesh translucency (Beevers and Hopkirk 1990). If freezing injury occurs, it usually appears first at the stem end and progresses to the stylar end. The flesh of damaged fruit may become somewhat yellow with prolonged storage (Crisosto et al. 1999).

Pericarp granulation and pericarp translucency may occur independently, but both are associated with long-term storage. The presence of ethylene in storage may exacerbate symptoms. These disorders may simply be a consequence of senescence, as other causes are not well defined (Crisosto et al. 1999).

The presence of ethylene in CA storage can cause white-core inclusions, which are distinct white patches of core tissue that are obvious in ripe fruit. Symptoms may develop as early as 3 weeks in storage, when atmospheric composition is favorable for development of the disorder (Crisosto et al. 1999).

Postharvest Pathology

Kiwifruit from all growing areas may deteriorate due to infection by *Botrytis cinerea*, which causes gray mold decay. This fungus may infect the fruit through senescent flower parts, penetrate the fruit directly, or enter through wounds (see *Curing*). Other types of decay of lesser commercial significance are blue mold, caused by *Penicillium expansum*, and phomopsis, caused by *Phomopsis actinidiae*. An appropriate fungicide application program in the orchard coupled with harvest management practices to reduce wounding is the primary means of reducing incidence of decay (Snowdon 1990). As fruit soften, they become more susceptible to all types of decay, so harvesting at the appropriate maturity and good temperature management in the storeroom, plus the use of CA, all are important in controlling decay (Crisosto et al. 1999).

Various types of pitting also are attributed to fungal infection (Manning and Beever 1992, Testoni et al. 1997). Symptoms typically do not occur until fruit have been stored for several months, and direct isolation of the fungi usually is required to distinguish between fungal pitting and physiological pitting.

Quarantine Issues

There are no quarantine issues in the United States. However, importers and exporters should contact APHIS or other regulatory bodies in receiving countries to ensure quarantine requirements are met.

Suitability as Fresh-Cut Product

The potential does not seem good for national or regional distribution of fresh-cut kiwifruit. However, some restaurants do serve fresh-cut kiwifruit on salad bars and in fruit medleys, so there is a degree of consumer demand for the product. Agar et al. (1999) reported that fresh-cut slices of kiwifruit could be stored for 9 to 12 days if calcium treatments and modified atmospheres were used. Emerging technologies in fresh-cut processing may facilitate greater availability in retail markets.

Special Considerations

One of the most troublesome concerns for storage of kiwifruit is management of ethylene in the atmosphere. Enormous losses are incurred when fruit soften prematurely in storage without ripening. The effectiveness of various ethylene removal techniques—for example, catalytic converters, potassium permanganate filters, ozone generators, and simple ventilation systems—must be evaluated carefully for a specific situation. For example, the frequency of opening the storeroom doors; proximity of the storeroom to sources of ethylene, such as the packing house itself or nearby roadways; and presence of decaying fruit in the storeroom all influence the efficacy of ethylene removal. Innovative managers should have a means of measuring ethylene in the storeroom and in the surrounding area.

References

Agar, I.T., R. Massantini, B. Hess-Pierce, and A.A. Kader. 1999. Postharvest CO_2 and ethylene production and quality maintenance of fresh-cut kiwifruit slices. J. Food Sci. 64:33-440.

AMS [USDA Agricultural Marketing Service]. 1986. United States Standards for Grades of Kiwifruit. Effective October 15, 1986. U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Beever, D.J., and G. Hopkirk. 1990. Fruit development and physiology. *In* I.J. Warrington and G.C. Weston, eds., Kiwifruit: Science and Management, pp. 97-126. Ray Richards Publisher, Auckland, New Zealand.

Crisosto, C.H., E.J. Mitcham, and A.A. Kader. 1999. Kiwifruit. Fresh Produce Facts. University of California, Davis, CA. *At* http://postharvest.ucdavis.edu/produce_information.

Ferguson, A.R. 1990a. The genus *Actinidia. In* I.J. Warrington and G.C. Weston, eds., Kiwifruit: Science and Management, pp. 15-35. Ray Richards Publisher, Auckland, New Zealand.

Ferguson, A.R. 1990b. Botanical nomenclature: *Actinidia chinensis, Actinidia deliciosa,* and *Actinidia setosa. In* I.J. Warrington and G.C. Weston, eds., Kiwifruit: Science and Management, pp. 36-57. Ray Richards Publisher, Auckland, New Zealand.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Kader, A.A. 1997. A summary of CA recommendations for fruits other than apples and pears. *In* E.J. Mitcham, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 3, pp 1-34. University of California, Davis, CA.

Kiwifruit Administrative Committee. 1999. 1999/2000 Season California Kiwifruit Packing Regulations Bulletin. Kiwifruit Administrative Committee, Sacramento, California. *At* http://www.kiwifruit.org.

Lallu, N. 1997. Low temperature breakdown in kiwifruit. Acta Hort. 444:579-585.

Lallu, N., M. Manning, and H. Pak. 1997. Best curing practices for the orchard and packhouse. New Zealand Kiwifruit Journal (March/April) pp. 35-37.

Manning, M., and D. Beever. 1992. An update on storage pitting research. NZ Kiwifruit Journal (Feb.) pp. 5-7.

McDonald, B. 1990. Precooling, storage, and transport of kiwifruit. *In* I.J. Warrington and G.C. Weston, eds., Kiwifruit: Science and Management, pp. 429-459. Ray Richards Publisher, Auckland, New Zealand.

Retamales, J., T. Cooper, and J. Montealegre. 1997. Effects of cooling and curing regime on ethylene production and storage behavior of kiwifruit. Acta Hort. 444:567-571.

Snowdon, A.L. 1990. Soft fruits and berry fruits. *In* A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 1, General Introduction and Fruits, pp. 255-266. CRC Press, Boca Raton, FL.

Testoni, A., B. Grassi, S. Quaroni, et al. 1997. Pitting on kiwifruit in storage caused by *Phialophora* sp. Acta Hort. 444:751-756.

Kohlrabi

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Scientific Name and Introduction

Brassica oleracea L., Gongylodes group, also known as kohlrabi and turnip-rooted cabbage, is a member of the Brassicaceae (Cruciferae) family. It is a native of northern Europe and grows best in cool climates. Kohlrabi is grown as an annual, with the enlarged stem being the most commonly used edible portion. The enlarged stem may have purple, white, or green skin, but the flesh is white. The leaves can also be eaten like collards. Kohlrabi is available from spring to late fall from various growing regions of North America.

Quality Characteristics and Criteria

Only young kohlrabi should be harvested, since mature product becomes woody and tough. Leaf stems are a good indicator of quality; they should be succulent and tender.

Horticultural Maturity Indices

Early- and mid-season kohlrabi are best harvested when they are about 5.1 to 6.4 cm (2 to 2.5 in) in diameter. Fall-grown kohlrabi may be grown to 10.2 to 12.7 cm (4 to 5 in) in diameter since they are less prone to becoming woody.

Grades, Sizes, and Packaging

There are no grade standards for kohlrabi. Topped kohlrabi is usually packaged in 11.4-kg (25-lb) film bags, 22.7-kg (50-lb) film bags, or 11-kg (24-lb) cartons containing 24 0.5-kg (1-lb) film bags. Those with tops are usually bunch-tied together much like beets, with 4 to 6 kohlrabi per bunch (Thompson and Kelly 1957).

Precooling Conditions

Hydrocooling, package-icing, and forced-air cooling are acceptable for kohlrabi, with tops on or with tops removed.

Optimum Storage Conditions

Topped kohlrabi can be stored for 2 to 3 mo at 0 °C (32 °F) and 98 to 100% RH (Kasmire and Cantwell 2002). Storage life is 2 to 4 weeks if tops are not removed. Storage life can be improved with the use of perforated film bags to maintain high RH.

Controlled Atmosphere (CA) Considerations

There is no benefit of CA (Kasmire and Cantwell 2002).

Retail Outlet Display Considerations

Kohlrabi should be displayed like root vegetables such as beets and carrots. They can be placed in iced displays.

Chilling Sensitivity

Kohlrabi are not chilling sensitive.

Ethylene Production and Sensitivity

Kohlrabi have a very low ethylene production rate of <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F) and a low sensitivity to ethylene exposure.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	10
5 °C	16
10 °C	31
15 °C	46

Data were adapted from Pieh (1965).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Kohlrabi becomes tough when stored beyond its expected storage life or under lower than recommended RH.

Postharvest Pathology

Important diseases during storage are bacterial soft rot (*Erwinia carotovora* [Jones] Bergey et al.) and black rot (*Xanthomonas campestris* [Pammel] Dowson) (Ramsey and Smith 1961).

Quarantine Issues

There are no quarantine issues.

Suitability as Fresh-Cut Product

Peeled and sliced kohlrabi has potential as a fresh-cut product.

Special Considerations

The freezing point is -1 °C (30.2 °F) (Kasmire and Cantwell 2002). Peeled and cut kohlrabi does not produce strong off odors when held in low-O_2 atmospheres (Forney and Jordan 1999).

References

Forney, C.F., and M.A. Jordan. 1999. Anaerobic production of methanethiol and other compounds by *Brassica* vegetables. HortScience 34(4):696-699.

Kasmire, R.E. and Marita Cantwell. 2002. Postharvest handling systems: flower, leafy and stem vegetables. *At* http://vric.ucdavis.edu/postharvest/leaf.

Pieh, K. 1965. Cooling of fruits and vegetables. Deut. Gartenbau 13:136-140

Ramsey, G.B., and M.A. Smith. 1961. Market Diseases of Cabbage, Cauliflower, Turnips, Cucumbers, Melons, and Related Crops. Agriculture Handbook 184, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Thompson, H.C., and W.C. Kelly. 1957. Vegetable Crops, 5th ed., pp. 313-314. McGraw-Hill, New York, NY.

Leek

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Scientific Name and Introduction

The leek, *Allium porrum* L. (syn. *Allium ampeloprasum* L. var. *porrum*), is an onionlike plant belonging to the Liliaceae family. The edible portion consists of the elongated bases of the foliage leaves (a false stem) and the lower parts, which are blanched white from being underground. There are three major types of leek: European leek, which develops a short and thick pseudostem; Turkish leek, which develops a relatively long and thin pseudostem; and kurrat, which does not produce a pseudostem. The kurrat type is grown in the Mediterranean and the Middle East for its leaves.

Quality Characteristics and Criteria

High-quality leeks are firm and smooth, free of blemishes, and have characteristic white stems with dark-green leaves. The cut bottoms should be flat, because rounded bottoms may indicate prolonged storage.

Horticultural Maturity Indices

Leeks can grow as tall as 50 to 100 cm (20 to 39 in) in height and are harvested when the base diameter reaches 2.54 cm (1 in).

Grades, Sizes, and Packaging

There are no established USDA quality standards for leeks. Leeks are commonly trimmed so that only a 30.5-cm (12-in) portion of the green top remains. They can, depending on diameter, be bunched in groups of three and placed in polyethylene film bags to prevent moisture loss. They are usually packaged in 4.5-kg (10-lb) cartons or wire-bound crates, holding ten 0.45-kg (1-lb) film bags. Some crates may be packed with 18 to 24 bunches, with a net weight of up to 13.6 kg (30 lb).

Precooling Conditions

Hydrocooling, crushed ice, and vacuum-cooling are the most common methods to promptly cool harvested leeks to 0 °C (32 °F).

Optimum Storage Conditions

Leeks can be stored for 2 to 3 mo at 0 °C (32 °F) with 95 to 100% RH. High RH is essential to prevent wilting. Good refrigeration retards elongation and curvature that develops in leeks at 10 to 21 °C (50 to 70 °F). Leeks held in polyethylene-lined crates remain saleable for 5 to 6 weeks at 0 °C (32 °F) under crushed ice, 4 weeks at 0 °C without ice, more than 2 weeks at 4.4 °C (40 °F), and 13 days at 10 °C (50 °F). Leeks stored in nonlined crates keep for 3 weeks at 0 °C (32 °C) , 8 days at 4.4 °C (40 °F), and 1 week at 10 °C (50 °F), with or without crushed ice (Hruschka 1978). Freshly harvested leeks held naked in consumer-unit perforated polyethylene bags or in nonperforated (sealed) polyethylene bags remain attractive and saleable for up to 10 weeks. They can last up to 10 weeks under crushed ice at 0 °C (32 °F); for 10 weeks without ice at 0 °C (32 °F); for 12 days at 10 °C (50 °F); and 6 days at 21 °C (70 °F).

Controlled Atmosphere (CA) Considerations

Storage for 4 to 5 mo at 0 °C (32 °F) is possible with CA, though there will be some loss of quality. Recommended CA conditions are 1 to 3% O_2 in combination with either 2 to 5% CO_2 (Saltveit 1997) or 5 to 10% CO_2 (Kurki 1979). Such CA retards yellowing and decay development. Levels of 15 to 20% CO_2 cause tissue injury.

Retail Outlet Display Considerations

Leeks should be held as close to 0 °C (32 °F) as possible and preferably away from products that produce ethylene.

Chilling Sensitivity

Leeks are not sensitive to chilling and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Leeks produce very low levels of ethylene: <0.1 µL kg^{-1} h^{-1}. Leeks are moderately sensitive to ethylene. Detrimental effects include softening and increased decay.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	10 to 20
4.4 °C	20 to 29
10 °C	50 to 70
15.6 °C	75 to 117
21 °C	110
26.7 °C	107 to 119

Data from Hruschka (1978).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Slight elongation and geotrophic curvature may occur, even at 0 °C (32 °F). Leeks held in polyethylene-lined crates elongate less than 1% per week at 0 °C (32 °F) under crushed ice, 3% per week at 0 °C (32 °F) without ice, 13% per week at 4.4 °C (40 °F), and 22% per week at 10 °C (50 °F) (Hruschka 1978). No attempt has been made to establish a relation between elongation and curvature, though varying degrees of curvature have been observed in such treatments. Senescent yellowing develops more rapidly at warmer temperatures, and moderate wilting is apparent when leeks lose about 15% of their weight.

Postharvest Pathology

Most diseases that attack onions may also affect leeks.

Quarantine Issues

None are known.

Suitability as Fresh-Cut Product

No current potential exists.

Special Considerations

Cultivar, preharvest and postharvest conditions, degree of trimming, and method of packing will all influence the storage life of leeks.

Acknowledgments

Some of the information in this chapter is from the University of Oregon website, “Commercial Vegetable Production Guides, Leeks,” at http://horticulture.oregonstate.edu/content/vegetable-production-guides.

References

Hruschka, H.W. 1978. Storage and Shelf Life of Packaged Leeks. Marketing Research Report 1084, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Kurki, L. 1979. Leek quality changes during CA storage. Acta Hort. 93:85-90.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California, Davis, CA.

Lemon

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Scientific Name and Introduction

Lemons (*Citrus limon* L. Burman f.) are grown year round in California, the major producer. Arizona and to a lesser extent Florida also produce a significant portion of the lemon crop. The primary varieties are 'Eureka' and 'Lisbon.' Both have firm, smooth skins, juicy flesh, and few seeds. The exact origin of the lemon is unknown, but some have linked it to northwestern India.

Quality Characteristics and Criteria

The primary quality characteristics are intensity and uniformity of yellow color, size, shape, smoothness, firmness, and freedom from decay and defects including freezing damage, drying, mechanical damage, rind stains, red blotch, shriveling, and discoloration. Lemons should be firm and have smooth, thin skins. Ripe lemons should have a pleasant citrus fragrance. Lemons with discolored, bruised, or wrinkled skins should be avoided.

Horticultural Maturity Indices

The generally accepted standard is a minimum juice content of 28 to 30% by volume, depending on the grade.

Grades, Sizes, and Packaging

Grading includes U.S. No. 1, U.S. Export No. 1, U.S. Combination, and U.S. No. 2. Common packaging specifications are 40-lb (18.2-kg) cartons, 10-lb (4.6-kg) mini-pack cartons, 8-lb (3.6-kg) consumer cartons, and 2-, 3-, and 5-lb (0.9-, 1.4-, and 2.3-kg) bags. Sizes include 75, 95, 115, 140, 165, 200, and 235 count.

Precooling Conditions

Most packing houses do not precool lemons because the anticipated benefit is too modest, or they may need to degreen the fruit with ethylene, which requires 20 °C (68 °F) pulp temperatures.

Optimum Storage Conditions

Yellow lemons harvested when dark green have a much longer postharvest life than those picked yellow, which must be marketed more rapidly due their shorter shelf-life. Lemons should be stored between 7 and 12 °C (45 and 54 °F) depending on the maturity-ripeness stage at harvest, season of harvest, storage time, and production area. They can be stored for up to 6 mo under the right conditions. Optimum RH is 85 to 95%. Because lemons are chilling sensitive, they should not be stored for prolonged periods below 10 °C (50 °F), though 3 to 4 weeks storage at 3 to 5 °C (37 to 41 °F), which is typical for some receivers, is usually tolerated without harm. Removal of ethylene from storage rooms can reduce senescence and fungal decay. It is generally recognized that proper storage of lemons improves quality (juice content, flavor, and color).

Adequate ventilation must be maintained during storage. Cartons should be kept off the floor to prevent them becoming wet from condensation. Lemons should be stored away from produce having a strong odor. Also, decay can occur from skin cuts or scratches caused by rough handling. Lemons must be handled with care, and shipping containers should not be dropped on the floor. Any affected product should be removed immediately to prevent mold from spreading.

Controlled Atmosphere (CA) Considerations

Controlled atmosphere conditions of 7.5 to 10% O_2 and up to 10% CO_2 can delay senescence, including loss of green color, but the risk of injury to the fruit is high and CA is only rarely used. Levels of CO_2 sufficient to inhibit fungal growth (>10%) are not used because high CO_2 induces nonpersistent but objectionable off flavors due to the accumulation of volatiles from fermentation. Also, levels of O_2 sufficient to control fungi (<1%) are not used because when O_2 is <5%, persistent off flavors can develop.

Retail Outlet Display Considerations

Lemons should not receive a water sprinkle or top ice.

Chilling Sensitivity

Chilling injury can be a major disorder of lemon, and it is therefore important not to store lemons below 10 °C (50 °F). Symptoms include pitting of the skin (termed "peteca"), interior discoloration, red blotch, and loss of juice. Chilling injury severity depends on cultivar, production area, harvest time, maturity-ripeness stage at harvest, and time-temperature of postharvest handling operations. Moderate to severe chilling injury is usually followed by decay.

Ethylene Production and Sensitivity

Rates of ethylene production are generally <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F). If degreening is desired, lemons can be treated with 1 to 10 µL L^{-1} ethylene for 1 to 3 days at 20 to 25 °C (68 to 77 °F). However, it should be noted that this exposure may accelerate deterioration and incidence of decay, since lemons are sensitive to ethylene exposure. They should not be stored together with ethylene-producing produce.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
10 °C	10 to 12
15 °C	14 to 24
20 °C	20 to 28

Data from Arpaia and Kader (2001).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Several disorders of lemon fruit are significant. Oleocellosis or oil spotting, a rind blemish that involves the breaking of oil cells due to physical stress on turgid fruits, results in the release of oil that damages surrounding tissues. Not harvesting lemons when they are turgid and careful handling reduce the severity of this disorder. Peteca, another rind disorder, begins in white portion of peel and develops sunken brown pits. It is favored by low temperatures before or after harvest, oil applications in the grove, and an imbalance of calcium and potassium in the peel. Some reduction in peteca is obtained by gibberelic acid applications to trees and by avoiding storage of susceptible lemons below 13 °C (55 °F).

Membrane stain, an internal disorder in which the membranes between segments, or carpellary walls, show irregular brown or black areas. It is reduced by avoiding storage of lemons below 13 °C (55 °F) and improving ventilation in storage.

Postharvest Pathology

There are three main postharvest pathological diseases of lemon.

Green mold and *blue mold* are caused by *Penicillium digitatum* and *P. italicum*, respectively. Spores of these pathogens access the fruit rind through wounds. Symptoms begin as water-soaked areas at the fruit surface followed by growth of colorless mycelia, and then sporulation. Blue mold is more common when storage temperatures are low, and it spreads from fruit to fruit more readily than green mold. Fungicides thiabendazole, imazalil, and sodium ortho-phenyl phenate are used for these diseases, and partial control can be obtained with biological control agents and the immersion of fruit in soda ash or sodium bicarbonate. Incidence of these diseases is reduced by careful handling to minimize wounds.

Sour rot is caused by *Geotrichum citri-aurantii*, which enters lemons initially through wounds made by insects. Then infected fruit is digested by the pathogens, which spread rapidly from fruit to fruit. Sour rot is associated with cool, wet growing conditions. Partial control can be obtained by immersing fruit in soda ash, sodium bicarbonate, or sodium ortho-phenyl phenate after harvest and using minimal storage temperatures.

Other pathogens are occasionally troublesome in lemon storage, including *Alternaria citri* and the stem-end rot fungi *Diplodia natalensis*, as well as *Phomopsis citri*, *Botrytis cinerea*, *Trichoderma* spp., *Sclerotinia sclerotiorum*, and *Phytopthora* spp. Additional strategies to minimize postharvest decay include prompt cooling to the proper temperature range, maintaining optimum ranges of temperature and RH; excluding ethylene during transport and storage; using gibberelic acid before harvest to delay senescence of the fruit after harvest; and providing sanitation throughout the handling system.

Quarantine Issues

Most quarantine concerns for lemons address eliminating fruit flies, such as the Caribbean, Oriental, Mediterranean, and Mexican fruit flies. Heat, cold, and methyl bromide treatments are certified for this purpose, but they all pose risk of injury to lemons. Harvest and export of fruit from certified pest-free zones is another option to control fruit flies that eliminates risks of fruit injury, and this approach has also been employed against citrus black fly and Fuller rose beetle. Quarantine authorities are concerned that citrus black spot, an unsightly rind blemish caused by *Guignardia citricarpa* that occurs in South Africa and parts of Asia and South America, could potentially become established in Mediterranean countries and in North America.

Suitability as Fresh-Cut Product

Lemon sections, prepared by both manual and automatic processors, are distributed for use in the food service industry.

Acknowledgments

Some of the information in this chapter is from the Produce Marketing Association's "Fresh Produce Manual" and the University of California, Davis, website "Fresh Produce Facts" at http://postharvest.ucdavis.edu/produce_information. We express our appreciation to Laurie Houck, University of California, Davis, as well as to Bob Elliott and Chuck Orman, Sunkist Growers Fruit Sciences Division, for their helpful review of this chapter.

References

Arpaia, M.L., and A.A. Kader. 2001. Lemon. Recommendations for Maintaining Postharvest Quality. At http://postharvest.ucdavis.edu/produce_information.

Eaks, I.L. 1961. Effect of temperature and holding periods on physical and chemical characteristics of lemon fruit. J. Food Sci. 26:593-599.

Eckert, J.W., and I.L. Eaks. 1989. Postharvest disorders and diseases of citrus fruits. *In* W. Reuther, E.C. Calavan, and G.E. Carman, eds., The Citrus Industry, vol. 5, pp. 179-260. University of California Press, Oakland, CA.

Houck, L.G., and J.W. Snider. 1969. Limitations of modified atmospheres for decay control of citrus fruits. Phytopathology 59:1031-1032.

Rygg, G.L., and E.M. Harvey. 1959. Storage of Lemons From the Desert Areas of Arizona and California. Marketing Research Report 310, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Rygg, G.L., and A.W. Wells. 1962. Experimental Storage of California Lemons in Controlled Atmospheres. Marketing Research Report 475, U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Timmer, L.W., and L.W. Duncan, eds. 1999. Citrus Health Management. APS Press, St. Paul, MN.

Wild, B.L., W.B. McGlasson, and T.H. Lee. 1976. Effect of reduced ethylene levels in storage atmospheres on lemon keeping quality. HortScience 11:114-115.

Lettuce

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Scientific Name and Introduction

Four distinct types of lettuce are produced in the United States: crisphead or iceberg *(Lactuca sativa* L. var. *capitata);* butterhead, bib, or Boston *(L. sativa*, var. *capitata);* cos or romaine *(L. sativa*, var. *longifolia);* and leaf *(L. sativa*, var. *crispa).* Two others types, stem or celtuce *(L. sativa* var. *asparagina)* and Latin are rarely found outside local or ethnic communities.

Crisphead lettuce produces large, heavy, compact folded heads with crisp, brittle, prominently veined leaves. Butterhead lettuce forms open heads with softer leaves having a smooth texture. Cos lettuce does not form a true head, but is composed of upright, large, elongated, and often coarser leaves. Leaf lettuce also does not produce a head, and the leaves are more spreading, delicate, smaller, and less elongate than cos.

Crisphead lettuce is the main type grown in the United States and is best adapted for long distance shipment. A greater percentage of all types of lettuce are being processed into fresh-cut salad mixes for commercial and home use. With proper vacuum-cooling and packaging, refrigerated transportation under controlled atmosphere can supply whole and packaged lettuce to national and international markets.

Quality Characteristics and Criteria

Head lettuce should be solid with no seed-stem, defects, or decay. In general, high-quality lettuce should be clean, free of browning, crisp and turgid, and bright light green.

Horticultural Maturity Indices

Head lettuce is harvested when the heads are well formed and solid (Ryall and Lipton 1979). Maturity is based on head compactness, and the firmness of the head is related to its susceptibility to certain postharvest disorders. Soft heads are easily damaged, while fairly firm heads have higher respiration rates. Firm heads have maximal storage life, while hard and extra-hard heads are more prone to develop russet spotting, pink rib, and other physiological disorders.

Grades, Sizes, and Packaging

Head lettuce is graded by size and firmness, while leafy types are graded by size (Hardenburg et al. 1986). Lettuces, as with other leafy vegetables, must be kept clean and free of soil and mud. This is easier when grown on mineral soils than on muck (organic) soils. A strong bitter taste and toughness develops if harvest is delayed or if lettuce is overmature, and then the product becomes unmarketable.

Because lettuce is very fragile, it should be handled as little as possible. Field packing and palletizing eliminate a major source of mechanical damage, but they require specialized handling equipment and vacuum-cooling facilities to be practical. The stem is cut at ground level and the head trimmed of unusable leaves. Harvesting and field packing by hand is assisted by various equipment including conveyors and mobile packing stations. Heads can be wrapped or bagged in plastic film by the cutter or the packer. Wrapped or loose heads are then placed in cardboard containers that are stapled closed and palletized. Leaf, butterhead, and cos types are cut, trimmed, and tied into compact bundles before being placed in cartons.

Crisphead or iceberg lettuce is usually packaged in 20- to 22-kg (43- to 48-lb), 24-count cartons. Cos or romaine lettuce is commonly packaged in 24-count cartons. Leaf lettuce is usually packaged in 9- to 11-kg (20- to 25-lb) or 24-count cartons. Butterhead or Boston lettuce is usually packaged in 9-kg (20-lb) cartons. Bibb and greenhouse-grown lettuce are commonly packaged in 4.5-kg (10-lb) cartons.

Lettuce harvested for processing is placed in large bulk bins for transportation to the precooling or processing facility. Lettuce may be cored in the field or at a local or regional processing facility. At the processing facility, heads are cut, washed in cold water, and centrifuged to remove excess water. Cut lettuce is often mixed with other types of lettuce or greens, shredded carrot, and red cabbage to produce a salad bag mix. The mix may be treated with a processing aid composed of a chlorine-containing compound and/or an antioxidant or preservative during washing or before packaging. The package is made from special films that are selected to maintain a desired lower O_2 and higher CO_2 concentration than in air. The bags are then placed in cartons for temporary cold storage or for immediate shipment to market. Since gas composition in bags results from a dynamic interplay between tissue respiration and film permeability, it is important to maintain proper temperature and to know the respiratory characteristics of the enclosed tissue.

Precooling Conditions

Vacuum-cooling is the preferred method for precooling all lettuces (Ryall and Lipton 1979, Hardenburg et al. 1986). For effective vacuum-cooling, containers and film wraps are perforated or readily permeable to water vapor. If heads of lettuce are dry and warmer than 25 °C (77 °F), clean water is sprinkled on them the before closing the cartons to aid cooling. A modification called hydrovacuum reduces water loss during cooling. Thorough precooling is essential because mechanically refrigerated trucks do not have enough cooling capacity to cool warm lettuce during transit. Field heat retained in the densely packed cartons can be removed by forced air where vacuum-cooling facilities are not available, but it is much less effective. Hydrocooling is effective for nonheading lettuce types but should not be used with head lettuce since the water retained in the head fosters decay.

Optimum Storage Conditions

Lettuce should be quickly cooled and maintained as close to 0 °C (32 °F) as possible with 98 to 100% RH. Head types are better adapted to prolong storage than are the other types, but none keep longer than 4 weeks, and about half that time at 5 °C (41 °F). Film liners or individual polyethylene head wraps are desirable for attaining high RH; however they should be perforated or be permeable to maintain a noninjurious atmosphere and to avoid 100% RH on removal from storage. Lettuce is easily damaged by freezing, so all parts of the storage room must be kept above the highest freezing point of lettuce, -0.2 °C (31.6 °F).

Though most lettuce is hand-harvested, some mechanical harvesters are available for product destined for processing into bag mixes. The attendant greater damage to the tissue and the induced higher rates of respiration and water loss requires greater attention to maintaining the optimal storage conditions of temperature and RH.

Controlled Atmosphere (CA) Considerations

Lettuce, especially crisphead and fresh-cut, respond favorably to CA (Saltveit 1997a). Levels of 1 to 3% O_2 at temperatures of 0 to 5 °C (32 to 41 °F) reduce russet spotting in susceptible lots. Intact heads do not benefit from elevated CO_2, and injury—brown stain—may develop when lettuce is transferred from storage in >2% CO_2 to air at 10 °C (50 °F) (Ke and Saltveit 1989). A 2 to 5% O_2 atmosphere maintains appearance of lettuce and inhibits pink rib and butt discoloration compared to air. Brown stain is intensified when O_2 is reduced to 2 to 3%, but the effect differs by cultivar. If lettuce needs to be in transit overseas for a month, an atmosphere of 2% CO_2 and 3% O_2 is recommended because the reduction in decay achieved by 2% CO_2 outweighs the danger of injury. Romaine and leaf lettuce appear to tolerate a slightly higher CO_2 level when packaged than head lettuce. Browning is a major problem with fresh-cut lettuce, and is controlled by packaging in

<1% O_2 and 10% CO_2 (Lopez-Galvez et al. 1996, Smyth et al. 1998). The elevated level of CO_2 is more effective at reducing browning of the cut surfaces than it is at inducing brown stain.

Retail Outlet Display Considerations

Lettuce should be maintained under cold conditions to maximize storage and shelf-life. Periodic sprays of cold water minimize dehydration. Avoid storage with commodities that produce ethylene such as apples and tomatoes. All lettuces are very susceptible to water loss and to ethylene-induced disorders, and they rapidly deteriorate at elevated temperatures.

Chilling Sensitivity

Not chilling sensitive, but freezing at -0.2 °C (31.6 °F) must be avoided.

Ethylene Production and Sensitivity

Ethylene production is very low, but exposure to ethylene can result in damage such as russet spotting and leaf yellowing.

Respiration Rates

Temperature	Head lettuce	Leaf lettuce
	-------mg CO_2 kg^{-1} h^{-1}-------	
0 °C	6 to 17	19 to 27
5 °C	13 to 20	24 to 35
10 °C	21 to 40	32 to 46
15 °C	32 to 45	51 to 74
20 °C	51 to 60	82 to 120
25 °C	73 to 91	120 to 173

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Some of the more common disorders of head lettuce include tipburn, russet spotting, brown stain, and pink rib (Ryall and Lipton 1979, Saltveit 1997b). Hard heads are more susceptible to these disorders than firm lettuce. Tipburn is of field origin, but occasionally increases in severity after harvest. Leaves with tipburn have brown, often necrotic leaf margins. Russet spotting, which is caused by exposure to ethylene and its induction of the synthesis, accumulation, and oxidation of phenolic compounds at temperatures around 5 °C (41 °F), occasionally causes serious losses. Russet spots appear as dark brown, oval lesions on the midribs, and on the green leaf tissue in severe cases. It is easily controlled by making sure the storage atmosphere is free of ethylene and that the temperature is below 2 °C (36 °F).

Lettuce should not be stored with ethylene-producing commodities such as apples, cantaloupes, pears, and peaches. Storage in a low-O_2 atmosphere (1 to 8%) is very effective in controlling russet spotting. Brown stain is causedby exposure to >2.5% CO_2 and appears as large, irregularly shaped brown spots or streaks mostly on the midrib. Pink rib occurs in overmature heads stored at elevated temperatures and appears as a diffuse pink discoloration of the midrib; the cause of this disorder is unknown.

Postharvest Pathology

Bacterial soft rot, the most serious disease of lettuce, often starts on bruised leaves and results in a slimy breakdown of the tissue (Saltveit 1997b). A similar breakdown of tissue follows fungal infection by *Sclerotinia* and gray mold rot caused by *Botrytis cinerea*. Trimming and storage at 0 °C (32 °F) greatly reduce the severity of these disorders.

Quarantine Issues

None are known.

Suitability as Fresh-Cut Product

Suitability is very high, especially in salad mixes with other leafy greens.

Special Considerations

Lettuce is fragile and must be handled with care to avoid mechanical damage and to minimize discoloration and pathological problems. Temperatures must be kept low and RH high to prevent loss of turgor and wilting. Ethylene must be avoided.

Acknowledgments

Some of the information in this chapter, notably the respiration data, was taken from the University of California, Davis, website "Fresh Produce Facts" at http://postharvest.ucdavis.edu/produce_information and from the Produce Marketing Association's "Fresh Produce Manual."

References

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook 66, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Ke, D., and M.E. Saltveit. 1989. Carbon dioxide-induced brown stain development as related to phenolic metabolism in iceberg lettuce. J. Amer. Soc. Hort. Sci. 114(5):789-794.

Lopez-Galvez, G., M.E. Saltveit, and M. Cantwell. 1996. The visual quality of minimally processed lettuce stored in air or controlled atmospheres with emphasis on romaine and iceberg types. Postharv. Biol. Technol. 8:179-190.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transporation and Storage of Fruits and Vegetables, 2nd ed., vol. 1, Vegetables and Melons. AVI Pub. Co., Westport, CT.

Saltveit, M.E. 1997a. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California Davis, CA.

Saltveit, M.E. 1997b. Postharvest diseases. *In* R.M. Davis, K.V. Subbarao, R.N. Raid, and E.A. Kurtz, eds., Compendium of Lettuce Diseases, pp. 57-59. APS Press, St. Paul, MN.

Smyth, A.B., J. Song, and A.C. Cameron. 1998. Modified atmosphere packaged cut iceberg lettuce: Effect of temperature and O_2 partial pressure on respiration and quality. J. Agric. Food Chem. 46:4556-4562.

Lime

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Scientific Name and Introduction

Limes are thought to have originated in northeast India. Persian lime (also known as Bearss or Tahiti, *Citrus latifolia* Tan.) is the principal type grown in the United States. Commercial Persian lime production in the United States is now less than 2,000 ha and is limited to south Florida and southern California (Saunt 2000). Persian lime and key lime (*Citrus aurantifolia* Swing.) trees are popular in backyard settings, where they are commonly placed in large pots that are easily moved indoors during cold weather. Persian limes are seedless or nearly so, whereas key limes contain numerous seeds.

Quality Characteristics and Criteria

High-quality limes should be oval and firm with smooth peel and deep green (Persian) or green and yellow (key lime) color. Limes should be turgid and free from decay, splitting, and blemishes.

Horticultural Maturity Indices

High quality, mature limes have a juice content of 30% or higher, by volume (Arpaia and Kader 2000). U.S. consumers prefer a mature, green lime; these have a significantly longer postharvest-life than those picked when yellow. In some other countries, yellow limes are preferred because of their higher juice content (Arpaia and Kader 2000).

Grades, Sizes, and Packaging

Persian limes must attain a size of 4.76 cm (1.87 in) in diameter and a juice content of 42% by volume. There are no size requirements for key lime, but juice content must be 42% by volume (Wardowski et al. 1995). Persian limes are packed in 10-lb (4.5-kg), 20-lb (9.1-kg) , and 40-lb (18.2-kg) cartons for storage and shipping (Roy et al. 1996).

Ethylene Production

The typical rate of ethylene production is very low at <0.1 μL kg^{-1} h^{-1} at 20 °C.

Respiration Rate

Under optimal storage conditions, respiration rate of limes is <10 mg CO_2 kg^{-1} h^{-1} (Arpaia and Kader 2000).

Optimum Storage Conditions

Limes should be cooled and stored at 10 °C (50 °F) with 95% RH. Under optimal conditions, limes can be stored up to 8 weeks. CA storage can retard senescence, but commercial use is very limited.

Physiological Disorders

Stylar-end breakdown can be a significant problem with limes. Stylar-end breakdown begins as an apparent breakdown of tissues at the stylar end of the fruit. Typically the stylar end takes on a wet appearance. Large, mature fruit are more susceptible. Incidence of the disorder can be aggravated by high field heat and rough handling (Davenport and Campbell 1977, Malo and Campbell 1994). Exposing limes to temperatures below the optimum storage temperature can result in chilling injury characterized by peel pitting. Oleocellosis can develop on the peel if hand-harvest begins early in the morning or immediately after rainfall, when the peel is turgid.

Postharvest Pathology and Control

Key lime is very susceptible to stem-end rot caused by *Diplodia natalensis* and anthracnose *(Colletotricum)*. Stem-end rot caused by *D. natalensis*, *Phomopsis citri*, and *Alternaria citri* are important postharvest diseases in Persian lime. In addition, green and blue mold (*Penicillium digitatum* and *P. italicum*, respectively) can enter through wounds made during harvesting and handling and appear in storage. Careful handling to minimize mechanical damage can help reduce blue and green mold. Proper sanitation of packing line equipment and use of postharvest fungicides reduce postharvest diseases.

Quarantine Issues

Appearance of citrus canker (*Xanthomonas axonopodis* pv. citri) has restricted movement of limes grown in south Florida. Compliance with the Citrus Canker Eradication Program (Florida Department of Agriculture and Consumer Services 2000) is required to market limes from quarantined areas.

Suitability as Fresh-Cut Product

No current potential exists.

References

Arpaia, M.L., and A.A. Kader. 2000. Lime. Recommendations for Maintaining Postharvest Quality. At http://postharvest.ucdavis.edu/produce_information.

Florida Department of Agriculture and Consumer Services. 2000. Citrus Canker Eradication Program. At http://www.freshfromflorida.com/pi/canker/pdf/cankerflorida.pdf.

Davenport, T.L., and C.W. Campbell. 1977. Stylar-end breakdown in ‘Tahiti’ lime: Aggravating effects of field heat and fruit maturity. J. Amer. Soc. Hort. Sci. 102:484-486.

Malo, S.E., and C.W. Campbell. 1994. The Tahiti Lime. Fruit Crops Department Fact Sheet FC-8, IFAS, Florida Cooperative Extension Service, University of Florida, Gainesville, FL

Roy, M., C.O. Andrew, and T.H. Spreen. 1996. Persian Limes in North America: An Economic Analysis of Production and Marketing Channels. Florida Science Source, Inc., Lake Alfred, FL.

Saunt, J. 2000. Citrus Varieties of the World. Sinclair International Ltd., Norwich, England, U.K.

Wardowski, W., J. Whigham, W. Grierson, and J. Soule. 1995. Quality Tests for Florida Citrus. Bull. SP66, University of Florida Cooperative Extension Service. University of Florida, Gainesville, FL.

Litchi

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Scientific Name and Introduction

Litchi (*Litchi chinensis* Sonn.), also spelled lychee, originated in southern China where it has been cultivated for at least 2,000 years. The tree has somewhat exacting requirements that vary with cultivar for flowering, hence there is substantial year-to-year variation in supply (Nakasone and Paull 1998). The round to egg-shaped fruit, about 2.5 cm (1 in) in diameter, has a thin leathery red skin with blunt or sharp spines. The edible, translucent-opaque flesh (aril) encloses a large (occasionally small), black seed.

Quality Characteristics and Criteria

Skin color and fruit size are external quality criteria. Internal criteria are seed size and flesh sweetness and juiciness. A bright-red fruit with no browning is preferred, along with freedom from bird, insect, and mechanical damage; cracking; and decay.

Horticultural Maturity Indices

Red skin color and flesh have the optimum range of sugar-to-acid ratio for the cultivar. During litchi maturation, acid levels decline and sugar levels increase (Paull et al. 1984). Fruit do not continue to ripen after harvest.

Grades, Sizes, and Packaging

There are no U.S. or international standards. One-piece fiberboard boxes holding 2.25 kg (5 lb) or 4.5 kg (10 lb) with polyethylene film liners are used. Fruit are also packed into 0.5-pint (0.12-L) styrene containers.

Precooling Conditions

Room-cooling is used for precooling.

Optimum Storage Conditions

Storage at 2 to 5 °C (36 to 41 °F) with 90 to 95% RH should result in 3 to 5 weeks of storage life. At 20 °C (68 °F) with 60% RH, fruit will last only 3 to 5 days. Fruit need to be carefully sorted before storage to remove any damaged or decayed fruit or fruit with insect stings (Campbell 1959, Paull and Chen 1987).

Controlled Atmosphere (CA) Considerations

An atmosphere of 3 to 5% O_2 and 5% CO_2 at 5 to 7 °C (41 to 45 °F) is recommended (Kader 1994, 1998, Vilasachandran et al. 1997). Higher levels of CO_2 (10 to 15%) can lead to off flavors (Vilasachandran et al. 1997). MAP has been tried with sealed polyethylene bags either with (Ragnoi 1989) or without SO_2 pads or treatment (Scott et al. 1982, Paull and Chen 1987). Using polyethylene film bags probably prevents dehydration that leads to rapid skin browning (Akamine 1960, Paull and Chen 1987).

Retail Outlet Display Considerations

Litchi should be displayed refrigerated, preferably in polystyrene containers or plastic bags. If litchi are left directly exposed to ambient air, the skin will rapidly brown.

Chilling Sensitivity

Litchi have low sensitivity to chilling. However, dehydration during storage often leads to loss of skin color and browning and is referred to as chilling injury.

Ethylene Production and Sensitivity

Litchi have a low rate of ethylene production: <1 nL kg^{-1} h^{-1}. There are no reports on the response of this nonclimacteric fruit to ethylene exposure. Ethylene may lead to early aril deterioration.

Respiration Rates

Fruit do not continue to ripen after harvest (Joubert 1986), and respiration rate declines during storage (Akamine and Goo 1973).

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	10 to 16
10 °C	19 to 29
20 °C	46 to 74
25 °C	75 to 128

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

The major disorder is the rapid browning of the shell from a bright red color (Paull and Chen 1987, Holcroft and Mitcham 1997). The browning is associated with water loss and injury (insect stings). The browning associated with insect stings may go through to the pinkish-white inner surface of the shell. A breakdown (softening and loss of turgidity) of flesh occurs in senescent fruit after prolonged storage and overmaturity. The condition starts at the blossom end. Field and sometimes postharvest skin cracking can occur. Cracked fruit should be culled.

Postharvest Pathology

Numerous postharvest diseases can occur, but most have their origins preharvest. Good field sanitation and culling of fruit that show damage from fruit-piercing insects, cracks, and sunscorch are effective in minimizing losses (Prasad and Bilgrami 1973, Scott et al. 1982). Disease organisms include *Aspergillus* spp. (Roth 1963, Prasad and Bilgrami 1973, Scott et al. 1982), *Pestalotiopsis* spp. (Prasad and Bilgrami 1973), *Peronophythora* spp. (Ho et al. 1984), sour rot caused by *Geotrichum candidum*, and yeasty rots (Roth 1963). Other organisms found to cause rots include *Botryodiplodia theobroma*, *Colletotrichum gloesporioides*, and *Rhizopus oryzae* (Roth 1963, Prasad and Bilgrami 1973, Scott et al. 1982).

Quarantine Issues

Litchi is a fruit fly host and requires treatment before entry into the United States from fruit-fly-infected areas. Potential treatments include irradiation, heat, and cold treatments.

Suitability as Fresh-Cut Product

There are no published data. The skin and seed can be removed with little damage to the aril flesh. The aril can be placed on trays and overwrapped.

Special Considerations

Fumigation with SO_2 followed by a dip in hydrochloric acid can preserve red skin color (Paull et al. 1994). Careful application can avoid an increase in aril sulfite residues and avoid off flavors (Paull et al. 1998). Sulfites are not approved on fresh produce in the United States, except for grapes. Most other countries have sulfite residue limits for edible portions (Tongdee 1994).

References

Akamine, E.K. 1960. Preventing the darkening of fresh lichees prepared for export. Technical Progress Report 127, Hawaii Agricultural Experiment Station, Honolulu, HI.

Akamine, E.K., and T. Goo. 1973. Respiration and ethylene production during ontogeny of fruits. J. Amer. Soc. Hort. Sci. 98:381-383.

Campbell, C.W. 1959. Storage behavior of fresh 'Brewster' and 'Bengal' lychees. Proc. Florida St. Hort. Soc. 72:356-360.

Ho, H.H., J.Y. Lu, and L.Y. Gong. 1984. Observation on asexual reproduction by *Peronophythora litchii*. Mycologia 76:745-747.

Holcroft, D.M., and E.J. Mitcham. 1997. Postharvest physiology and handling of litchi (*Litchi chinesis* Sonn.). Postharv. Biol. Technol. 9:265-281.

Joubert, A.J. 1986. Litchi. *In* S.P. Monselise, ed., CRC Handbook of Fruit Set and Development, pp. 233-246. CRC Press, Boca Raton, FL.

Kader, A.A. 1994. Modified and controlled atmosphere storage of tropical fruits. *In* B.R. Champ, E. Highley, and G.I. Johnson, eds., Postharvest Handling of Tropical Fruits. International Conference on Postharvest Handling of Tropical Fruits, Chiang Mai, Thailand, July 1993, pp. 239-249. ACIAR Proceedings no. 50, ACIAR, Canberra, Australia.

Kader, A.A. 1998. Produce facts—lychee. Perishables Handling Quarterly, no. 94, University of California, Davis, CA.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K.

Paull, R.E., and J.N. Chen. 1987. Effect of storage temperature and wrapping on quality characteristics of litchi fruit. Sci. Hort. 33:223-236.

Paull, R.E., N.J. Chen, J. Deputy, et al. 1984. Litchi growth and compositional changes during fruit development. J. Amer. Soc. Hort. Sci. 109:817-821.

Paull, R.E., M.E. Reyes, and M. Reyes. 1994. Litchi and rambutan insect disinfestation: treatments to minimize induced pericarp browning. Postharv. Biol. Technol. 6:139-148.

Paull, R.E., M.E. Reyes, and M. Reyes. 1998. Sulfite residues on litchi fruit with sulfur dioxide. Postharv. Biol. Technol. 14:229-233.

Prasad, S.S., and R.S. Bilgrami. 1973. Investigations on diseases of 'Litchi.' vol. 3, Fruit rots and their control by postharvest treatments. Indian Phytopath. 26:523-527.

Roth, G. 1963. Postharvest decay of litchi fruit (*Litchi chinesis* Sonn.). Technical Communication, Department of Agricultural Technical Services, Pretoria, South Africa.

Ragnoi, S. 1989. Controlled Atmosphere Storage of Fruits and Vegetables, pp. 179. CAB International, Wallingford, U.K.

Scott, K.J., B.I. Brown, G.R. Chaplin, et al. 1982. The control of rotting and browning of litchi fruit by hot benomyl and plastic film. Sci. Hort. 16:253-262.

Tongdee, S.C. 1994. Sulfur dioxide fumigation in postharvest handling of fresh longan and lychee for export. *In* B.R. Champ, E. Highley, and G.I. Johnson, eds., Postharvest Handling of Tropical Fruits. International Conference on Postharvest Handling of Tropical Fruits, Chiang Mai, Thailand, July 1993, pp. 186-195. ACIAR Proceedings no. 50, ACIAR, Canberra, Australia.

Vilasachandran, T., S.A. Sargent, and F. Maul. 1997. Controlled atmosphere storage shows potential for maintaining postharvest quality of fresh litchi. *In* A.A. Kader, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, Abstract 54, University of California, Davis, CA.

Longan

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Scientific Name and Introduction

This small fruit (*Dimocarpus longan* [Lour.] Steud.), a relative of the litchi, is 2.5 to 3 cm (1 to 1.2 in) in diameter with a smooth, thin, yellowish-brown shell and a sweet translucent flesh (aril) surrounding a large hard nonedible seed (Nakasone and Paull 1998). The pulp comes away cleanly from the shell and seed.

Quality Characteristics and Criteria

Shell color, size, and shape; seed size; and sweetness are criteria. Fruit should be free of insect damage and skin blemishes; defective fruit are culled while being sorted for size. See Jiang et al. (2002) for further information.

Horticultural Maturity Indices

Maturity is judged by shape, skin color, and flavor of each cultivar. Most fruit can be picked from a tree with one harvest, unless multiple flowerings have occurred. No definite harvest index exists for longan, but growers usually note changes in skin appearance—mature fruit develop a smooth and relatively darker skin (Wong and Ketsa 1991).

Grades, Sizes, and Packaging

One-piece fiberboard crates are used, holding either 4.5 kg (10 lbs) or 2.25 kg (5 lbs), with plastic liners if fruit are not already packed in polystyrene containers. Fruit are clipped from the stem, as hand removal often leads to some inadvertent skin removal.

Precooling Conditions

Room or forced-air cooling is used for precooling. Longan in plastic baskets can be hydrocooled, though hydrocooled longan should not be treated with SO_2. SO_2 fumigation damages hydrocooled fruit skin by producing brown spots on both the inner and outer skin surfaces. It also results in greater SO_2 residue remaining on the fruit (Suwanagul 1992). SO_2 treatment of fruit to be sold as fresh is not approved in the United States.

Optimum Storage Conditions

The recommendation storage conditions are 4 to 7 °C (41 to 46 °F) with 90 to 95% RH (Paull and Chen 1987). Fruit can be held for 2 to 3 weeks, though the skin loses it yellowish coloration, becoming brown. At lower temperatures, there is rapid loss of eating quality, and above 10 °C (50 °F), postharvest diseases are a concern. The expected storage life of longan held at high RH (Suwanagul 1997) is—

	-----------Storage life-----------	
Temperature	Untreated	SO_2-treated
	--------------days-----------------	
0 ºC	14 to 28	21 to 42
4 ºC	14	14 to 28
10 ºC	7 to 14	14
20 ºC	3 to 5	7
30 ºC	1 to 2	3 to 5

Controlled Atmosphere (CA) Considerations

No controlled atmosphere studies have been reported, though modified atmosphere packaging in 0.03 mm (1/1000 in) polyethylene bags was tested for 7 days at room temperature, followed by 35 days at 4 °C (39 °F). A modified atmosphere of 1 to 3% O_2 delays browning and maintains SSC and vitamin C content (Zhang and Quantick 1997). Treatment with 1% O_2 results in a slight off flavor.

Retail Outlet Display Considerations

Longan should be displayed refrigerated. Misting is not recommended so as to avoid microbial growth.

Chilling Sensitivity

At storage temperatures, <5 °C (41 °F), a slight off flavor can develop after about 1 week. The peel of longan stored at 0 °C (32 °F) turns dark brown, while SO_2-fumigated longan remain yellowish-brown. The dark brown peel of longan that develops at very low temperatures is regarded as chilling injury (La-Ongsri et al. 1993).

Ethylene Production and Sensitivity

Longan fruit have a low rate of ethylene production: <1 nL kg^{-1} h^{-1}. There are no reports on ethylene sensitivity.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	3.5 to 11.3
10 °C	16.0 to 25.0
20 °C	30.0 to 53.0

Data from Liao et al. (1983).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Desiccation is a major problem that leads to a rapid loss of bright yellowish color of the skin, which turns to a dull brown (Jiang et al. 2002).

Postharvest Pathology

Longan suffers similar postharvest diseases to litchi. Fungi associated with skin browning and darkening of the skin along with mycelium include *Lasiodiplodia theobromae, Pestalotiopsis* sp., *Cladosporium* sp., *Fusarium* sp., and *Aspergillus niger* (Sardsud et al. 1994).

Quarantine Issues

Longan is a fruit fly host. Suitable treatments include hot air, vapor heat treatment, and irradiation.

Suitability as Fresh-Cut Product

Peeled, deseeded fruit aril can be used as a fresh-cut product.

Special Considerations

Longan are fumigated with SO_2 in Thailand and other countries to prevent skin browning and to control postharvest disease (Tongdee 1994). Though very effective, SO_2 fumigation is not approved for use in the United States for fruit to be sold as fresh. Asian consumers prefer longan in bunches. They assume that single fruit have fallen from the bunch because it has been dropped or that fruit are not fresh. Individual fruit may also have a higher rate of weight loss.

References

Jiang, Y.M, Z.Q. Zhang, D.C. Joyce, and S. Ketsa. 2002. Postharvest biology and handling of longan (*Dimocarpus longan* Lour.) fruit. Postharv. Biol. Technol. 26:241-252.

La-Ongsri, S., S. Gomolmanee, and O. Wara-Aswapati. 1993. Reducing chilling injury symptoms in sulfur dioxide fumigated longan fruits. *In* B.R. Champ, E. Highley, and G.I. Johnson, eds., Postharvest Handling of Tropical Fruits. International Conference on Postharvest Handling of Tropical Fruits, Chiang Mai, Thailand, July 1993, pp. 20. ACIAR Proceedings no. 50, ACIAR, Canberra, Australia.

Liao, M.L., M.S. Liu, and J.S. Yang. 1983. Respiration measurement of some important fruits in Taiwan. Acta Hort. 138:227-246.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K.

Paull, R.E., and N.J. Chen. 1987. Changes in longan and rambutan during postharvest storage. HortScience 22:1303-1304.

Sardsud, V., U. Sardsud, C. Sittigul, and T. Chaiwangsri. 1994. The effects of post-fumigation washing treatments and storage temperature on disease development in fresh longan. *In* G.I. Johnson and E. Highley, eds., Development of Postharvest Handling Technology for Tropical Tree Fruits. A Workshop Held in Bangkok, Thailand, 16-18 July 1992, pp. 77. ACIAR Proceedings no. 58, ACIAR, Canberra, Australia.

Suwanagul, A. 1997. Postharvest management of lychee and longan. *In* Proceedings of the Workshop on New Technology for Lychee and Longan Production, Chiang Mai, Thailand, pp. 105-120. Thailand Institute of Scientific and Technological Research, Bangkok, Thailand.

Tongdee, S.C. 1994. Sulfur dioxide fumigation in postharvest handling of fresh longan and lychee for export. *In* B.R. Champ, E. Highley, and G.I. Johnson, eds., Postharvest Handling of Tropical Fruits. International Conference on Postharvest Handling of Tropical Fruits, Chiang Mai, Thailand, July 1993, pp. 186-195. ACIAR Proceedings no. 50, ACIAR, Canberra, Australia.

Wong, K.C., and S. Ketsa. 1991. *Dimocarpus longan* Lour. *In* E.W.M. Verheij and R.E. Coronel, eds., Plant Resources of South-East Asia, vol. 2, Edible Fruits and Nuts, pp. 146-151. Pudoc Scientific Publishers, Wageningen, The Netherlands.

Zhang, D., and P.C. Quantick. 1997. Preliminary study on the effects of modified atmosphere packaging on postharvest storage of longan fruit. *In* A.A. Kader, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, CA, July 1997, vol. 3, pp. 90-96. University of California, Davis, CA.

Longkong

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Scientific Name and Introduction

There are at least two major types, with a number of intermediate types, of *Lansium domesticum* Jack.: langsat (Malay, Thailand), longkong (Thailand, intermediate type), and duku (Malay, Thailand). Other names include lanson (Philippines), and intermediate types are referred to as duku-langsat in Malaysia (Nakasone and Paull 1998). There is considerable inconsistency in the naming of the different types (Yaacob and Bamroongrugsa 1992). Peninsular Thailand to Borneo is the major area of cultivation. Besides the Philippines, *L. domesticum* is also cultivated in Vietnam, Burma, India, Sri Lanka, Australia, Surinam, and Puerto Rico.

Quality Characteristics and Criteria

Langsat fruit are more ovoid, roughly 30 to 60 mm (1.2 to 2.4 in) in diameter, while duku are rounder and 40 to 50 mm (1.6 to 2 in) in diameter; longkong is intermediate, nearly seedless, has a brittle skin, and is the same size as langsat. There are 15 to 25 fruit per longkong raceme and 4 to 12 in duku. The skin of young fruit is pale green and turns yellow when ripe, frequently with brown blemishes. The langsat has a thin skin that contains a milky white sticky sap. Duku has a thicker—up to 6 mm (0.25 in)—skin and no latex. Longkong has a slightly thicker skin than langsat and less sap that is not sticky. The green seed is covered by a white translucent flesh that is slightly sour in langsat. Langsat tends to vary from sweet to sour; duku is sweet. Both fruit have five separate segments with one to five seeds in langsat and one or two in duku. During ripening, astringency in the flesh declines while sugars increase six-fold (Paull et al. 1987). The skin bruises very easily, leading to brown discoloration.

Horticultural Maturity Indices

Fruit are harvested at the full ripe stage indicated by the skin color change from light to dark yellow, dryness of the sepals, and the peduncle (stem) losing most of its green color. The flesh is transparent when ripe. Fruit on the bunch generally ripen together over a very short period. Four to five harvests per tree are necessary. It is essential to harvest as soon as possible before over-ripe fruit abscise from the peduncle. Fruit to be shipped long distances are harvested when 70 to 80% ripe to avoid excessive fruit drop. Fruit should be picked when dry, as they can become moldy if packed wet.

Grades, Sizes, and Packaging

There are no U.S. or international standards. Fruit are generally graded by size and color and normally sold in single-layer fiberboard cartons holding 2.25 kg (5 lb) of fruit, with padding, or sometimes in trays with liners.

Precooling Conditions

Room cooling is used because forced-air cooling causes moisture loss.

Optimum Storage Conditions

The most recent recommendation for storage is 18 °C (46 °F) with 90% RH (Piyasaengthong et al. 1997), giving about 21 days of storage life. Previously, 11 to 14.4 °C (34 to 58 °F) with 85 to 90% RH for 2 weeks was recommended, which gave 24.3% weight loss (Pantastico 1975). Others have recommended 11 to 13 °C (52 to 55 °F) with 85 to 90% RH for 14 days (Srivastava and Mathur 1955).

Controlled Atmosphere (CA) Considerations

Fruit stored at 14 °C (58 °F) in 3% O_2 and 0% CO_2 had 16 days of postharvest life, compared to 9 days for fruit held in air (Pantastico et al. 1975). High CO_2 aggravated postharvest skin browning, especially at 10% O_2; browning can also occur in fruit held in polyethylene film bags. Holding in plastic bags (0.08 mm thickness) reduces weight loss but increases surface browning (Brown and Lizada 1984). Preliminary recommendations are 5% O_2 and 0% CO_2 (Yahia 1998).

Retail Outlet Display Considerations

Fruit are commonly displayed in overwrapped trays or closed styrene clam shell containers with no holes at 15 °C (59 °F). They should not be misted.

Chilling Sensitivity

Chilling leads to skin browning; at 15 °C symptoms develop after 21 days (Piyasaengthong et al. 1997).

Ethylene Production and Sensitivity

Fruit produce low amounts of ethylene, with internal concentrations of 2 to 6 µL kg^{-1}. There are no reported responses to ethylene treatment; it may lead to premature senescence.

Respiration Rates

Respiration rates decline after harvest, and small fruit have a higher rate than large fruit (Srivastana and Mathur 1955, Pantastico et al. 1968).

Temperature	mg CO_2 kg^{-1} h^{-1}
9 °C	40 to 50
20 °C	50 to 90

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Abrasion and impact injury, water loss, and chilling injury are the three major disorders. Mechanical injury (abrasion, impact, and compression) leads to skin darkening and browning. Chilling injury symptoms are pitting and brown scalding of the skin.

Postharvest Pathology

Anthracnose, aspergillus, and rhizopus surface rots on the skin have been reported. Packing dry fruit and using fungicides can minimize losses.

Quarantine Issues

Longkong is a fruit fly host; irradiation at 300 grays has potential for disinfestation.

Suitability as Fresh-Cut Product

No current potential.

References

Brown, B.I., and M.C.C. Lizada. 1985. Modified atmospheres and deterioration of lanzones (*Lansium domesticum* Correa.). Postharvest Research Notes 1(2):36.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K.

Pantastico, E.B. 1975. Postharvest Physiology, Handling and Utilization of Tropical and Subtropical Fruits and Vegetables. AVI Pub. Co., Westport, CT.

Pantastico, E.B., D.B. Mendoza, and R.M. Abilay. 1968. Some chemical and physiological changes during storage of lanzones (*Lansium domesticum* Correa.). The Philippines Agriculturist 52:505-517.

Paull, R.E., T. Goo, and N.J. Chen. 1987. Growth and compositional changes during development of lanzone fruit. HortScience 22:1252-1253.

Piyasaengthong, Y., S. Suanpairoj, P. Pakamat, and C. Ruensamran. 1997. The optimum for storaging longkong (*Aglaia dookoo* Griff). *In* 35th Kasetsart University Conference, Bangkok, Thailand. (English summary.)

Srivastana, H.C., and P.B. Mathur. 1955. Studies in the cold storage of langsat. J. Sci. Food Agric. 6:511-513.

Yaacob, O., and N. Bamroongrugsa. 1992. *Lansium domesticum* Correa. *In* E.Verheij and R.E. Coronel, eds., Plant Resources of South-East Asia, vol. 2, Edible Fruits and Nuts. Pudoc Scientific Publishers, Wageningen, The Netherlands.

Yahia, E. 1998. Modified and controlled atmospheres for tropical fruits. Hort. Rev. 22:123-183.

Loquat

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Scientific Name and Introduction

Loquat (*Eriobotrya japonica* L.) belongs to the rose family and is a subtropical evergreen fruit tree. Fruits grow in loose clusters and are round or oval, weighing about 20 to 80 g (0.7 to 2.8 oz). Fruit have a thin but tough skin. Ripe fruit flesh is soft and juicy, varying in color from white to deep orange. Loquat originated in midwestern China and is widely cultivated in the subtropical regions of southern China, Japan, Israel, and the Mediterranean area. In the United States, loquats grow in Hawaii, California, and the Gulf States.

Quality Characteristics and Criteria

High-quality loquat have SSC >12%, moderate TA (0.3 to 0.6%), and low flesh firmness. Loquat cultivars have a rapid rate of fruit softening.

Horticultural Maturity Indices

The quality of loquats is highly dependent on the degree of ripening. Loquats harvested at the fully ripe stage have optimum quality. However, in commercial situations where transport and shelf-life are involved, loquats are generally harvested at the eating-ripe stage before becoming fully ripe. In most cultivars, harvest date is determined by skin color changes described for each cultivar.

Grades, Sizes, and Packaging

Size grades of the cultivar ‘Tanaka’ are large, >60 g (2.1 oz); medium, 50 to 59 g (1.9 oz); small, 40 to 49 g (1.6 oz); and SS, 30 to 39 g (1.2 oz). Packages commonly employ soft materials because of the fruit’s susceptibility to bruising.

Precooling Conditions

In order to maintain quality and storage life, loquat should be precooled to <5 °C (41 °F) within 20 h of harvest (Shinbori and Nakai 1991).

Optimum Storage Conditions

Recommended conditions for commercial storage are 0 to 5 °C (32 to 41 °F) with >90% RH. Loquat fruit can be kept in good condition for 3 to 4 weeks at 0 °C (32 °F) and 2 weeks at 10 °C (50 °F) (Guelfat-Reich 1970, Ding et al. 1998). Use of polyethylene bags retards weight loss and minimizes decreases in organic acids (Ding et al. 1997).

Controlled Atmosphere (CA) Conditions

No information is available.

Retail Outlet Display Considerations

A refrigerated shelf at 5 to 12 °C (41 to 54 ºF) is good.

Chilling Sensitivity

Loquat fruit are not sensitive to chilling.

Ethylene Production and Sensitivity

Loquat fruit produce relatively low amounts of ethylene and are not particularly sensitive to ethylene exposure after harvest.

Respiration Rates

Respiration rates of loquat are influenced by temperature and decrease rapidly over the first 4 days of storage. By the fourth day of storage, respiration rates of stored fruit were—

Temperature	mg CO_2 kg^{-1} h^{-1}
1 °C	11.2
5 °C	12.4
10 °C	30.6
20 °C	80.0

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Fruit are easily bruised and scratched, and the damaged areas usually turn brown or black, so careful handling and packaging during and after harvest are important. Also, internal browning and brown surface spotting occur during long-term or high-CO_2 storage (Ding et al. 1999).

Postharvest Pathology

Cooling fruit and holding them at <5 °C (41 °F) are effective at controlling spoilage.

Quarantine Issues

None are known.

Suitability as Fresh-Cut Product

No current potential exists.

Special Considerations

Loquats must be handled with care to avoid mechanical damage, and low-temperature storage is essential for extending postharvest life.

References

Ding, C.-K., K. Chachin, Y. Hamauzu, et al. 1998. Effects of storage temperatures on physiology and quality of loquat fruit. Postharv. Biol. Technol. 14:309-315.

Ding, C.-K., K. Chachin, and Y. Ueda. 1997. Effects of polyethylene bag packing and low-temperature storage on physical and chemical characteristics of loquat fruit. *In* A.A. Kader, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 3, pp. 177-184. University of California, Davis, CA.

Ding, C.-K., K. Chachin, Y. Ueda, et al. 1999. Effects of high CO_2 concentration on browning injury and phenolic metabolism in loquat fruits. J. Jap. Soc. Hort. Sci. 68:275-282.

Guelfat-Reich, S. 1970. Storage of loquat *(Eriobotrya japonica).* Fruits 250(3):169-173.

Shinbori, F., and S. Nakai. 1991. Qualitative changes during maturation and keeping qualities of loquats fruits. J. Jap. Soc. Hort. Sci. 60(Suppl. 2):590-591.

Luffa

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Specific Name and Introduction

There are two main species of cultivated luffa (loofah). Angled luffa or Chinese okra *(Luffa acutangula),* a green, immature fruit with longitudinal ridges, is consumed like summer squash. Smooth luffa or sponge gourd (*Luffa aegyptiaca* Mill) is sometimes eaten as a vegetable, but mature fruit are mainly used to make sponges for cosmetics and cleaning (Ellington and Wehner 1996). Both are members of the Cucurbitaceae family.

Quality Characteristics and Criteria

Edible fruit are harvested while immature. If angled luffa are left to mature, blossom-end enlarges, stem-end shrinks, and bitter flavor develops (Zong et al. 1993). Quality loss is most often associated with loss of green color.

Grades, Sizes, and Packaging

There are no U.S. grades for luffa.

Horticultural Maturity Indices

Luffa are harvested immature and selected based on size.

Optimum Storage Conditions

Angled luffa can be stored for up to 2 weeks at 10 to 12 °C (50 to 54 °F) with 90 to 95% RH (Zong et al. 1992, 1993, Cantwell 1997).

Controlled Atmosphere (CA) Considerations

There is no published information on CA for luffa.

Retail Outlet Display Considerations

Top-icing is not acceptable due to luffa's chilling sensitivity. Water sprays are acceptable.

Chilling Sensitivity

Fruit are sensitive to chilling at <10 °C (50 °F) (Zong et al. 1993). Symptoms include skin discoloration, watery lesions under the skin, and enhanced decay.

Ethylene Production and Sensitivity

Angled luffa produce very low levels of ethylene: <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F). However, luffa is sensitive to ethylene during postharvest handling, which results in a loss of green color and reduced quality (Zong et al. 1993).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	14
5 °C	27
10 °C	36
15 °C	63
20 °C	79

Data from Zong et al. (1992, 1993).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Luffas should be handled with care; damage to longitudinal ribs leads to water loss and decay. Fruit are susceptible to dehydration and toughening of the peel.

Postharvest Pathology

No specific information is available.

Quarantine Issues

None are known.

Suitability as Fresh-Cut Product

No current potential exists.

Special Considerations

Care must be taken with selection of the correct immature stage; damage to the ribs must be carefully controlled as it leads to water loss and decay.

References

Cantwell, M. 1997. Properties and recommended conditions for storage of fresh fruits and vegetables. At http://postharvest.ucdavis.edu/produce_information.

Ellington, T.L., and T.C. Wehner. 1996. Postharvest treatments for producing sponges from immature fruits of luffa gourds. Cucurbit Genet. Coop. Rpt. 19:85-86.

Zong, R., M.I. Cantwell, and L.L. Morris. 1993. Postharvest handling of Asian specialty vegetables under study. Calif. Agric. 47(2):27-29.

Zong, R., M.I. Cantwell, L.L. Morris, and V. Rubatzky. 1992. Postharvest studies on four fruit-type Chinese vegetables. Acta Hort. 318:345-354.

Mandarin (Tangerine)

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Scientific Name and Introduction

Mandarin originated in China and southeast Asia. The names “tangerine” and “mandarin” have often been used synonymously. The term “tangerine” was first used in the 19th century to describe mandarins with deep orange-red external color. The mandarin/tangerine citrus group is very diverse, and attempts have been made to assign members into different categories and species. *Citrus unshiu* (satsuma), *C. deliciosa* (Mediterranean mandarin), *C. nobilis* (king mandarin) and *C. reticulata* (common mandarin) are known worldwide, but only *C. reticulata* and associated hybrids are of economic importance in the United States (Saunt 2000). ‘Dancy,’ ‘Fallglo,’ ‘Robinson,’ ‘Sunburst,’ and ‘Clemantine’ are popular varieties in the United States. Mandarin-like varieties, either tangors (mandarin × orange hybrids) such as ‘Temple’ and ‘Murcott’ or tangelos (mandarin × grapefruit hybrids) such as ‘Minneola’ and ‘Orlando,’ are also grown.

Quality Characteristics and Criteria

High-quality mandarin have a turgid, deep orange-red peel relatively free of blemishes. The fruit should be elliptical and firm. The peel should be easily removed from the flesh. The edible portion should be juicy and contain few or no seeds.

Horticultural Maturity Indices

Maturity standards require that mandarin have a set minimum SSC:TA ratio and have at least 50% peel surface color break.

Grades, Sizes, and Packing

Mandarin are packed in 4/5-bushel cartons for shipping and storage. Marketable mandarin range from size 56 (56 fruit per carton) to size 210 (210 fruit per carton).

Optimum Storage Conditions

Mandarin are stored at 5 to 8 °C (41 to 46 °F) with 95% RH for periods up to 4 weeks. Chilling injury can occur in storage if temperatures fall below 5 °C (41 °F). Storage duration depends on variety, maturity, and decay control. Thiabendazole (TBZ) can be incorporated into fruit coatings and used to control postharvest decays during storage.

Ethylene Production and Sensitivity

Mandarin are nonclimacteric and do not exhibit a rise in respiration and ethylene associated with ripening. Ethylene production is typically <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F).

Respiration Rates

Respiration rates at optimum storage temperatures are generally <10 mg CO_2 kg^{-1} h^{-1} (Arpaia and Kader 2000).

Temperature	mg CO_2 kg^{-1} h^{-1}
5 ºC	4 to 8
10 ºC	6 to 10
15 ºC	12 to 20
20 ºC	20 to 30

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Degreening

Some mandarin-growing areas, such as Florida, have persistent high temperatures that prevent natural color break in the peel. In these cases, ethylene is used to degreen (cause the destruction of chlorophyll) early-season mandarin. Ethylene is used at 1 to 5 µL L^{-1} at 28 to 29 °C (82 to 84 °F) with 95% RH. Duration of ethylene exposure ranges from 12 h to 3 days. One complete air change per hour should enter the degreening room to avoid buildup of CO_2, which can inhibit ethylene action, and to assist in uniform temperature and ethylene distribution (Wardowski 1996).

Physiological Disorders

Mandarin have thin peels that are readily injured under conditions that promote high peel-water content. Excessive soil moisture before harvest predisposes mandarin to zebra-skin. Normal handling on packing-line machinery causes peel epidermal cells to rupture in areas over the fruit segment. Zebra-skin can be exacerbated by degreening. Oleocellosis can occur on the peel when excessive squeezing force is used to harvest fruit by hand. Cells encircling oil glands die when oil from ruptured glands leak into the surrounding tissues. Generally fruit are more susceptible to oleocellosis when peel turgidity is high. Puffiness is characterized by separation of the peel from the pulp on the tree or in storage. Fruit of advancing maturity appear to be most susceptible to puffiness.

Stem-end rind breakdown, SERB, is characterized by collapse and sinking of the peel in irregularly shaped regions near the stem end. SERB is closely associated with excessive water loss. Late-season mandarin are most susceptible to SERB. Chilling injury is characterized by peel pitting followed by increased susceptibility to postharvest decay. Severity of chilling injury increases with temperatures below 5 °C (41 °F) and longer durations. Mandarin are susceptible to granulation, or section-drying. Susceptibility is influenced by variety and overmaturation (Grierson 1986).

Postharvest Pathology

Stem-end rot (Diplodia natalensis and *Phomopsis citri)* is a significant problem on mandarin, especially where degreening is required in early season fruit. Stem-end rots develop as latent infections on the fruit button (calyx and disc) before harvest and begin to grow through the core after harvest. Decay develops unevenly at the stem and stylar ends, resulting in uneven margins.

Anthracnose, caused by *Colletotrichum gloesporiodes*, is a major decay of mandarin. Characterized by brown peel lesions, anthracnose appears on early-season mandarin that have undergone lengthy degreening periods.

Brown rot (Phytophthora citrophthora) develops from infections that take place in the grove before harvest. Brown rot has a characteristic rancid odor and is characterized by tan lesions that quickly overtake the entire fruit under optimum conditions.

Green and blue mold (*Penicillium digitatum* and *P. italicum*, respectively) develop on mandarin as a result of wounds made during harvesting and handling (Eckert and Brown 1986, Whiteside et al. 1988).

Drenching harvested mandarins with TBZ before they arrive at the packinghouse is recommended for controlling *Diplodia, Phomopsis,* anthracnose, and *Penicillium*. Application of aqueous imazalil or TBZ in the coating treatment aids in control. Minimizing degreening time by delaying harvest will assist in controlling stem-end rot caused by *Diplodia* and anthracnose. Brown rot is most effectively controlled by preharvest treatment with copper-containing fungicides. Careful harvesting and handling can reduce injuries that allow entrance of wound pathogens such as *Penicillium*. Good sanitation of packinghouse equipment and storage areas will help control the spread of postharvest pathogens.

Quarantine Issues

The appearance of citrus canker *(Xanthomonas axonopodis* pv. *citri)* has restricted movement of mandarin grown in affected areas in Florida. Compliance with the Citrus Canker Eradication Program (Florida Department of Agriculture and Consumer Services 2000) is required for harvesting, packing, and shipping mandarin from quarantined areas to domestic markets.

Cold treatment is an approved quarantine treatment for citrus grown in areas infested with tropical fruit flies. In Florida, the Caribbean fruit fly *(Anastrepha suspensa)* may be found in citrus groves during late spring and summer. Cold treatment involves storage of fruit below 2 ºC (36 °F) for specified periods to ensure their freedom from fly infestation. However, because of susceptibility to chilling injury, fruit may be stored at higher temperatures of 10 to 15 °C (50 to 59 °F) for about 1 week prior to cold treatment to increase resistance to chilling injury.

Suitability as Fresh-Cut Product

Some potential exists for separated segments.

References

Arpaia, M.L., and A.A. Kader. 2000. Mandarin/ Tangerine. Recommendations for maintaining postharvest quality. University of California, Davis, CA. At http://postharvest.ucdavis.edu/ produce_information.

Florida Department of Agriculture and Consumer Services. 2000. Citrus Canker Eradication Program. At http://www.freshfromflorida.com/pi/ canker/pdf/cankerflorida.pdf.

Eckert, J.W., and G.E Brown. 1986. Postharvest diseases and their control. *In* W.F. Wardowski, S. Nagy, and W. Grierson, eds., Fresh Citrus Fruits, pp. 315-360. AVI, Westport, CT.

Grierson, W. 1986. Physiological disorders. *In* W.F. Wardowski, S. Nagy, and W. Grierson, eds., Fresh Citrus Fruits, pp. 361-378. AVI, Westport, CT.

Saunt, J. 2000. Citrus Varieties of the World. Sinclair International, Norwich, England.

Wardowski, W.F. 1996. Recommendations for degreening Florida fresh citrus fruit. Circular 1170, University of Florida, Institute of Food and Agricultural Science, Gainesville, FL.

Whiteside, J.O., S.M. Garnsey, and L.W. Timmer, eds. 1988. Compendium of Citrus Diseases. APS Press, St. Paul, MN.

Mango

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Scientific Name and Introduction

Mango (*Mangifera indica* L.) is cultivated throughout the tropics and warmer subtropics. Of the numerous varieties, Florida's 'Tommy Atkins,' 'Kent,' 'Keitt,' and 'Haden' are the most common in the United States. The fruit's skin is yellow or green with a golden to red blush, depending on the variety. Fruit can be round, oval, or kidney shaped. Some varieties have a turpentine-like smell and taste.

Quality Characteristics and Criteria

Skin coloration, size, appropriate shape for the variety, appearance, freedom from defects and decay, absence of fiber in the flesh, and a turpentine-like flavor are the most common quality parameters. Wilted, grayish discoloration and pitting are undesirable. Some fruit varieties ('Haden') have pinhead-sized black spotting that is not regarded as a defect.

Horticultural Maturity Indices

The general criteria for maturity of most cultivars of mango are (1) the fruit "shoulders" have risen above the stem-end and (2) there is a slight skin color break on the first fruit of a crop. Early fruit from a single flowering should only be harvested after a slight skin color change; 2 weeks later all full-sized fruit can be harvested, even if there is no apparent change in skin color. Other indices include SSC and TA, specific gravity, and days from blooming. These indices depend on cultivar and season (Hatton et al. 1965, Kanes et al. 1982).

Grades, Sizes, and Packaging

There are no U.S. or international grade standards. Fruit are sold in 16-kg (35-lb) cartons as well as 6-kg (14-lb) flat single-layer cartons and 4.5-kg (10-lb) single-piece fiberboard boxes with various counts.

Precooling Conditions

Fruit are normally forced-air cooled or room-cooled, preferably within 24 h of harvest (Mattern et al. 1972).

Optimum Storage Conditions

Storage at 10 to 13 °C (50 to 55 °F) with 85 to 90% RH should give a shelf-life of 14 to 28 days for mature green fruit, depending on variety. Ripe fruit can be stored at 7 to 8 °C (45 to 46 °F). Diseases are the principal factor limiting storage life. Optimum ripening temperature is 20 to 23 °C (68 to 73 °F) for best appearance, palatability, and decay control (Jobin-Decor 1988).

Controlled Atmosphere (CA) Considerations

Different cultivars show various responses to CA. The optimum storage atmosphere for prolonging storage and shipping is 3 to 5% O_2 and 5 to 10% CO_2 at 7 to 9 °C (45 to 48 °F) with 90% RH (Yahia 1998). Ripening delays are minor and may not be economic in all situations. Polyethylene or other film bags, with and without an ethylene-absorber, give some delay in ripening. However, some film bags can also result in off flavor and abnormal skin coloration.

Retail Outlet Display Considerations

Mangoes can be displayed at store temperature and should not be misted. Bruised and diseased fruit should be removed from display.

Chilling Sensitivity

Chilling susceptibility varies with cultivar; 'Haden' and 'Keitt' are particularly susceptible. Most cultivars show injury below 10 °C (50 °F), especially if fruit have just reached maturity. Tolerance to chilling increases during ripening (Medlicott et al. 1990). The symptoms include grayish, scaldlike discoloration on the skin, followed by pitting, uneven ripening, and poor flavor and color development (Hatton et al. 1965, Medlicott et al. 1990). Heat treatment prior to storage reduces injury in 'Keitt' (McCollum et al. 1993).

Ethylene Production and Sensitivity

Mangoes have moderate ethylene production: 1 to 2 µL kg^{-1} h^{-1} at 20 °C (68 °F). Ethylene induces faster and more uniform softening (Lakshminarayana 1973, Barmore 1974). Ethylene treatment can be done prior to shipping (Barmore and Mitchell 1977). There is disagreement in the literature regarding effect of ethylene treatment on quality (Chaplin 1988). This may relate to maturity when treated. Treatment of immature fruit leads to softening, but the fruit have poor flavor.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
4.5 °C	10 to 22
10 °C	23 to 46
15 °C	45 to 90
20 °C	75 to 151

Data from Karmarkar and Joshi (1941) and Lam (1987).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Heating for insect disinfestation elevates respiration 3- to 5-fold; after cooling, rates remain higher than those of unheated fruit for 4 to 6 days (Mitcham and McDonald 1993).

Physiological Disorders

Some disorders, such as chilling injury and high CO_2 injury, are induced after harvest, while others are inherent. Inherent disorders occur intermittently and are unpredictable; for example, jelly seed, which results in watery, translucent tissue around the seed giving an over-ripe appearance. It does not develop after harvest unless it was present at harvest (Young and Miner 1961). Some cultivars are very susceptible, such as 'Tommy Atkins' (Lelyveld and Smith 1979). Soft nose and internal breakdown (or spongy tissue) are other disorders (Lim and Khoo 1985), though it is possible these are the same condition. Sap burn is a major problem with some cultivars (O'Hare 1994), such as 'Kensington,' while 'Irvin' is less susceptible (Loney et al. 1992); washing with water and detergent helps avoid damage (Brown et al. 1986).

Postharvest Pathology

Anthracnose *(Colletotrichum gloesporioides)*, which is caused by preharvest infection and does not spread postharvest, and the postharvest stem-end rots caused by several fungi that infect before and after harvest (often as wound invaders that spread postharvest) are the two most common diseases (Johnson and Coates 1993). Anthracnose appears as fruit ripen and first appears as superficial black spots and streaks that then become sunken (Fitzell and Peak 1984).

Alternaria rot *(Alternaria alternata)*, a preharvest infection, can sometimes be a problem, while the postharvest wound infections can occasionally be severe, such as black mold (*Aspergillus* spp.) and transit rot (*Rhizopus* spp.). Disease control begins in the field followed by postharvest sanitation, as well as avoidance of latex burn (stain) and mechanical injury. Hot-water treatment (46 °C for 60 to 120 min) and fungicides can be used, depending on the cultivar (Spalding and Reeder

1986). Hot-water brushing at 55 °C (131 ºF) for 20 s shows good control (Prusky et al. 1999).

Quarantine Issues

As a fruit fly host, mango must be treated prior to import into the United States. Hot water at 47 °C (116 °F) for 65 to 90 min, vapor heat with fruit core temperature of 46 to 48 °C (115 to 118 °F), and irradiation (300 grays) are potential treatments.

Suitability as Fresh-Cut Product

Fresh-cut pieces and slices are frequently found in markets. Browning of the flesh can be a problem.

References

Barmore, C.R. 1974. Ripening mangoes with ethylene and ethephon. Proc. Florida St. Hort. Soc. 87:331-334.

Barmore, C.R., and E.F. Mitchell. 1977. Ethylene pre-ripening of mangoes prior to shipment. Citrus Industry 58:18-19, 22-23.

Brown, B.I., I.A. Wells, and C.F. Murray. 1986. Factors affecting the incidence and severity of mango sap-burn and its control. ASEAN Food J. 2:127-132.

Chaplin, G.R. 1988. Advances in postharvest physiology of mango. Acta Hort. 231:639-648.

Fitzell, R.D., and C.M. Peak. 1984. The epidemiology of anthracnose disease of mango: inoculum sources, spore production and disposal. Ann. Appl. Biol. 104:53-59.

Hatton, T.T. Jr., W.F. Reeder, and C.W. Campbell. 1965. Ripening and Storage of Florida Mangos. Marketing Research Report 725, U.S. Department of Agriculture, Washington, DC.

Jobin-Decor, M.P. 1988. Mango ripening guide. Queensland Agric. J. 114:369-371.

Johnson, G.I., and L.M. Coates. 1993. Postharvest diseases of mango. Postharv. News Info. 4:27n-34n.

Kanes, O., M. Boulet, and F. Costaigne. 1982. Effect of chilling-injury on texture and fungal rot of mangoes (*Mangifera indica* L.). J. Food Sci. 47:992-995.

Karmarkar, D.V., and B.M. Joshi. 1941. Respiration studies of the alphonse mango. Ind. J. Agric. Sci. 11:993-1005.

Lakshminarayana, S. 1973. Respiration and ripening patterns in the life cycle of the mango fruit. J. Hort. Sci. 48:227-233.

Lelyveld, L.J. van, and J.H.E. Smith. 1979. Physiological factors in the maturation and ripening of mango (*Mangifera indica* L.) fruit in relation to the jelly seed physiological disorder. J. Hort. Sci. 54:283-287.

Lam, P.F. 1987. Respiration rates and ethylene production of ripening Harumanis mangoes after different chilling storage periods. MARDI Res. Bull. 95:15-19.

Lim, T.K., and K.C. Khoo. 1985. Diseases and Disorders of Mango in Malaysia. Tropical Press, Kuala Lumpur, Maylasia.

Loney, B.R., S.P. Robinson, J.J. Brophy, and E.K. Chacko. 1992. Mango sap-burn, components of the fruit sap and their role in causing skin damage. Austral. J. Plant Physiol. 19:449-457.

Mattern, F., W. Pennock, and L.S. Valles. 1972. Supplying the New York market with high quality Puerto Rican mangoes. J. Agric. Univ. Puerto Rico 56:1-10.

McCollum, T.G., S. D’Aquino, and R.E. McDonald. 1993. Heat treatment inhibits mango chilling injury. HortScience 28:197-198.

Medlicott, A.P., J.M.M. Sigrist, and O. Sy. 1990. Ripening of mangoes following low temperature storage. J. Amer. Soc. Hort. Sci. 115:430-434.

Mitcham, E.T., and R.E. McDonald. 1993. Respiration rate, internal atmosphere and ethanol and acetaldehyde accumulation in heat-treated mango fruit. Postharv. Biol. Technol. 3:77-86.

O'Hare, T.J. 1994. The susceptibility of Thai and Australian mango cultivars to sap injury and possible means of control. *In* G.I. Johnson and E. Highley, eds., Development of Postharvest Handling Technology for Tropical Tree Fruits, pp. 21-24. Australian Centre for International Agricultural Research Proceedings 58, ACIAR, Canberra, Australia.

Prusky, D., Y. Fuchs, I. Kobiler, et al. 1999. Effects of hot water brushing, prochloraz treatment and waxing on the incidence of black spot decay caused by *Alternaria alternata* on mango fruits. Postharv. Biol. Technol. 15:165-174.

Spalding, D.H., and W.F. Reeder. 1986. Decay and acceptability of mangoes treated with combination of hot water, imazalil and γ-radiation. Plant Dis. 70:1149-1150.

Yahia, E.M. 1998. Modified and controlled atmospheres for tropical fruits. Hort. Rev. 22:123-183.

Young, T.W., and J.T. Miner. 1961. Relationship of nitrogen and calcium to 'soft-nose' disorder in mango fruits. J. Amer. Soc. Hort. Sci. 78:201-208.

Mangosteen

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Scientific Name and Introduction

Mangosteen (*Garcinia mangostana* L.) is one of the most praised of tropical fruit. It is also known as mangostanier, mangoustanier, mangouste, mangostier (French), mangostan (Spanish), manggis, mesetor, semetah, sementah (Malaysian), manggustan, mangis, mangostan (Philippine), mongkhut (Cambodian), mangkhut (Thai), cay mang cut (Vietnamese), manggis, manggistan (Dutch), and mangostao, mangosta, or mangusta (Portuguese) (Nakasone and Paull 1998).

The globe-shaped, smooth berry is 4 to 7 cm (1.6 to 2.8 in) across and has a persistent calyx. The pericarp is 6 to 10 mm (0.24 to 0.4 in) thick and turns purple during ripening. It contains a bitter, yellowish latex and purple-staining juice. The edible white aril has 4 to 8 segments with 1 or 2 larger segments containing apomictic seeds; there is no true seed.

Quality Characteristics and Criteria

Fruit have pinkish-red skin when mature, turning to a dark purple skin and white flesh. The skin should be thick and soft, but firm, when ripe. Fruit have a soft, sweet, slightly acid flesh with a pleasant flavor. Misshapen and damaged fruit should be removed. Burst latex vessels leave a yellow dried latex on the skin that should be scraped off, followed by washing the fruit with a soft brush. Fruit are graded to remove damaged fruit and for size. Some Thai growers and exporters coat cleaned fruit with lacquer, giving fruit skin damaged by thrips prior to harvest a more attractive appearance.

Horticultural Maturity Indices

Skin color is the major criterion used to judge maturity. Immature fruit that have a light, greenish-yellow skin with scattered pinkish spots do not ripen to full flavor if harvested. The minimum harvest stage for high quality fruit is when the skin has distinct irregular, pink-red spots over the whole surface. Fruit are at the edible, ripe stage when the skin has darkened to reddish-purple, no latex remains in the skin, and the flesh segments separate easily from the skin (Tongdee and Suwanagal 1989). Careful handling is essential in order to avoid mechanical injury.

Grades, Sizes, and Packaging

There are no U.S. or international standards. Fruit are graded by size and color. Mangosteens are normally sold in single-layer, fiberboard cartons holding 2.25 kg (5 lb) with padding, or sometimes in trays with fruit individually wrapped to prevent injury (20 to 24 fruit per tray). In Southeast Asia, fruit are sold in baskets or strung in bundles of 10 to 25 fruit.

Precooling Conditions

Room-cooling is normally used (Augustin and Azudin 1986).

Optimum Storage Conditions

Recommendations vary from 4 to 6 °C (39 to 42 °F) with 85 to 90% RH for 7 weeks (Pantastico 1975) to 13 °C (56 °F) with 85 to 90% RH for 14 to 25 days. Storage at 4 °C (39 °F) or 8 °C (46 °F) can lead to significant hardening of the skin (Augustin and Azudin 1986), though the flesh may still be acceptable after 44 days. Current practice is to store fruit at 12 to 14 °C (54 to 57 °F), giving storage life of about 20 days without chilling injury. Application of surface coatings reduces weight loss and prevents calyx wilting (Choehom 1997).

Controlled Atmosphere (CA) Considerations

An atmosphere of 5% O_2 and 5% CO_2 has been used for 1 mo (Yahia 1998) and resulted in best overall retention of peel appearance and internal quality (Rattanachinnakorn et al. 1996). Holding fruit in polyethylene film bags reduces weight loss and disease (Daryono and Sabari 1986); however, it is not clear if the effects are due to the prevention of water loss or to the modified atmosphere in the bags.

Retail Outlet Display Considerations

Fruit are commonly displayed in overwrapped trays or in closed styrene, clam-shell containers with no perforations at 10 to 14 °C (50 to 57 °F). They should not be misted.

Chilling Sensitivity

Storage at <10 °C (50 °F) leads to rapid hardening and darkening of pericarp when fruit are returned to ambient temperature (Uthairatanakij and Ketsa 1996, Choehom 1997).

Ethylene Production and Sensitivity

Mangosteen is a climacteric fruit. Ethylene production is about 29 nL kg^{-1} h^{-1}. The respiratory peak occurs sooner when fruit are treated with ethylene. Ethylene treatment triggers autocatalytic ethylene production (Noichinda 1992).

Respiration Rates

Respiration rate is 21 mg (12 µL) CO_2 kg^{-1} h^{-1} at 25 °C. Heat production is 4,620 BTU ton^{-1} day^{-1} (1,281 kcal $tonne^{-1}$ day^{-1}).

Physiological Disorders

Fruit damage during harvesting and marketing can affect >20% of fruit. The "gamboges" disorder occurs where latex seeps into the flesh (aril), turning it yellow and giving it a bitter taste. "Gamboges" also moves onto the outer surface of the fruit. This is a preharvest disorder of unknown cause that makes it difficult to separate the aril from the surrounding tissue, even in ripe fruit; it causes hardening of the pericarp. This should not be confused with impact injury that leads to hardening of the pericarp at the point of impact and aril collapse, dehydration, pink color development, or browning (Tongdee and Suwanagul 1989). A drop of 10 cm can cause slight pericarp damage, indicated as hardening at the point of impact within 24 h. Higher drops causing significantly greater damage often lead to downgrading of the fruit (Tongdee and Suwanagul 1989, Ketsa and Atantee 1998).

Another disorder of mangosteen fruit is translucent aril *(nue-kaew)*, believed to be induced by heavy rain during fruit growth and development, even if just before harvest (Laywisakul 1994). The specific gravity of fruit with translucent aril is >1.0, while that of normal aril is <1.0. This allows separation of fruit by floating them in water (Podee 1998). Fruit with translucent aril have lower SSC and TA than normal fruit (Pankasemsuk et al. 1996).

Postharvest Pathology

Botryodiplodia theobromae, *Diplodia* spp., *Pestalotia flagisettula, Phomopsis* spp., and *Rhizopus* spp. have been reported; they harden the skin and decay the aril.

Quarantine Issues

Mangosteen is a fruit fly host. Irradiation at 300 grays has potential for disinfestation. Alternatively, harvested fruit are carefully cut open and the aril inspected; fruit are then frozen whole and shipped.

Suitability as Fresh-Cut Product

Some potential exists.

References

Augustin, M.A., and M.N. Azudin. 1986. Storage of mangosteen (*Garcinia mangostana*, L.). ASEAN Food J. 2:78-80.

Choehom, R. 1997. Effect of waxing and plant growth regulators on quality and storage-life of mangosteen (*Garcinia mangostana* L.) fruit during cold storage. Graduate Special Problem, Department of Horticulture, Kasetsart University, Bangkok, Thailand.

Daryono, M., and S. Sabari. 1986. The practical method of harvest time on mangosteen fruit and its characteristics in storage. Bull. Penelitian Hort. Indonesia 14(2):38-44.

Ketsa, S., and S. Atantee. 1998. Phenolics, lignin, peroxidase activity and increased firmness of damaged pericarp of mangosteen fruit after impact. Postharv. Biol. Technol. 14:117-124.

Laywisakul, S. 1994. Factors Influencing the Development of Translucent Disorder in Mangosteen. M.S. thesis, Kasetsart University, Bangkok, Thailand.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K.

Noichinda, S. 1992. Effect of Modified Atmosphere on Quality and Storage-Life of Mangosteen (*Garcinia mangostana* L.) Fruit. M.S. thesis, Kasetsart University, Bangkok, Thailand.

Pankasemsuk, T., J.O. Garner Jr., F.B. Matta, and J.L. Silver. 1996. Translucent flesh disorder of mangosteen fruit (*Garcinia mangostana* L.). HortScience 31:112-113.

Pantastico, E.B., ed. 1975. Postharvest Physiology, Handling and Utilization of Tropical and Subtropical Fruits and Vegetables. AVI, Westport, CT.

Podee, R. 1998. Nondestructive Methods for Separation of Translucent Pulp in Mangosteen by Specific Gravity and X-Ray Computed Tomography. M.S. thesis, Chiang Mai University, Chiang Mai, Thailand.

Rattanachinnakorn, B., J. Phumhiran, and S.S. Nanthachai. 1996. Controlled atmosphere storage of mangosteen. *In* Annual Technical Conference and Proceedings of the Horticulture Research Institute, Department of Agriculture, Bangkok, Thailand.

Tongdee, S.C., and A. Suwanagul. 1989. Postharvest mechanical damage in mangosteen. ASEAN Food J. 4:151-155.

Uthairatanakij, A., and S. Ketsa. 1995. Physico-chemical changes of pericarp of mangosteen fruits after low temperature storage. *In* S. Vijaysegaran, M. Pauziah, M.S. Mohamed, and S. Ahmad Tarmizi, eds., Proceedings of the International Conference on Tropical Fruits, vol. 1, pp. 411-422. Malaysian Agricultural Research and Development Institute, Serdang, Salangor, Maylasia.

Yahia, E.M. 1998. Modified and controlled atmospheres for tropical fruits. Hort. Rev. 22:123-183.

Mushroom

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Scientific Name and Introduction

Mushrooms (*Agaricus bisporus* (Lange) Sing.) (button mushrooms) are cultivated worldwide. Highest production is in the United States, China, France, Holland, United Kingdom, and Poland. They are eaten fresh in salads or as a cooked vegetable. A large volume is canned.

Quality Characteristics and Criteria

Quality is based on maturity, size, trimming, freedom from open veils, disease, spots, insect injury and decay. A uniform, well-rounded cap with a smooth, glossy surface and fully intact veil indicate high quality. The cap should be white or dark brown. Lack of growth medium on caps and absence of browning or other discoloration are also quality factors. Visible open caps and absence of a stipe are negative factors.

Horticultural Maturity Indices

Mushrooms are harvested by maturity, not by the size of the caps. Proper maturity is reached when the caps are well rounded and the partial veil is completely intact. The stipe should have a small length:thickness ratio and should be sufficient to permit some trimming without cutting caps.

Grades, Sizes, and Packaging

U.S. grades are No. 1 and No. 2. Sizes are Small (button), 1.9 to 3.2 cm (0.75 to 1.25 in); Medium, 3.2 to 4.5 cm (1.25 to 1.8 in); and Large, 4.5 cm (1.8 in), measured as cap diameter. Grades discriminate for maturity, shape uniformity, cleanliness, and trim quality. Mushrooms are packed in trays or cartons with a perforated polyethylene film overwrap (Suslow and Cantwell 1998).

Precooling Conditions

Mushrooms should be precooled to 2 to 4 C (32 to 39 °F) immediately after harvest. Hydrocooling and forced-air cooling are often used. Freshly harvested mushrooms keep their quality longer throughout their shelf-life if immediately packed and vacuum-cooled and then transported at a low temperature. The same procedure is applied to cut mushrooms.

Optimum Storage Conditions

Mushrooms can be held for 7 to 9 days upon rapid cooling and storing at 0 to 1 °C (32 to 34 °F) with 95% RH. Storing at 2 °C (36 °F) shortens storage life to 3 to 5 days by accelerating surface browning, stipe elongation, and veil opening (Umiecka 1986). High RH is essential to prevent desiccation and loss of glossiness. Moisture loss is correlated with stipe blackening and veil opening. Mushrooms should be packed in cartons with a perforated overwrap of polyethylene film to reduce moisture loss. It is important to avoid water condensation inside packages. There are no chemical treatments to extend storage life of mushrooms intended for fresh consumption.

Controlled Atmosphere (CA) Considerations

Mushrooms derive a moderate benefit from storage under 3 to 21% O_2 and 5 to 15% CO_2 (Saltveit 1997). A 3% O_2 and 10% CO_2 CA extends storage life to 12 to 15 days at 0 C (32 °F) (Suslow and Cantwell 1998). A 10 to 15% CO_2 CA reduces cap opening, browning, and stipe elongation. Mushroom quality was maintained in 8% O_2 and 10% CO_2 (Zheng and Xi 1994). Storage under low O_2 and high CO_2 inhibits cap opening and internal browning but causes yellowing of the cap surface. Levels of O_2 <1% can favor growth of *Clostridium botulinum* and the development of off odors and off flavors, as well as cap opening and stipe elongation. For this reason, CA is not commonly used (Carrier 1995).

Retail Outlet Display Considerations

Mushrooms should be kept on refrigerated shelves at <4 °C (40 °F). Mushrooms absorb odors from green onions; they should not be transported or displayed together.

Chilling Sensitivity

Mushrooms are not chilling sensitive, but they freeze below -0.6 °C (31 °F). Freezing injury appears as water-soaked and extremely soft caps (Suslow and Cantwell 1998).

Ethylene Production and Sensitivity

Mushrooms produce very low amounts of ethylene: 0.1 L kg^{-1} h^{-1} at 20 °C (68 °F). Since ethylene causes browning of mushroom caps, they should be kept separate from ethylene-producing fruits and vegetables.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	28 to 44
5 °C	70
10 °C	97
20 °C	240 to 288

Data from Suslow and Cantwell (1998).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Low storage temperatures are needed to reduce continued development of mushrooms after harvest. Common disorders include upward bending of caps and opening of the veil. Mushrooms are easily bruised by rough handling and develop brown discolored tissue.

Postharvest Pathology

Disease is generally not an important source of postharvest loss in comparison with physiological senescence and improper handling or bruising. All diseased caps must be eliminated at harvest. Bacterial blotch or *Pseudomonas* spp. can become a problem during extended storage at elevated temperatures (Suslow and Cantwell 1998).

Quarantine Issues

None are known.

Suitability as Fresh-Cut Product

Fresh-cut mushrooms are becoming increasing popular at the wholesale and retail level.

References

Carrier Corporation. 1995. Controlled Atmosphere Handbook. A Guide for Shipment of Perishable Cargo in Refrigerated Containers. Carrier, Syracuse, NY.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 4, pp. 98-117. University of California, Davis, CA.

Salunkhe, D.K., and S.S. Kadam. 1998. Handbook of Vegetable Science and Technology. Marcel Dekker, New York, NY.

Suslow, T.V., and M. Cantwell. 1998. Mushroom. Recommendations for Maintaining Postharvest Quality. *At* http://postharvest.ucdavis.edu/produce_information.

Umiecka, L. 1986. Effect of the material quality, treatment, package methods, and storage conditions on export quality of several mushroom races. Biul. Warzywniczy 29:271-292.

Zheng, Y.H., and Y.F. Xi. 1994. Preliminary study on colour fixation and controlled atmosphere storage of fresh mushrooms. J. Zbej. Agr. Univ. 20:165-168.

Nectarine

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Scientific Name and Introduction

Nectarine *(Prunus persica* var. *nectarina)* has been described for nearly as long as the peach, but its origin is unknown. Because nectarine may have arisen from peach seeds, most peach-growing areas worldwide have also introduced nectarine cultivars.

U.S. Grades for nectarines are U.S. Fancy, U.S. Extra No. 1, U.S. No. 1, U.S. No. 2, and Reserved and can be found at the USDA, AMS website entitled "United States Standards for Grades of Nectarine" at http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5050395.

California is a major producer and shipper of nectarines in the United States. Current shipments of fresh nectarines have approached 20 million 10-kg (22-lb) packages. More than 130 cultivars are raised commercially. In recent years, an important development has been the breeding of white-flesh nectarine cultivars. In the San Joaquin Valley, harvest of early cultivars starts in mid May, and harvest of late cultivars of nectarines is completed in mid September. Nectarines are exported mainly to Canada, Taiwan, Hong Kong, Mexico, and Brazil.

Quality Characteristics and Criteria

Greater consumer acceptance is attained for fruit with high SSC. TA and SSC:TA are also important in consumer acceptance. In general, nectarines have more TA than peaches. No minimum flavor-quality standard has been established for nectarines. Fruit with 9 to 13.5 N (2 to 3 lb-force) of flesh firmness are considered ready to eat. Fruit with <27 N (6 lb-force) firmness are highly accepted by consumers.

Horticultural Maturity Indices

In California, harvest date is determined by skin ground color, which changes from green to yellow in most cultivars. A color chip guide is used to determine maturity of each cultivar except white-fleshed cultivars. A two-tier maturity system is used in California: (1) U.S. Mature (minimum maturity); and (2) Well-Mature or Tree Ripe. Well-Mature and Tree Ripe have the same definition according to the California Department Food and Agriculture Division of Inspection Services.

Measurement of fruit firmness is recommended for cultivars in which skin ground color is masked by full red color development before maturation. In these, a maximum maturity index can be applied. Maximum maturity is defined as the minimum flesh firmness (measured with a penetrometer with an 8-mm tip) at which fruit can be handled without bruising. Bruising susceptibility varies among nectarine cultivars.

Grades, Sizes, and Packaging

Fruit should be hand-picked into bags, baskets, or totes and then dumped into bins on trailers between tree rows in the orchard. If fruit are picked into totes, the totes are usually placed directly inside bins.

Nectarines should be transported from the orchard to a packinghouse and cooled as soon as possible after harvest. At the packinghouse, fruit are dumped (mostly using dry bin dumps) and cleaned. Sorting is done to eliminate fruit with visual defects and sometimes to divert fruit of high surface color to a high-quality pack. Sizing segregates fruit by either weight or dimension.

Most of the yellow-flesh nectarines are packed into 2-layer (tray) boxes. Small yellow-flesh nectarines are generally volume-fill packed. Most of the white-flesh and "tree ripe" nectarines are packed into 1-layer (tray) boxes.

Limited volumes of partially-ripe to ripe nectarines are "ranch packed" at the point of production. In a typical "tree ripe" operation, fruit are picked into buckets or totes that are carried by trailer to the packing area. Packers work directly from buckets to select, grade, size, and pack fruit into plastic trays.

Optimum Storage Conditions

Fruit can be cooled in field bins using forced-air cooling or hydrocooling. Forced-air cooling in side-vented bins can be done by the tunnel or the serpentine method. Hydrocooling is normally done by a conveyor type hydrocooler or in place.

Fruit in field bins can be cooled to intermediate temperatures of 5 to 10 °C (41 to 50 °F) provided they are packed the next day. If packing is to be delayed beyond the next day, fruit should be thoroughly cooled in bins to near 0 °C (32 °F). With cultivars susceptible to internal browning, fast cooling (within 8 h) and maintaining fruit temperature near 0 °C (32 °F) are recommended.

Nectarines in packed containers should be cooled to near 0 °C (32 °F). Even nectarines that were thoroughly cooled in bins will warm substantially during packing and should be thoroughly recooled using forced-air cooling after packing.

Stone-fruit storage and long-distance shipments should be at or below 0 °C (32 °F). Maintaining these low temperatures requires knowledge of the freezing point of the fruit and of the temperature fluctuations in storage and transport systems. Temperature during truck transportation within the United States, Canada, and Mexico should be <2 °C (36 °F). Holding stone fruits at these low temperatures minimizes losses to rotting organisms, excessive softening, and water losses, as well as reducing severity of internal browning in susceptible cultivars.

Optimum Temperature

The optimum storage temperature is -1 to 0 °C (30 to 32 °F). The freezing point varies, depending on SSC, from -3 to -1.5 °C (27 to 30 °F). A RH of 90 to 95% with an air velocity of approximately 50 ft^3 min^{-1} is suggested during storage.

Controlled Atmosphere (CA) Considerations

The major benefits of CA (1 to 2% O_2 and 3 to 5% CO_2) during storage and shipment are retention of fruit firmness, stability of color, and limiting of internal browning. CA of 10% O_2 and 10% CO_2 is sometimes used to reduce internal breakdown during storage and shipment. CA with O_2 <1% and CO_2 >20% should be avoided because of associated development of off flavors and browning.

Retail Outlet Display Considerations

If firmness is <27 N (6 lb-force), nectarines should be displayed on a cold table. If firmness is >27 N (6 lb-force), fruit should be displayed on a dry table.

Chilling Sensitivity

Some of the mid- and late-season cultivars are susceptible to chilling injury or internal breakdown. Chilling injury symptoms develop faster and more intensely when fruit are stored between about 2 and 8 °C (36 and 46 °F) than in those stored at 0 °C (32 °F) or below. Recently released mid- and late-season cultivars have low susceptibility to internal browning.

Ethylene Production and Sensitivity

In the following table, the lower end of the range is for mature but unripe fruit; higher values are for ripe fruit:

Temperature	µL C_2H_4 kg^{-1} h^{-1}
0 ºC	0.01 to 5
5 ºC	0.02 to 10
10 ºC	0.05 to 50
20 ºC	0.10 to 160

In general, nectarines harvested at the "well-mature" or riper stages will ripen properly without exogenous ethylene application. In some cultivars, exposure to 100 µL L^{-1} ethylene results in more uniform ripening of nectarines picked at the "U.S. mature" stage.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	4 to 6
10 °C	16 to 24
20 °C	64 to 110

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Internal breakdown (IB), or chilling injury, is a physiological problem characterized by internal flesh browning, flesh mealiness or leatheriness, flesh bleeding, failure to ripen, and flavor loss. In most cases, the red color development inside the flesh (bleeding) is not an IB symptom, and it does not affect taste. These symptoms develop during ripening after a cold-storage period, and thus are usually detected by consumers. However, there is large variability in susceptibility to IB among cultivars. In general, nectarines are less susceptible to IB than peaches. In susceptible cultivars, IB symptoms develop faster and more intensely when fruit are stored at temperatures between about 2 and 8 °C (36 and 46 °F) than when stored at 0 °C (32 °F) or below. At the shipping point, fruit should therefore be cooled and held near or below 0 °C (32 °F) if possible. During transportation if IB-susceptible cultivars are exposed to approximately 5 °C (41 °F), it can significantly reduce their postharvest life. Several treatments to delay and limit development of this disorder have been tested. Among them, preripening fruit before storage is a successful commercially used treatment in the United States. Success of CA (10% CO_2 and 10% O_2) depends on cultivar, market life, and shipping time.

Inking (black staining) is a cosmetic problem affecting only the skin of nectarines. It is characterized by black or brown spots or stripes. These symptoms appear generally 24 to 48 h after harvest. Inking is a result of abrasion damage in combination with contamination by heavy metals (iron, copper, and aluminum). This usually occurs during harvesting and hauling, though it may occur during postharvest handling. Careful fruit handling, short hauling, avoiding any foliar nutrient sprays within 15 days before harvest, and following suggested preharvest fungicide spray guidelines are recommended to reduce inking.

Postharvest Pathology

Brown rot is caused by *Monilinia fructicola* and is the most important postharvest disease of stone fruits. Infection begins during flowering and fruit rot may occur before harvest but often appears postharvest. Orchard sanitation to minimize infection sources, preharvest fungicide application, and prompt cooling after harvest are among the control strategies. Also, postharvest fungicide treatment may be used.

Gray mold is caused by *Botrytis cinerea* and can be serious during wet spring weather. It can occur during storage if the fruit has been contaminated through harvest and handling wounds. Avoiding mechanical injuries and good temperature management are effective control measures.

Rhizopus rot is caused by *Rhizopus stolonifer* and can occur in ripe or near-ripe fruit at 20 to 25 °C (68 to 77 °F). Cooling fruit and keeping them at <5 °C (41 °F) is effective against this fungus.

Quarantine Issues

Because some insects such as *Conotracherlus nenuphar* (plum curculio), *Cydia pomonella* (codling moth), *Rhagoletis pommonella* (apple maggot), and *Tetranychus pacificus* (Pacific spider mite) are not present in some import markets, phytosanitary restrictions have been established. Issues with exotic pest quarantine, addressing imported and exported nectarines, can change rapidly. APHIS issues rules regarding import requirements and provide information to assist exporters in targeting markets and defining what entry requirements a particular country might have for nectarines. APHIS, in cooperation with the State plant boards, developed a database called “Excerpt” to track phytosanitary requirements for each country. APHIS provides phytosanitary inspections and certifications that declare nectarines free of pests to facilitate compliance with foreign regulatory requirements.

For nectarines, there are three main ways to deal with these phytosanitary requirements: inspection prior to shipment (including use of screened crates transported in sealed containers), methyl bromide fumigation, and a systems approach.

A phytosanitary certificate is required to import California nectarines into Taiwan. Nectarines must be free of *Anarsia ineatella* (peach twig borer), *Conotracherlus nenuphar* (plum curculio), *Cydia pomonella* (codling moth), *Erwinia amylovora* (fire bright), *Rhagoletis pomonella* (apple maggot), *Tetranychus pacificus* (Pacific spider mite), and *Ceratitis capitata* (Mediterranean fruit fly). If these conditions cannot be met, then fruit must be treated with an appropriate treatment prior to shipment. Details of the treatment must be recorded on the phytosanitary certificate.

Suitability as Fresh-Cut Product

The optimal ripeness for preparing fresh-cut nectarines slices is the partially ripe (>27 to 49 N, >6 to 11 lb-force) or ripe (>13 to 27 N, >3 to 6 lb-force) flesh firmness stages. These slices can be kept at 0 °C (32 °F) with 90 to 95% RH for 2 to 12 days, depending on cultivar and ripeness, while retaining good eating quality.

Special Considerations

Because nectarines are a climacteric fruit, they are harvested at a minimum or higher maturity but are not fully ripe; that is, they are not ready to eat. Nectarines must be ripened before consumption to satisfy consumers.

Acknowledgments

Some of the information in this chapter is from the University of California, Davis, website “Produce Facts” at http://postharvest.ucdavis.edu/produce_information.

Further Reading

Ceponis, M.J., R.A. Cappellini, J.M. Wells, and G.W. Lightner. 1987. Disorders in plum, peach and nectarine shipments to the New York market, 1972-1985. Plant Dis. 71:947-952.

Crisosto, C.H. 1994. Stone fruit maturity indices: a descriptive review. Postharv. News Info. 5(6):65N-68N.

Crisosto, C.H., F.G. Mitchell, and S. Johnson. 1995. Factors in fresh market stone fruit quality. Postharv. News Info. 6(2):17N-21N.

Crisosto, C.H., F.G. Mitchell, and Z. Ju. 1999. Susceptibility to chilling injury of peach, nectarine, and plum cultivars grown in California. HortScience 34:1116-1118.

Kader, A.A., and F.G. Mitchell. 1989. Postharvest physiology. *In* J.H. LaRue and R.S. Johnson, eds., Peaches, Plums, Nectarines: Growing and Handling for Fresh Market, pp. 154-164. Pub. no. 3331, University of California, Davis, CA.

Gorny, J.R., B. Hess-Pierce, and A.A. Kader. 1998. Effect of fruit ripeness and storage temperature on the deterioration rate of fresh-cut peach and nectarine slices. HortScience 33:110-113.

Gorny, J.R., B. Hess-Pierce, and A.A. Kader. 1999. Quality changes in fresh-cut peach and nectarine slices as affected by cultivar, storage atmosphere and chemical treatments. J. Food Sci. 64:429-432.

Lurie, S. 1992. Controlled atmosphere storage to decrease physiological disorders in nectarines. Intl. J. Food Technol. 27:507-415.

Lill, R.E., E.M. O'Donoghue, and G.A. King. 1989. Postharvest physiology of peaches and nectarines. Hort. Rev. 11:413-452.

Netted Melon

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Scientific Name and Introduction

Cucumis melo L. (Reticulatus group), commonly called cantaloupe or muskmelon, is a member of the Cucurbitaceae family (Bailey et al. 1976). True cantaloupes, members of the Cantaloupensis group, are nonnetted fruit common to Cantaluppi, Italy, and are seldom grown in the United States. Western Shipper melons (grown in Arizona, California, and Texas) are grown principally for domestic and export markets, while Eastern Choice melons (grown in the eastern United States) are more perishable and are used principally for local consumption. A heavy, uniform, tan-colored net and bright orange flesh characterizes the external appearance of Western Shipper and Eastern Choice melons. Eastern Choice melons are often deeply sutured, while Western Shipper melons usually lack sutures.

Charentais, galia, ananas, and Persian melons are not commonly grown in the United States, but are gaining popularity as specialty melons. The French Charentais is a round, sparsely netted melon with a grey-green rind having pronounced dark-green longitudinal tracts; it has a sweet, highly-scented, orange flesh. Galia melons from Israel are characterized by a fine, uniform net, round shape, and green flesh (Karchi and Govers 1977). Ananas melons have a sparse, cracked net and white, very sweet flesh. The shape and netting of Persian melons are similar to those of Western Shipper type melons, but Persian melons are larger, about 6 lb (2.7 kg) each, and have a bright, orange-pink flesh.

Quality Characteristics and Criteria

To meet U.S. grade standards, melons must have sufficient maturity to ensure completion of ripening, sufficient firmness (not soft or wilted), shape and netting characteristic for their type, a stem scar not wet and slippery (wet slip), no sunscald (solar injury), flesh and rind free of decay by fungi or bacteria, and absence of damage (USDA 1981). Damage includes liquid in the seed cavity, hail injury, surface mold, aphid honeydew, scars, cracks, ground spot rind disorders, bruises, and mechanical damage. A minimum SSC of 11% and 9% is required for U.S. grades Fancy and U.S. No. 1, respectively. State market-order quality standards may exceed Federal grade requirements.

Horticultural Maturity Indices

Stem separation and background rind color are used to indicate acceptable maturity for harvest. As netted melons begin to ripen, a separation layer, or abscission zone, develops at the point where the stem attaches to the fruit. Most netted melons are commercially harvested when half of the stem has separated from the melon (referred to as half-slip) (Kasmire et al. 1970). Abscission zone development often corresponds to a change from green to yellow in rind background color. If picked at proper maturity, netted melons will continue to soften and become more aromatic after harvest (Shellie 1995, Ayub et al. 1996). Netted melons harvested prematurely by cutting the stem prior to abscission-zone development may produce little aroma, have low SSC, and do not properly ripen (Lyons et al. 1962).

Grades, Sizes, and Packaging

U.S. Grades for cantaloupes (USDA 1981) include U.S. Fancy, U.S. No. 1, U.S. Commercial, and U.S. No. 2. The difference among grades reflects levels of tolerance for quality criteria. A minimum

SSC of 11% is required for U.S. Fancy and 9% for U.S. No 1. There are six common size classes (9, 12, 15, 18, 23, and 30) based on the number of fruit of uniform size and weight that fit into a standard 40-lb (18-kg) cardboard shipping box.

Precooling Conditions

Precooling to a fruit center temperature of 10 to 15 °C (50 to 59 °F) soon after harvest is recommended to delay ripening and retain sugar content. Hydrocooling, forced-air cooling, and top-icing are acceptable, but hydrocooling is most efficient (Kader 1992).

Optimum Storage Conditions

Optimum is 2 to 7 °C (36 to 45 °F) with 95% RH (Saltveit 1997). The expected shelf-life at these recommended conditions is 10 to 14 days.

Controlled Atmosphere (CA) Considerations

CA in transit or storage has some potential for extending shelf-life. The recommended level of O_2 is 3 to 5% for reducing respiration and ethylene production. The recommended level of CO_2 is 10 to 20% for reducing loss of sugar and inhibiting surface mold. Storage in an atmosphere containing >10% CO_2 may result in a carbonated taste that is lost during subsequent storage in air. Off flavors, odors, and impaired ripening may develop if netted melons are stored in <1% O_2 or >20% CO_2 (Kader 1992, Saltveit 1997).

Retail Outlet Display Considerations

The shelf-life of netted melons can be maximized by storage under refrigeration and by avoiding postharvest exposure to ethylene.

Chilling Sensitivity

Sensitivity decreases as fruit mature. Full-slip, netted melons may be stored for 5 to 14 days at 0 to 2 °C (32 to 36 °F). Less mature melons may be damaged by storage at <2 °C (36 °F). Injury symptoms include pitting, surface decay, and failure to ripen (Wang 1990).

Ethylene Production and Sensitivity

Netted melons are climacteric fruit that produce 10 to 100 µL kg^{-1} h^{-1} ethylene (Kader 1992) from 4 days prior to stem separation to as late as 10 days after harvest (Shellie and Saltveit 1993, Shellie 1995). Postharvest exposure to ethylene reduces shelf-life and should be avoided. Exogenous ethylene application after harvest will not ripen netted melons harvested prematurely, nor will it prevent normal postharvest decline in SSC.

Respiration Rates

Netted melons have a moderate rate of respiration (Kader 1992).

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	5 to 6
4 to 5 °C	9 to 10
10 °C	14 to 16
15 to 16 °C	34 to 39
20 to 21 °C	45 to 65
25 to 27 °C	62 to 71

Data from Sholz et al. (1963).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Solar injury causes patchy ground color, or “bronzing,” and net discoloration. Severely injured tissue becomes sunken or wrinkled (Snowdon

1992). Vein track browning, a darkening of the longitudinal tracts between netted areas, is caused by exposure to sun or high temperature at harvest (Snowdon 1992). Netted melons are easily injured and should never be dropped more than 60 cm (2 ft). Harvest and packing equipment should be padded to reduce scuffing of netting (Ryall and Lipton 1979). Avoidance of wounding during handling (compression, bruising, or scuffing) and storage under recommended conditions provides protection against physical injury and decay.

Postharvest Pathology

Fusarium rot is the most common disease (Zitter et al. 1996). Symptoms vary depending on *Fusarium* species, but large fissures and an enlarged or thickened, dark-tan net at the lesion site is common. A distinct delineation is apparent between diseased and healthy tissue. There is often no sign of infection before harvest, but numerous spongy white lesions may develop internally postharvest. Fungicide application in a hot-water dip, 1 min at 57 °C (135 °F), can suppress fusarium fruit rot. Other less common diseases include black rot incited by *Didymella bryoniae* or *Phomopsis cucurbitae*, rhizopus soft rot *(Rhizopus stolonifer)*, bacterial brown spot *(Erwinia ananas)*, bacterial soft rot *(Erwinia carotovora)*, and alternaria rot *(Alternaria alternata)*.

Quarantine Issues

Melons entering the United States must be disinfested of external feeders (noctuid moths, thrips, and *Copitarsia* species) by fumigation with methyl bromide (APHIS 1998). Methyl bromide was identified in 1987 as having an ozone-depleting potential of 0.4 and is scheduled for global phase-out under the Montreal Protocol. Title VII of the U.S. Clean Air Act required phasing out production and importation of substances with ozone-depleting potentials of 0.2 or greater. Use of methyl bromide for preshipment and quarantine is exempt from these restrictions, but limited supply and increased costs may make methyl bromide undesirable in the near future.

Suitability as Fresh-Cut Product

Harvest maturity, cultivar, growing location, cultural practices, and postharvest handling influence quality of the processed product. Netted melons destined for fresh-cut sale should be harvested at the earliest maturity acceptable for minimum sugar content and proper ripening and be precooled immediately after harvest. Firm cultivars should be selected that have a high sugar content, bright orange flesh, and small cavity—that is, a high piece yield. Melons should be rinsed in 200 µL L^{-1} of 5.25% NaOCl at 5 °C (41 °F) at pH 6.5 to 7.0 for 5 min. The whole melon is cut into cubed pieces with sharp blades. Pieces should then be rinsed with 150 µL L^{-1} of the above chloride solution at 5 °C (41 °F) for 30 sec prior to packaging. A shelf-life of 6 to 10 days can be expected for orange-fleshed melon cubes stored at 0 to 5 °C (32 to 41 °F). A modified atmosphere of 8 to 10% CO_2 in air is beneficial for retarding microbial growth, as well as slowing softening and other quality changes.

Special Considerations

Use of liners in cardboard shipping boxes may reduce fruit moisture loss and extend storage life (Lester and Bruton 1986).

References

APHIS [USDA Animal and Plant Health Inspection Service]. 1998. T101-o-2 MB Methyl bromide fumigation of melons for external feeders. *In* Treatment Manual, http://www.hsdl.org/?view&did=28976, U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine, Hyattsville, MD.

Ayub, R., M. Guis, M. Ben Amor, et al. 1996. Expression of ACC oxidase antisense gene inhibits ripening of cantaloupe melon fruits. Nat. Biotech. 14:862-866.

Bailey, L.H., and E.Z. Bailey. 1976. Hortus Third. Macmillan, New York, NY.

Kader, A.A., ed. 1992. Postharvest Technology of Horticultural Crops, 2nd ed., p. 192. DANR Pub. no. 3311, University of California, Oakland, CA.

Karchi, Z., and A. Govers. 1977. Galia melon—a new F_1 hybrid for export and the local market. Hassadeh 57:630-634 (In Hebrew; English Summary).

Kasmire, R.F., L. Rappaport, and D. May. 1970. Effects of 2-chloroethylphosphonic acid on ripening of cantaloupes. J. Amer. Soc. Hort. Sci. 95:134-137.

Lester, G.E., and B.D. Bruton. 1986. Relationship of netted muskmelon fruit water loss to postharvest storage-life. J. Amer. Soc. Hot. Sci. 111:727-731.

Lyons, J.M., W.B. McGlasson, and H.K Pratt. 1962. Ethylene production, respiration, and internal gas concentrations in cantaloupe fruits at various stages of maturity. Plant Physiol. 37:31-36.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation, and Storage of Fruits and Vegetables, vol. 1. AVI Pub. Co., Westport CT.

Saltveit, M.E. 1997. A summary of CA and MA requirement and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 4, pp. 98-117. University of California, Davis CA.

Shellie, K.C. 1995. Enhancing ripening characteristics of ‘Netted, Orange-flesh’ and ‘Smooth, Green-flesh’ type melons (*Cucumis melo* L.). *In* G.E. Lester and J.R. Dunlap, eds., Cucurbitacae ’94: Evaluation and Enhancement of Cucurbit Germplasm, pp. 101-103. Gateway Printing, Edinburg, TX.

Shellie, K.C., and M.E. Saltveit. 1993. The lack of a respiratory rise in muskmelon fruit ripening on the plant challenges the definition of climacteric behaviour. J. Exp. Bot. 44:1403-1406.

Scholz, E.W., H.B. Johnson, and W.R. Buford. 1963. Heat evolution rates of some Texas-grown fruits and vegetables. J. Rio Grande Valley Hort. Soc. 17:170-175.

Snowdon, A. 1992. Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables. CRC Press, Boca Raton FL.

USDA [U.S. Department of Agriculture]. 1981. United States Standards for Grades of Cantaloupes. U.S. Department of Agriculture, Washington, DC.

Wang, C.Y. 1990. Chilling Injury of Horticultural Crops. CRC Press, Boca Raton FL.

Zitter, T.A, D.L. Hopkins, and C.E. Thomas. 1996. Compendium of Cucurbit Diseases. American Phytopathological Society, St. Paul MN.

Nopalitos

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Scientific Name and Introduction

Cactus stems (“nopalitos” in Spanish) are the rapidly growing succulent stems (cladodes) of the prickly pear cactus (*Opuntia* spp.). They are a warm-season vegetable but are available year-round, being grown in California as a specialty vegetable or imported from Mexico where they are a traditional vegetable. Though the young stems of many *Opuntia* species can be eaten, most commercial plantings of nopalitos are from *O. ficus-indica* and *O. inermis*. Nopalitos are mostly water (92%) and carbohydrates, as well as fiber (4 to 6%), and a little protein (1 to 2%). They also contain some minerals, principally calcium (1%), and moderate amounts of vitamin C and vitamin A. They are similar in composition to dark-green leaf lettuces (Rodríguez-Felix and Cantwell 1988).

Quality Characteristics and Criteria

Good-quality nopalitos are fresh, turgid, and a brilliant green color. In the early stages of growth, vestigial true leaves, usually subtended by spines, are present on the stems. The leaves often abscise by the time nopalitos reach commercial size; however, green true leaves on the stem are an additional indication of freshness. Nopalitos should be harvested when young and tender, but not early in the morning so as to avoid a high acid content (see *Special Considerations*).

Horticultural Maturity Indices

Nopalitos are harvested based on size and can be Small (<10 cm [4 in] long) or Medium (<20 cm [8 in] long). Medium weigh about 100 g (0.2 lb). Overmature nopalitos are thick with lots of spongy white tissue and are acidic in flavor.

Grades, Sizes, and Packaging

There are no grades. Nopalitos are packed according to size and quality. The fruit are typically loose-packed in 4.5- to 9.0-kg (10- or 20-lb) cartons or boxes.

Precooling conditions

Nopalitos should be cooled to about 5 °C (41 °F) to reduce loss of visual appearance (shiny surface) that results from water loss. They are usually room-cooled, but also may be forced-air cooled. Hydrocooling should be avoided as it favors discoloration in damaged areas (especially where spines have penetrated the surface) and decay.

Optimum Storage Conditions

Good quality can be maintained for 3 weeks at 5 °C (41 °F) and 2 weeks at 10 °C (50 °F) with 95 to 99% RH (Cantwell et al. 1992). Major factors limiting storage life of nopalitos are decay and dehydration (Cantwell, 1995). Nopalitos stored under ambient conditions rapidly lose their brilliant shiny appearance, become dull green and may begin to yellow and curve inward due to water loss. Some discoloration (chilling injury) occurs if stored longer than 3 weeks at 5 °C (41 °F) (Cantwell et al. 1992).

Controlled Atmosphere (CA) Considerations

No information is available on the potential benefits of CA or MAP for nopalitos. For diced product, 5 to 10% CO_2 may be beneficial (Cantwell, 2002, unpublished).

Retail Outlet Display Considerations

Nopalitos should be kept in a refrigerated display case to reduce water loss and curvature. They should not be sprinkled or top-iced.

Chilling Sensitivity

Nopalitos are chilling sensitive when stored below 10 °C (50 °F). Chilling damage may be manifested as a superficial bronzing or discoloration and increased susceptibility to decay. Symptoms may appear after 3 weeks at 5 °C (41 °F) (Cantwell et al. 1992) or sooner (Ramayo-Ramirez et al. 1978).

Ethylene Production and Sensitivity

Ethylene production rates are very low: 0.05, 0.1 and 0.22 nL kg^{-1} h^{-1} at 5, 10 and 20 °C (41, 50, and 68 °F), respectively (Cantwell et al. 1992). Nopalitos are not sensitive to ethylene exposure, but exposure at warm temperatures will enhance yellowing.

Respiration Rates

The following are average rates for 10-cm (4-in) nopalitos over a 7-day period at the indicated temperatures. Initial rates are about 50% higher. Respiration rates of 20-cm (8-in) stems are about 50% lower than rates of 10-cm (4-in) stems.

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	16 to 19
10 °C	38 to 42
15 °C	52 to 59
20 °C	68 to 79

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

See above section on *Chilling Sensitivity*.

Postharvest Pathology

Decay at the cut stem end may be a problem if nopalitos are stored for more than 2 weeks. Decay can be avoided by insuring that nopalitos are not damaged when cut from the plant. Fungicide dips reduce postharvest decay of nopalitos but are not used commercially (Ramayo-Ramírez et al. 1978).

Quarantine Issues

None are known.

Suitability as Fresh-Cut Product

Some types of nopalitos are spiny, and therefore a cleaned and diced product is an attractive option. Reducing brown discoloration at cut surfaces and preventing fluid (mucilage) loss are the main problems in handling diced cactus stems. Cut nopalitos cannot be washed before marketing, because washing will cause mucilage to exude and enhance discoloration of cut surfaces. Notwithstanding the chilling sensitivity of intact nopalitos, they should be stored between 0 and 5 °C (32 and 41 °F) (Cantwell, 2002, unpublished). Shelf-life of diced nopalitos was 1 day at 20 °C (68 °F) and 6 days at 5 °C (41 °F) (Rodríguez-Felix and Soto-Valdez 1992). Moderate CO_2 (5 to 10%) CA may be useful to reduce discoloration and other visual defects of cut nopalitos (Cantwell, 2002, unpublished).

Special Considerations

Cactus stems should be harvested and handled with care to avoid mechanical damage, especially from spines on one stem penetrating the neighboring stem. Spine damage leads to a rusty-brown discoloration and pathological problems

Because the prickly pear plant is a crassulacean acid metabolism (CAM) plant and fixes CO_2 at night as malic acid before converting it to sugars during the day, the acid content of nopalitos may fluctuate greatly and affect their flavor

(Rodríguez-Felix and Cantwell 1988). Therefore, it is recommended that stems be harvested 2 to 3 h after sunrise. Small nopalitos, however, are not CAM-active. Also, low temperature storage at 5 °C (41 °F) maintains acid levels, while warmer storage conditions of 15 to 20 °C (59 to 68 °F) result in decreased acid (Cantwell et al. 1992).

References

Cantwell, M. 1995. Postharvest management of fruits and vegetable stems. *In* G. Barbera, P. Inglese, and E. Pimienta-Barrios, eds., Agroecology, Cultivation and Uses of Cactus Pear, pp. 120-136. Plant Production and Protection Paper 132, United Nations, Food and Argiculture Organization, Rome, Italy.

Cantwell, M., A. Rodriguez-Felix, and F. Robles-Contreras. 1992. Postharvest physiology of prickly pear cactus stems. Sci. Hort. 50:1-9.

Ramayo-Ramírez, L., C. Saucedo-Veloz, and S. Lakshminarayana. 1978. Prolongación de la vida de almacenamiento del nopal hortaliza (*Opuntia inermis* Coulter) por refrigeración. Chapingo, Nuevo Epoca 10:30-32.

Rodríguez-Felix, A., and M. Cantwell. 1988. Developmental changes in composition and quality of prickly pear cactus cladodes (nopalitos). Plant Foods for Human Nutrition 38:83-93.

Rodríguez-Felix, A., and H. Soto-Valdez. 1992. Quality changes of diced nopal during storage in polyethylene bags. *In* P. Felker, and J.R. Moss, eds., Proceedings of the 3rd Annual Texas Prickly Pear Conference, Kingsville, TX, pp. 22-25.

Okra

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Scientific Name and Introduction

Okra (*Abelmoschus esculentus* (L.) Moench, also known as *Hibiscus esculentus* L.) is a member of the mallow (Malvaceae) family and can be found as an annual (primarily in the United States) or as a perennial in India and Africa (Lamont 1999). In the United States, Mexico, and Japan, the young fruiting pods are the edible portion, while young leaves and mature seeds may be consumed in other countries (Duzyaman 1997). Other names include quingumbo, bhendi, bhindi, gumbo, gombo, quaio, and lady's finger.

In the United States, most fresh market okra is from California and the Southern United States and Mexico. 'Clemson Spineless' is the best-known fresh market cultivar; while low-mucilage, low-fiber, high-chlorophyll types such as 'Emerald' and 'Louisiana Green Velvet' are grown for processing. A few fresh-market hybrids—'Annie Oakley,' 'North and South,' and 'Cajun Delight'—are now available.

Most okra cultivars produce green pods, but a few varieties produce yellow ('Blondy') or dark red ('Burgundy') pods. Usually, pods have 4 to 10 distinct ribs or ridges ('Emerald' is completely round, with no ribs). Pods are prized for their unique flavor and high mucilaginous content (being used as a thickening agent).

Quality Characteristics and Criteria

High quality pods are 5 to 15 cm (2 to 6 in) long, flexible, bright-green, and turgid. Seeds should not be protruding through the epidermis, and ridges should be free of blackening and bruising.

Horticultural Maturity Indices

Okra pods are harvested when immature and high in mucilage but before becoming highly fibrous—generally within 2 to 6 weeks after flowering (Ramaswamy and Rangana 1982).

Grades, Sizes, and Packaging

Okra is graded by size; absence of defects, decay, insects, and dirt; shape; and tenderness. Fancy pods are <9 cm (3.5 in); Choice are 9 to 11 cm (3.5 to 4.25 in); and Jumbo are >11 cm (4.25 in). Fresh okra is most commonly presented in 0.45-kg (l-lb) clamshell boxes or as bulk weight or volume-filled 11.4-kg (25-lb) bins.

Precooling Conditions

Okra should be marketed within 36 h of harvest and shipped under refrigeration. Storage in unventilated containers without refrigeration can cause degradation of color. Some growers use hydrocooling or forced-air cooling.

Optimum Storage Conditions

Okra pods lose weight readily and are chilling sensitive. Pods can be stored for 7 to 14 days at 7 to 10 °C (45 to 50 °F) with >90% RH.

Controlled Atmosphere (CA) Considerations

There is a slight benefit from storage at 7 to 12 °C (45 to 54 °F) in 4 to 10% CO_2 (Saltveit 1997). Other combinations have also shown some benefit, including 5 to 10% CO_2 at 5 to 8 °C (41 to 46 °F) and 3 to 5% O_2 and 0% CO_2 (Baxter and Waters 1986). Levels of CO_2 >20% can cause off flavors.

Retail Outlet Display Conditions

Okra should be kept dry, refrigerated, and humidified.

Chilling Sensitivity

Okra pods are highly sensitive to chilling, especially very young (more mucilaginous) pods. As little as 2 days at 2 °C (36 °F) can cause chilling injury. Chilling injury shows up within 24 h at 20 °C (68 °F) after pods have been held 7 days at 2 or 5 °C (36 to 68 °F). Symptoms include presence of water-soaked areas, exuding lesions, and appearance of mold or mildew, especially if held at 5 °C (41 °F) (Perkins-Veazie and Collins 1992). Green pods turn a brown-olive-green, yellow varieties turn brown, and burgundy varieties become a dull brown-red.

Ethylene Production and Sensitivity

Okra produce small amounts of ethylene during storage: 0.5 µL kg^{-1} h^{-1} (Baxter and Waters 1986). Okra pods exposed to >1 µL L^{-1} ethylene for 3 or more days show yellowing (Perkins-Veazie, 2002, unpublished).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
2 to 3 °C	10 to 32[1]
4 to 5 °C	21[1] to 55
10 °C	86 to 95
15 to 16 °C	138 to 153
20 to 21 °C	248 to 274
25 to 27 °C	328 to 362

[1]Data from Perkins-Veazie (2002 unpublished) for 'Annie Oakley,' 'Blondy,' and 'Clemson Spineless 80' pods 4 to 12 cm (1.5 to 4.75 in) long; other data from Scholz et al. (1963).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Pods are susceptible to chilling injury, yellowing, shrivel from weight loss, and warty pods (nitrogen deficiency).

Postharvest Pathology

Cladosporium, gray mold *(Botrytis cinerea)*, mildew, yeasts, *Rhizopus stolonifer*, *Rhizoctonia solani*, and *Psuedomonas* pv *syringae* (Snowdon 1992) can all be problematic in okra.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Suitability is unknown. Okra is generally consumed after cooking.

Special Considerations

The ridges on okra pods damage easily. Avoid storing okra with melons, onions, and potatoes, since pods will trap their odors and develop off flavors.

References

Baxter, L., and L. Waters Jr. 1986. Controlled atmosphere effects on physical changes and ethylene evolution in harvested okra. HortScience 25:92-95.

Duzyaman, E. 1997. Okra: botany and horticulture. Hort. Rev. 29:41-72.

Lamont, W. 1999. Okra—a versatile vegetable crop. HortTechnology 9:179-184.

Perkins-Veazie, P.M., and J.K. Collins. 1992. Cultivar, packaging, and storage temperature differences in postharvest shelf life of okra. HortTechnology 2:350-352.

Ramaswamy, H.S., and S. Rangana. 1982. Maturity parameters for okra (*Hibiscus esculentus* (L) Moench var Posa Cawani). Can. Inst. Food Sci. Technol. J. 15(2):140-143.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., Proceedings of the 7th International Controlled Atmosphere Research Conference, vol. 4, pp. 98–117. University of California Postharvest Horticulture Series no. 18, University of California, Davis, CA.

Scholz, E.W., H.B. Johnson, and W.R. Buford. 1963. Heat evolution rates of some Texas-grown fruits and vegetables. J. Rio Grande Valley Hort. Soc. 17:170-175.

Snowdon, A.L. 1992. Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables, pp. 94-95. CRC Press, Boca Raton, FL.

Olive

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Scientific Name and Introduction

A member of the Oleaceae family (*Olea europaea* L.), the olive is a small tree native to the eastern Mediterranean region. The ancient Egyptians, Greeks, Romans, and other Mediterranean nations cultivated olives for their oily drupes. The part used for consumption is the fleshy mesocarp, from which edible oil is extracted, or fruit may be pickled and the mesocarp and exocarp eaten.

Olives are a drupe, botanically similar to cherry and other stone fruits. It consists of carpel, and the wall of the ovary has both fleshy and dry portions. The skin (exocarp) is free of hairs and contains stomata. The flesh (mesocarp) is the tissue eaten, and the pit (endocarp) encloses the seed. Fruit shape, size and pit size, and surface morphology vary greatly among cultivars.

Quality Characteristics and Criteria

For green olives, criteria are color and freedom from mechanical damage, shriveling, surface blemishes, scale and other insect injury, and decay. These are processed according to California black-ripe style or Spanish green style fermented olives. For black olives, criteria are color, freedom from defects, and oil content of 12 to 25% (depending on cultivar). These are processed (Greek or Italian style) or used for oil extraction.

Horticultural Maturity Indices

For green olives, size and color (even coloration of pale green with a minimum of whitish spots [lenticels] through a straw color) indicate when to harvest. An olive is considered mature if it exudes a characteristic white juice when squeezed. For black olives, skin color and removal force are used; fruit reach this stage 3 to 4 mo after the green stage.

Grades, Sizes, and Packaging

Harvesting of olives represents 50 to 70% of the total production labor cost and 30 to 40% of the gross returns from the crop. Harvested fruit begin to lose moisture immediately. When harvested during hot, sunny weather, olives should be put in the shade until hauled away. Sun-exposed fruit gets sunburn and will grade as culls. Rough handling causes bruises and grade reduction.

A few growers harvest their fruit mechanically, using tree shakers and catching frames. The use of mechanical harvesting is likely to increase in the future. Olives are harvested for pickling in California from mid September to mid November, depending on cultivar, local conditions, and needs of the canneries. Optimum harvesting time is determined by the color and texture of the olive. Overmature or badly bruised fruit frequently spoils during processing. To get the best return, fruit should be delivered to the cannery as soon as possible after harvest.

Optimum Storage Conditions

Olives should be stored at 5 to 7.5 °C (41 to 46 °F) with 90 to 95% RH. Temperatures <5 °C (41ºF) cause chilling injury of fresh olives.

Controlled Atmosphere (CA) Considerations

Optimum CA is 2 to 3% O_2 and 0 to 1% CO_2, which delays senescence and softening for up to 12 weeks at 5 °C (41 ºF) and 9 weeks at 7.5 °C (46 °F). Atmospheres with <2% O_2 can cause off flavors, and CO_2 >5% may increase severity of chilling injury if olives are stored below 7.5 ºC

(46 ºF). This information is for fresh green olives. Fresh black olives should be processed as soon after harvest as possible, but if necessary black olives can be kept in 2% O_2 at 5 °C (41 °F) for up to 4 weeks.

Chilling Sensitivity

Olives are sensitive to temperatures <5 °C (41 °F). Symptoms in ‘Ascolano,’ ‘Manzanillo,’ ‘Mission,’ and ‘Sevillano’ fruit are a slight, tannish to brown discoloration which develops in the flesh adjacent to the pit. Over time, the discoloration becomes more intense and progresses through the flesh into the skin, at which time the olive has the appearance of having been boiled.

Chilling injury becomes visible on olives stored for >2 weeks at 0 °C (32 °F), 5 weeks at 2 °C (35 °F), or 6 weeks at 3 °C (38 °F). The order of susceptibility to chilling injury, from most to least susceptible, is ‘Sevillano,’ ‘Ascolano,’ ‘Manzanillo,’ and ‘Mission.’

Ethylene Production and Sensitivity

Green olives produce <0.1 µL kg^{-1} h^{-1} ethylene, and black olives produce 0.5 µL kg^{-1} h^{-1} at 20 °C (68ºF). Though olives produce very little ethylene, they are moderately sensitive to ethylene at concentrations >1 µL L^{-1}, which causes a loss of green color and flesh firmness.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	10 to 20
7.5 °C	16 to 24
10 °C	24 to 32
20 °C	40 to 80

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Nailhead is characterized by surface pitting and spotting. It results from death and collapse of epidermal cells, creating air pockets underneath the skin. Symptoms are observed on olives kept at 10 °C (50 °F) for >6 weeks or at 7.5 °C (46 °F) for >12 weeks. CO_2 injury is evidenced by internal browning and increased incidence and severity of decay. It results from exposure to >5% CO_2 for more than 4 weeks.

Postharvest Pathology

Postharvest diseases occur if olives have been chilled at temperatures below 5 °C (41 °F), mechanically damaged, not cooled promptly after harvest to 5 to 7.5 °C (41 to 46 °F), or exposed to undesirable atmospheres (>5% CO_2 or <2% O_2).

Quarantine Issues

Since olive fruit fly *(Bactrocera oleae)* is present in many California olive-growing areas, a limited amount of fresh olives is imported from Mexico and Argentina. A very limited amount is exported to Canada. These exported and imported fresh olives are not fumigated with methyl bromide.

Issues associated with exotic pest quarantines addressing either imported or exported fresh olives can change rapidly. APHIS issues rules regarding import requirements. This agency provides information to assist exporters in targeting markets and defining what entry requirements a particular country might have for fresh olives. APHIS, in cooperation with the State plant boards, developed a database called “Excerpt” to track phytosanitary requirements for each country. APHIS provides phytosanitary inspections and certifications that declare fresh olives free of pests to facilitate compliance with foreign regulatory requirements.

Suitability as Fresh-Cut Product

Fresh olives are not edible or suitable as a fresh-cut product.

Special Considerations

Olives for pickling are harvested either unripe, in which case they remain green, or ripe, when they are purple and turn black during pickling. Olives for oil extraction can be harvested from the straw-color stage through the black-ripe stage.

Acknowledgments

Most of the information in this chapter is from the University of California, Davis, website on "Produce Facts" at http://postharvest.ucdavis.edu/produce_information.

Further Reading

Agar, I.T., B. Hess-Pierce, M.M. Sourour, and A.A. Kader. 1998. Quality of fruit and oil of black-ripe olives is influenced by cultivar and storage period. J. Agr. Food Chem. 46:3415-3412.

Ferguson, L., G.S. Sibbett, and G. Martin. 1994. Olive production in California. DANR Pub. no. 3353, University of California, Davis, CA.

Fernandez, A.G., M.J. Fernandez-Diez, and M.R. Adams. 1997. Table Olive Production and Processing. Chapman & Hall, London, U.K.

Kader, A.A., G. Nanos, and E. Kerbel. 1990. Storage potential of fresh 'Manzanillo' olives. Cal. Agric. 44(3):23-24.

Maxie, E.C. 1963. Storing olives under controlled temperature and atmospheres. Cal. Olive Assoc. Ann. Tech. Rpt. 42:34-40.

Maxie, E.C. 1964. Experiments on cold storage and controlled atmosphere. Calif. Olive Assoc. Ann. Tech. Rpt. 43:12-15.

Maxie, E.C., P.B. Catlin, and H.T. Hartmann. 1960. Respiration and ripening of olive fruits. Proc. Amer. Soc. Hort. Sci. 75:275-291.

Olias, J.M., and J.M. Garcia. 1997. Olive. *In* S. Mitra, ed., Postharvest Physiology and Storage of Tropical and Subtropical Fruits, pp. 229-243. CAB Intl., Wallingford, U.K.

Onion

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Scientific Name and Introduction

Onions (*Allium cepa* L., Cepa group) is a biennial of the Alliaceae family. The edible portions of the bulb are the enlarged leaf bases and compact stem. Green onions, also called scallions, are eaten for their immature bulb and green foliage. The predominant flavor component results from activity of the enzyme alliinase in broken or crushed tissue, yielding the volatiles propyl disulfide and methyl propyl disulfide. Major onion producers are China, India, United States, Turkey, Japan, Spain, Holland, Poland, and Ukraine.

Quality Characteristics and Criteria

High-quality onions have mature bulbs with good firmness and compactness of fleshy scales. Size, shape, and the color of the dry skin should be typical for the variety. They should be free of mechanical or insect damage, decay, sunscald injury, greening of fleshy scales, sprouting, bruising, doubles, bottlenecks (onions which have abnormally thick necks with only fairly well developed bulbs), and any other defects.

Horticultural Maturity Indices

Harvest maturity depends on the purpose for which the onions are grown. Onions intended for storage should be harvested when 50 to 80% of the tops have fallen over and bulbs are mature with a thin neck. Yields are higher if they are harvested after the tops are completely dry, but then bulbs tend to have a shorter storage life. To hasten maturity, tops can be rolled with a light roller when 10% of them have fallen. About 7 days before lifting, bulbs can be undercut by a blade; such onions should not be used for long-term storage. Onions for bunching can be harvested from the time they are pencil-sized until they have proper bulb size.

Grades, Sizes, and Packaging

Grades for green onions include U.S. No. 1 and U.S. No. 2 based on external appearance and size. For U.S. No. 1, the overall length (excluding roots) must be 20 to 61 cm (8 to 24 in), and the diameter of the bulb 6.4 to 25.4 mm (0.25 to 1 in). Sizes are based on bulb diameter: Small, <12.7 mm (0.5 in); Medium, 12.7 to 25.4 mm (0.5 to 1 in); and Large, >25.4 mm (>1 in). Trimmed green onions are bunched and marketed as bulb-type in 9.1 and 12.7 kg (20 and 28 lb) cartons, and as 24, 36 and 48 count, bunched in 9.1, 5.0 and 5.9 kg (20, 11 and 13 lb) containers, respectively.

Grades of Bermuda-Granex-Grano type onions include U.S. No. 1, U.S. No. 2, and U.S. Combination and are based on external appearance and size. U.S. Combination consists of a mixture of U.S. No. 1 and U.S. No. 2 onions in which at least 50% (by weight) of the onions in each lot meet the requirements of U.S. No. 1 grade. Bulb diameters are defined as follows:

Small, 2.5 to 5.7 cm (1 to 2.25 in); Prepacker, 4.5 to 7.6 cm (1.75 to 3 in); Medium, 5.1 to 8.3 cm (2 to 3.25 in.); Large or Jumbo, 7.6 to 9.5 cm (3 to 3.75 in); and Colossal, >9.5 cm (3.75 in). Containers vary from 2.3 to 22.7 kg (5 to 50 lb) with 9.1 kg (20 lb) being the most common size.

For onions other than Bermuda-Granex-Grano and Creole types, there are five Grades:

U.S. No. 1, U.S. Export No. 1, U.S. Commercial, U.S. No. 1 Boilers, U.S. No. 1 Picklers, and U.S. No. 2. The sizing of onions in this group is the same as above. Containers are usually 9.1 kg (20 lb), except for export onions, which are packed in 25-kg (56-lb) containers.

Precooling Conditions

In order to maintain high quality, bunched green onions should be precooled to <4 °C (39 °F) within 4 to 6 h of harvest. Hydrocooling, forced-air cooling, and vacuum-cooling are used with crushed ice over the product to maintain temperature and moisture.

Dry onion bulbs for long-term storage should be precooled to 0 °C (32 °F) immediately after drying, or within 1 mo using cool outside air. The precooling method affects storability. Rapid precooling inhibits rooting and sprouting during storage. Natural cooling (slow) has a positive effect on storability when onions have a long rest period and weather conditions are good for curing. Gradual cooling at 1 °C (1.8 °F) per day in storage is less effective at inhibiting sprouting and rooting than rapid cooling (Grzegorzewska 1999).

Optimum Storage Conditions

Bunched green onions can be stored 3 to 4 weeks at 0 °C (32 °F) with 95 to 98% RH. Under these conditions, bunched onions stored in polyethylene-lined containers and top-iced maintain excellent quality for 1 mo. Storage life decreases to 1 week if the temperature is 5 °C (41 °F), and rapid yellowing and decay of leaves occurs at higher temperatures.

Pungent dry onions can be stored for 6 to 9 mo at 0 °C (32 °F) with 65 to 75% RH. High RH induces root growth, while high temperature induces sprouting. A combination of high temperature and high RH increases rotting and decreases quality. Storage below the freezing point of -1 to -2 °C (28 to 30 °F) is recommended in Europe. Mild type or sweet onions can be kept for 1 to 3 mo; they are stored in common storage with cool, circulating ambient air or in refrigerated cold rooms. Onions grown from seed store better than those grown from sets or transplants.

After harvest, onion bulbs enter a state of rest for 4 to 6 weeks, depending on cultivar and weather conditions during growth. Maleic hydrazide, a sprouting inhibitor, is often used to prevent root growth and sprouting during long-term storage. It is applied 2 weeks before harvest, when bulbs are mature and 50% of tops are down, but onion plants must still have five to eight green leaves in order to absorb and translocate the sprout inhibitor to bulbs.

Onions intended for storage should be dried well and cured in the field, under sheds, or in storage. After 2 weeks of field drying, onions can be transferred to storage rooms for final drying and curing. Forced-air ventilation at 25 to 27 °C (77 to 81 °F) using outside or heated air is commonly used to dry onions. Onions can be stored and dried on the floor in bulk 3 to 4 m deep or in 500 to 1,000 kg (1,100 to 2,200 lb) boxes. Drying is complete when the onion neck is tight, outer scales are dry and make a rustling noise when touched, and the skin color is uniform. Weight loss of 3 to 5% can occur during drying. Losses from neck rot are reduced by rapid drying immediately after harvest. After drying and curing, the temperature should be lowered gradually to the normal seasonal temperature, or bulbs can be precooled in cold storage at 0 °C (32 °F). In either case, condensation should be avoided as it encourages rot and changes the color of the dry skin.

In most European countries and in the Northern United States, onions are stored in common storage, using cool, ambient air to maintain optimum temperature and RH. In this condition, onions are usually stored only until the end of March or beginning of April, since further storage can cause losses to sprouting and rotting.

Refrigerated storage is used for onions that are to be marketed in late April to early July. For cold storage, onions are usually packed in crates or containers. Air circulation must be sufficient to maintain a constant temperature and remove moisture from inside storage containers. Onions packed in sacks can only be stored for a limited period, about 1 mo, since air movement through sacks is insufficient to maintain proper storage conditions. When stored below -1 to -2 °C (28 to 30 °F), onions should be thawed at 5 °C (41 °F) for 1 to 2 weeks before they are removed from storage. Rapid thawing damages onion bulbs.

Mild and sweet onions can be stored for only 1 to 4 mo, even in optimal cold storage. CA may extend the storage period. Onions tolerate storage at 30 to 35 °C (86 to 95 °F) for short periods before marketing or processing, but their quality and external color is less attractive than that of cold-stored onions.

Controlled Atmosphere (CA) Considerations

Bunched green onions can be stored for 6 to 8 weeks in 2% O_2 and 5% CO_2 at 0 °C (32 °F). They can tolerate 1% O_2 and up to 5% CO_2, but off flavor may develop if they are stored at >5 °C (41 °F) (Suslow and Cantwell 1998).

Low-O_2 atmospheres reduce respiration and extend storage life, while elevated CO_2 reduces sprouting and root growth. CA has been used for storage of pungent onions in England, Switzerland, and Poland (Adamicki 1998). An atmosphere of 3% O_2 and 5% CO_2 inhibits rooting, sprouting ,and disease development (Adamicki and Kepka 1974, Smittle 1988). However, onions stored in 3% O_2 and 10% CO_2 showed physiological disorders; high CO_2 caused injury, but neck rot (*Botrytis* spp.) was reduced (Sitton et al. 1997).

CA can have also residual effects. After storage for up to 226 days in 3% O_2 and 5% CO_2, sprouting of 'Wolska' onions at 20 °C (68 °F) was delayed for 10 days, compared to air-stored controls (Adamicki and Kepka 1974). It is possible to store onions in low O_2 (1 to 2%) with 2% CO_2 (Adamicki 1998, Tanaka et al. 1996). There is some commercial use of 3% O_2 and 5 to 7% CO_2 for sweet onion cultivars (Smittle 1989, Mikitzel et al. 1993, Sitton et al. 1997).

Retail Outlet Display Considerations

Onion bulbs can be displayed in small packages or in bulk at <5 °C (41 °F). This temperature effectively retards sprouting for up to 7 mo. Onions should not be stored with fruits and vegetables that tend to absorb odors.

Chilling Sensitivity

Onions are not sensitive to chilling and can be stored at -2 to -3 °C (28 to 27 °F), since the highest freezing point is -0.8 °C (31.6 °F). Storage at <-4 °C (25 °F) may cause freezing injury.

Ethylene Production and Sensitivity

Ethylene production is very low: < 0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F) (Suslow and Cantwell 1998). Sensitivity to ethylene is also low, but concentrations of >1,500 µL L^{-1} encourage sprouting of onion bulbs.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	3
5 °C	5
10 °C	7
15 °C	7
20 °C	8

Data from Robinson et al. (1975).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Onion bulbs are affected by several physiological disorders. Freezing injury causes soft, water-soaked, fleshy scales and rapid decay after transfer from cold storage to higher temperature, which results in microbial growth. Translucent scales resemble freezing injury and are prevented by prompt cold storage following curing. Translucent scales occur with loss of or changes in carbohydrate content. Storage of onions at >7% CO_2 can also lead to development of translucent scales. Late harvesting and a long drying period at high temperatures produce the highest incidence of translucent scales.

Watery scales is a thick leathery skin with watery, glassy, fleshy scales below. The watery scales may later be affected by fungal or bacterial growth. Late harvesting and prolonged field drying produce the highest occurrence of leathery skin. Scale greening, a green coloration of outer scales, is caused by exposure to light after curing. Ammonia injury is indicated by brown-black blotches resulting from leakage of ammonia during storage (Adamicki and Kepta 1974, Smittle 1988, Hoftun 1993, Suslow and Cantwell 1998, Solberg 1999).

Postharvest Pathology

A number of microorganisms attack onions postharvest.

Botrytis neck rot is indicated by watery decay, which begins at the neck and then attacks the entire bulb. A gray fungal mold then covers the neck of the bulb and later the whole bulb surface. Neck rot can be slowed after harvest, but it cannot be stopped, even during storage under optimum conditions. Proper drying in the field and during storage can decrease this postharvest fungal decay disease.

Black mold rot presents a black discoloration and shriveling at the neck and on outer scales caused by *Aspergillus niger* van Tiegh. Infection usually occurs in the field, but the disease spreads from bulb to bulb postharvest. The surface of bulbs must be dry during and after harvest to avoid infection. Storage at 0 °C (32 °F) with moderate RH prevents the spread of this disease.

Blue mold rot also produces watery soft rot of neck and outer scales, followed by formation of blue to blue-green mold of the fungus *Penicillium* spp. Harvest of mature bulbs, proper curing, and storage at 0 °C (32 °F) with 60 to 70% RH minimizes blue mold problems.

Bacterial soft rot, caused by *Erwinia carotovora* Jones, develops water-soaked individual scales, or the entire onion, with foul smelling, viscous, liquid-covered rotted areas. The disease progresses rapidly under warm, humid conditions. Harvesting at full maturity, proper drying, minimizing bruising, and maintaining optimum storage conditions prevent bacterial soft rot (Ryall and Lipton 1983, Suslow and Cantwell 1998).

Quarantine Issues

Onions intended for export should be free from *Ditylenchus dipsaci* Kühn.

Suitability as Fresh-Cut Product

Demand for fresh-cut onions (ready-to-eat) is increasing.

References

Adamicki, F. 1998. Effect of controlled atmosphere on storage and quality of onions. 25th International Horticulture Congress, Brussels, Belgium, vol. 1, pp. 365. International Society for Horticultural Science, Leuven, Belgium.

Adamicki, F., and A. Kepka. 1974. Storage of onions in controlled atmosphere. Acta Hort. 38:53-75.

Grzegorzewska, M. 1999. The Influence of Weather Conditions, Harvest Maturity and Cooling Methods on the Quality and Storage Ability of Onions. Ph.D. thesis, Research Institute of Vegetable Crops, Instytut Warzywnictwa, Skierniewice, Poland.

Hoftun, H. 1993. Internal atmosphere and watery scales in onion bulbs (*Allium cepa* L.). Acta Hort. 343:135-140.

Mikitzel, L.J., M.E. Patterson, and H. Waelti. 1993. The effect of CA storage on the postharvest life of sweet onions. *In* 6th International Controlled Atmosphere Research Conference, Ithaca, NY, June 1993, NRAES-71, vol. 2, pp. 789-796. Northeast Regional Agricultural Engineering Service, Cornell University, Ithaca, NY.

Robinson, J.E., K.M. Browne, and W.G. Burton. 1975. Storage characteristics of some vegetables and soft fruits. Ann. Appl. Biol. 81:399-408.

Sitton, J.W., J.K. Fellman, and M.E. Patterson. 1997. Effects of low-oxygen and high-carbon dioxide on postharvest quality, storage and decay of "Walla Walla" sweet onions. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 4, pp. 20-25. University of California, Davis, CA.

Solberg, S.O. 1999. Effects of harvesting and drying methods on internal atmosphere, outer scale appearance, and storage of bulb onions. J. Veg. Crop Prod. 42:23-35.

Ryall, A.L., and W.J. Lipton. 1983. Handling, Transportation, and Storage of Fruits and Vegetables, 2nd ed., vol. 1. AVI, Westport CT.

Smittle, D.A. 1988. Evaluation methods for 'Granes' onions. J. Amer. Soc. Hort. Sci.113:877-880.

Smittle, D.A. 1989. Controlled atmosphere storage of vidalia onions. *In* J.K. Fellman, ed., Proceedings of the 5th International Controlled Atmosphere Research Conference, Wenatchee, WA, pp.171-177.

Suslow, T., and M. Cantwell. 1998. Onions: dry. Recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

Tanaka, K., Y. Matsuo, and J. Egashira. 1996. Controlled atmosphere storage for onions. *In* T. Kozai, ed., Proceedings of the International Symposium on Plant Products in Closed Ecosystems, Narita, Japan, 1996, pp. 669-674. Acta Hort., Leuven, Belgium.

Orange

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Scientific Name and Introduction

The sweet orange (*Citrus sinensis* L. Osbeck) is a dicotyledonous, perennial evergreen of the Rutaceae family that leads other *Citrus* species in both production area and value. Fruit vary from spherical to oblong and are seedless (0 to 6 seeds) to seeded (>6 seeds). Peel color at maturity ranges from light to deep orange but may remain green under warm conditions. Late season 'Valencia' oranges may turn from orange to green ("regreen") under warm conditions.

Sweet oranges are generally classified into one of four groups: (1) round oranges such as 'Valencia,' 'Hamlin,' 'Pineapple,' and 'Shamouti'; (2) navel oranges such as 'Washington Navel'; (3) blood or pigmented oranges such as 'Moro' and 'Tarocco'; and (4) acidless oranges such as 'Succari.' In the United States, the leading orange-growing States are Florida, California, Texas, and Arizona. Of these, Florida is the largest producer of oranges; over 90% go for processing. California is the largest producer of oranges for the fresh market. Like other citrus fruits, oranges are nonclimacteric with no postharvest ripening phase.

Quality Characteristics and Criteria

A high-quality orange is mature, with good color intensity that is uniformly distributed over the surface. Fruit must be firm with a fairly smooth texture and shape that is characteristic of the variety. Fruit should be free from decay, defects, and blemishes.

Horticultural Maturity Indices

Maturity indices are based on percentage color break, SSC, TA, SSC:TA, and juice content. Specific regulations are established for different growing regions.

Florida: Minimum maturity indices for fresh fruit shipments change according to harvest date and are based on SSC and SSC:TA:

Date	SSC Minimum	SSC:TA ratio Minimum
	------------------%-------------	
Aug. 1 to Oct. 31	9.0	10.00
Nov. 1 to Nov. 15	8.7	10.15
Nov. 16 to July 31	8.5	10.25

Florida oranges also have minimum requirements for TA (0.4%) and juice content (4.5 gal per 1.6-bu box).

California and Arizona: For fruit with yellow-orange color on ≥25% of the surface, SSC:TA must be 8 or higher; and for fruit with green-yellow color on ≥25% of the surface, SSC:TA ratio must be 10 or higher.

Texas: To meet minimum maturity, fruit must have 8.5 to 8.9% SSC with a SSC:TA ratio of 10 or higher, or must have SSC of 9% or higher with a SSC:TA of 9 or higher. Texas oranges also have a minimum juice content of 4.5 gal per 1.6-bu box.

Grades, Sizes, and Packaging

U.S. grade standards for sweet oranges are based on maturity, color intensity and uniformity, firmness, shape, size, smoothness, and freedom from decay, as well as freedom from defects (bruises and abrasions), insects, fungal attack (for example, cake melanose), growth cracks, chemical burns, and physiological disorders. See http://www.ams.usda.gov/AMSv1.0/standards for more details on State-specific grade standards.

U.S. grades for Florida oranges (AMS 1997): U.S. Fancy, U.S. No. 1 Bright, U.S. No. 1, U.S. No. 1 Golden, U.S. No. 1 Bronze, U.S. No. 1 Russet, U.S. No. 2 Bright, U.S. No. 2, U.S. No. 2 Russet, U.S. No. 3. Standard packed sizes used in Florida include 64, 80, 100, 125, and 163 fruit per 28.2-L (4/5 bu) container (Florida Department of Citrus 1999).

U.S. grades for California and Arizona oranges (AMS 1999): U.S. Fancy, U.S. No. 1, U.S. Combination, U.S. No. 2. Standard packed sizes used in California include 24, 32, 36, 40, 48, 56, 72, 88, 113, 138, 163, 180, 210, 245, and 270 fruit per 28.5-L (4/5 bu) container (California Department of Food and Agriculture 1990).

U.S. grades for Texas and States other than Florida, California, or Arizona (AMS 1969): U.S. Fancy, U.S. No. 1, U.S. No. 1 Bright, U.S. No. 1 Bronze, U.S. Combination, U.S. No. 2, U.S. No. 2 Russet, U.S. No. 3. Standard packed sizes used in Texas and States other than Florida, California and Arizona include 48 or 50, 64, 80, 100, 125, 144, and 162 fruit per 24.7-liter (7/10-bushel) container (AMS 1969).

Well-vented polyethylene and plastic mesh bags of various sizes are also used to market oranges. Oranges may be individually seal-packaged (wrapped with various plastic films), but this practice has not been widely adopted.

Precooling Conditions

Rapid cooling is often neglected in many citrus packinghouses but should be seriously considered as a means of improving fruit quality at destination markets. Cooling reduces respiration, slows pathogen growth, reduces water loss, and increases shelf-life. Common cooling methods for oranges include room-cooling and forced-air cooling. Oranges can also be hydrocooled, but this practice is seldom used because of the increased risk of spreading decay organisms. For room-cooling and forced-air cooling, maintaining good airflow through cartons is important to rapidly remove heat from the product. To facilitate this, carton design should include at least 5% side venting, designed to line up with adjacent carton vents and allow airflow through the entire load.

Optimum Storage Conditions

Under normal weather conditions, fruit store better on the tree than in cold storage. Cold storage should not be attempted if the fruit storage potential has been expended by prolonged tree storage. Once harvested, fruit quality will not improve. Before being placed into storage, fruit should be precooled to slow respiration and treated with an approved fungicide to reduce decay. Oranges can be stored for up to 12 weeks under optimum storage conditions. Ultimate storage life depends on cultivar, maturity, preharvest conditions, and postharvest handling. Oranges begin to freeze in storage at about -1 °C (30 °F) (Whiteman 1957). During storage, fruit should be inspected often for signs of decay or disorders. Such problems will advance rapidly once the fruit are removed from cold storage.

Recommended storage conditions are—

Growing Region	Temperature	Relative Humidity
Florida & Texas	0 to 1 °C	85 to 90%
California & Arizona	3 to 8 °C	90 to 95%

Controlled Atmosphere (CA) Considerations

CA of 5 to 10% O_2 and 0 to 5% CO_2 may aid in retaining quality of oranges. Decreased O_2 levels help maintain firmness and retard senescence, while high CO_2 levels can inhibit the development of chilling injury. However, CA is not commonly used because tolerable O_2 and CO_2 levels do not significantly inhibit decay (Hatton and Cubbedge 1977), which limits shelf-life the most. Addition of 5 to 10% CO to CA may improve decay control but is dangerous because it is lethal to humans. Maintaining low ethylene (<1 µL L^{-1}) during CA storage may improve flavor retention and reduce stem-end decay (McGlasson and Eaks 1972).

Retail Outlet Display Considerations

Oranges should be displayed on nonrefrigerated shelves and inspected often to remove damaged or decaying fruit.

Chilling Sensitivity

California and Arizona oranges may develop chilling injury when held at temperatures below about 3 to 5 ºC (37 to 41 ºF). Oranges produced in Florida or Texas rarely show chilling injury. Symptoms of chilling injury include pitting, brown staining, increased decay, internal discoloration, off flavors, and watery breakdown that may take 60 days to develop at 5 °C (41 °F) or become evident 1 to 2 days after moving to room temperature (about 72 °F). After removing fruit from chilling temperatures, respiration and ethylene production both increase.

The development and severity of chilling injury in citrus is influenced by both preharvest and postharvest factors. Preharvest factors include cultivar, weather conditions, and even location of fruit on the tree (sun-exposed fruit are more susceptible to chilling injury). Postharvest development of chilling injury symptoms can be reduced by temperature conditioning before storage, use of high-CO_2 atmospheres (for example, in CA or through the use of wax coatings or plastic film wraps), intermittent warming, and use of benzimidazole fungicides (such as thiabendazole and benomyl). The best means of preventing chilling injury is storing fruit at nonchilling temperatures.

Ethylene Production and Sensitivity

Citrus produce very little ethylene: <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F). Ethylene is used to degreen oranges, especially early in the season when natural degreening has been delayed because of warm night temperatures. Degreening usually takes 1 to 3 days to complete and does not affect internal quality (SSC, TA, etc.). However, ethylene stimulates decay, such as anthracnose (Brown 1992) and stem-end rot (Barmore and Brown 1985), especially at >10 µL kg^{-1} h^{-1}. Ethylene also increases respiration in citrus.

Conditions for degreening (Kader and Arpaia 1992, Wardowski 1996) are—

	Florida	California
Temperature	28 to 29 ºC	20 to 25 ºC
Ethylene	5 µL L^{-1}	5 to 10 µL L^{-1}
RH	90 to 96%	90%
Ventilation (<0.1% CO_2)	1 air change per hour	1 to 2 air changes per hour
Air Circulation	100 ft^3 min^{-1} per 900-lb bin	1 room volume per min

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	2 to 6
5 °C	4 to 8
10 °C	6 to 10
15 °C	11 to 22
20 °C	20 to 31

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Creasing (albedo breakdown) results from the irregular deterioration of albedo cells (white spongy tissue) and the collapse of the overlaying flavedo (colored portion of the rind) into irregular grooves over the fruit surface. Such areas are weaker and often split, providing entry for pathogenic fungi and subsequent decay. This disorder is usually more common on thin-skinned, fully mature fruit. Conditions giving rise to creasing are complex and not well understood, but appear to be related to cultivar, potassium nutrition deficiencies, high levels of nitrogen, rootstock, water status, and temperature during fruit expansion. Because the disorder is associated with advanced fruit maturity, earlier fruit harvesting may also reduce the problem.

Granulation is caused by gel formation within juice vesicles that greatly reduces extractable juice content. It may occur primarily at the stem end (in 'Valencia' oranges), or extend through the center of the fruit (in navel oranges). In the United States, this is considered a preharvest disorder that appears more in fruit exposed to the sun, fruit from young or water-stressed trees, overmature fruit, or fruit from vigorously growing trees. In other parts of the world, the disorder also develops after harvest.

Oil spotting (oeocellosis) arises when mechanical damage releases oil from the oil glands. When fruit are very turgid, even slight pressure from bumps and abrasions can result in oil release and spotting. The oil is toxic to surrounding tissue and will inhibit degreening of that tissue. Symptoms appear as irregularly shaped green, yellow, or brown spots that darken over time and make the glands more prominent. The most effective means of prevention is not harvesting turgid fruit early in the morning, when dew is present, during foggy conditions, or immediately after rain or irrigation (Wardowski et al. 1997).

Postharvest pitting is characterized by clusters of collapsed oil glands (often 5 to 20) scattered over the fruit surface. It can begin to develop 2 days after packing. Collapsed regions turn bronze-brown or brown-black over time. This disorder is associated with low O_2 levels in fruit following application of wax coating having low O_2 permeability and holding at warm temperatures >10 °C (50 °F; Petracek et al. 1998).

Rind staining is associated with physiologically overmature fruit that are easily injured by mechanical abrasions, particularly navel oranges. Brown or reddish-brown blemishes develop 12 to 24 h after washing and waxing (Eaks 1964). In California, fruit are sprayed with gibberellic acid to delay peel senescence and reduce incidence of this disorder.

Stem-end rind breakdown (SERB) is characterized by the irregular collapse and darkening of rind tissue around the stem end of the fruit. A narrow ring of unaffected tissue immediately around the stem (button) is a distinctive symptom of SERB. In some growing regions, SERB has been correlated with a preharvest imbalance in nitrogen and potassium. Postharvest, SERB is primarily associated with drying conditions and fruit water loss, particularly between harvest and waxing. Postharvest practices that minimize water loss, such as maintaining high RH during degreening, rapid handling, avoiding excessive brushing, and promptly applying an even coat of wax, are currently the best means of reducing SERB.

Postharvest Pathology

Postharvest decay is the most important factor limiting shelf-life of oranges. Oranges are susceptible to a wide variety of fungal diseases, including green mold *(Penicillium digitatum)*, blue mold *(Penicillium italicum)*, diplodia stem-end rot *(Diplodia natalensis)*, phomopsis stem-end rot *(Phomopsis citri)*, brown rot *(Phytophthora citrophthora)*, sour rot *(Geotrichum candidum)*, and anthracnose rot *(Colletotrichum gleosporioides)*.

Factors such as growing region, production practices, cultivar, rootstock, and postharvest practices influence susceptibility to each of these pathogens. For example, stem-end rots are more prevalent under environmental conditions found in Florida and Texas. Green mold predominates in Florida, but blue mold does so in California. Postharvest decay can be reduced by harvesting at optimum maturity, gently handling fruit during harvest and postharvest operations, maintaining sanitary facilities and water handling systems, prompt cooling, storing at optimum temperature and RH, and using approved fungicides or biological control agents.

Quarantine Issues

Oranges are a fruit fly host, and when produced in areas where any fruit fly is found, must be treated for insect control before shipment to some markets. Approved disinfestation for oranges include methyl bromide fumigation, cold treatments, and vapor heat treatments. Use of methyl bromide is being phased out and will no longer be available by the year 2005. Cold treatments are commonly used but may result in chilling injury. Irradiation and controlled atmospheres are potential alternative disinfestation treatments.

All disinfestation treatments can result in phytotoxic injury to the fruit, with the degree of injury depending on preharvest factors such as cultivar and stage of maturity. As an alternative to disinfestation treatments, some production areas have established protocols that are accepted by receiving markets for certifying "fly-free" areas. Oranges grown in these areas do not have to be treated before shipment.

Suitability as Fresh-Cut Product

Consumers' preference for peeled, sectioned, or cubed oranges that are ready to eat has driven research and development of new technologies and equipment to help meet this demand. Fresh-cut oranges can maintain quality for about 12 days, but mechanically removing the peel has been problematic. Though there are several different peeling technologies developed or under development, none is yet widely adopted.

Acknowledgments

Some information in this chapter is from the University of California, Davis, website "Fresh Produce Facts" at http://postharvest.ucdavis.edu/produce_information.

References

AMS [USDA Agricultural Marketing Service]. 1969. United States Standards for Grades of Oranges (Texas and States Other Than Florida, California and Arizona). U.S. Department of Agriculture, Washington, DC.

AMS [USDA Agricultural Marketing Service]. 1997. United States Standards for Grades of Florida Oranges and Tangelos. U.S. Department of Agriculture, Washington, DC.

AMS [USDA Agricultural Marketing Service]. 1999. United States Standards for Grades of Oranges (California and Arizona). U.S. Department of Agriculture, Washington, DC.

Barmore, C.R., and G.E. Brown. 1985. Influence of ethylene on increased susceptibility of oranges to *Diplodia natalensis*. Plant Dis. 69:228-230.

Brown, G.E. 1992. Factors affecting the occurrence of anthracnose on Florida citrus. Proc. Intl. Soc. Citricult. 3:1044-1048.

California Department of Food and Agriculture. 1990. Administrative Code, Title 3. State of California, Sacramento, CA.

Eaks, I.L. 1964. The effect of harvesting and packing house procedures on rind staining of central California 'Washington' navel oranges. Proc. Am. Soc. Hort. Sci. 85:245-256.

Florida Department of Citrus. 1999. Official rules affecting the Florida citrus industry: pursuant to Chap. 601. Florida Statutes, Lakeland, FL.

Hatton, T.T., and R.H. Cubbedge. 1977. Status of controlled-atmosphere storage research of citrus fruit. *In* D.H. Dewey, ed., 2nd National Controlled Atmosphere Research Conference, pp. 250-259. Hort. Rpt. 28., Michigan State University, East Lansing, MI.

Kader, A.A., and M.L. Arpaia. 1992. Postharvest handling systems: subtropical fruits. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, 2nd ed., pp. 233-240. DANR Pub. no. 3311, University of California, Davis, CA.

McGlasson, W.B., and I.L. Eaks. 1972. A role for ethylene in the development of wastage and off-flavors in stored valencia oranges. HortScience 7:80-81.

Petracek, P.D., H. Dou,, and S. Pao. 1998. The influence of applied waxes on postharvest physiological behavior and pitting of grapefruit. Postharv. Biol. Technol. 14:99-106.

Wardowski, W.F. 1996. Recommendations for degreening Florida fresh citrus fruits. Circular 1170, University of Florida, Institute of Food and Agricultural Science, Gainesville, FL.

Wardowski, W.F., P.D. Petracek, and W. Grierson. 1997. Oil spotting (oleocellosis) of citrus fruit. Circular 410, University of Florida, Institute of Food and Agricultural Science.

Whiteman, T.M. 1957. Freezing points of fruits, vegetables and florist stocks. Marketing Research Report 196, U.S. Department of Agriculture, Washington, DC.

Papaya

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Scientific Name and Introduction

Papaya, papaw, or paw paw *(Carica papaya* L.) is cultivated throughout the tropics for its fruit (Nakasone 1986). Fruit are eaten green or ripe, in salads or fresh. The related Ecuadorian babaco *(C. pentagonia)* is also eaten fresh.

Fruit are pyriform (pear-shaped), spherical, or cylindrical. The pyriform, hermaphroditic fruit is the most common in commerce. These belong to the 'Solo' group and includes the cultivars 'Kapoho,' 'Rainbow,' 'Sunup,' 'Sunrise,' and 'Sunset'; these varieties weigh 300 to 700 g (10 to 25 oz). Other varieties range from 200 g to 10 kg (0.4 to 22 lbs), with flesh 1.5 to 4 mm (0.06 to 0.16 in) thick. Flesh is greenish-white in immature fruit to pale orange-yellow, salmon pink, or red, depending on cultivar, when ripe.

Quality Characteristics and Criteria

Size, shape, a smooth skin, and absence of blemishes are major quality characteristics. Consumers in Western countries also prefer fruit without a heavy musky, sweaty odor found in some Southeast Asian cultivars. Small, dry, brown-black "freckles" on the skin are nonpathogenic and do not detract from ripening or flavor (Reyes and Paull 1994).

Horticultural Maturity Indices

In Hawaii, minimum grade standard requires 11.5% SSC (Hawaii Department of Agriculture 1990), so fruit should have started ripening before harvest, indicated by some skin yellowing (Akamine and Goo 1971). Less mature fruit are lower in sugar and ripen poorly.

Grades, Sizes, and Packaging

The most common package size is a 4.5-kg (10-lb) carton; larger 10-kg (22-lb) cartons are also used. Cartons from areas requiring insect disinfestation are fully sealed to meet regulatory requirements, while fruit from other areas can be in open-topped cartons. Count size ranges from 6 to 18, depending on fruit and carton size. Fruit are marketed as color break, quarter, half, or three-quarters ripe and are normally ready to eat when there is 75% or more skin color. Foam mesh sleeves, foam padding on the bottom of cartons, or paper wrapping prevents abrasion injury, a major problem in fruit still having green areas of skin (Quintana and Paull 1993).

Precooling Conditions

Room-cooling and forced-air cooling are commonly used. Hydrocooling is possible. However, rapid cooling after insect disinfestation treatments can lead to skin scalding.

Optimum Storage Conditions

Store at 7 to 13 °C (45 to 55 °F) with 90 to 95% RH. At 7 to 10 °C (45 to 50 °F), storage life is limited by chilling injury, while at 10 to 13 °C (50 to 55 °F) fruit ripens slowly (Chen and Paull 1986). Papaya fruit at color-turning (break) stage can be stored at 7 °C (45 °F) for 14 days and will ripen normally when transferred to room temperature (Thompson and Lee 1971, Chen and Paull 1986). Ripe, full-color fruit can be held for >1 week at 1 to 3 °C (34 to 37 °F).

Controlled Atmosphere (CA) Considerations

Shelf-life was extended 1 to 1.5 days when papaya were stored at 12 °C (54 °F) in 1 to 1.5%

O_2 for 6 days (Akamine and Goo 1969). Low O_2 (1 to 5%), with or without high CO_2 (2 to 10%), reduces decay (Hatton and Reeder 1969) and delays ripening (Akamine 1959, Chen and Paull 1986). High CO_2 (30%) adversely affects internal color, aroma, and flavor, while there is no residual effect of 10% CO_2 on decay control, though skin degreening is delayed.

At 10 °C (50 °F), fruit can be stored for 36 days in 8% CO_2 and 3% O_2 and still have 5 days at 25 °C (77 °F) for retail (Cenci et al. 1997). Ethylene removal prior to storage has shown variable results (Nazeeb and Broughton 1978). CA recommendations are 2 to 5% O_2 plus 5 to 8% CO_2. However, no commercial use has so far been reported (Yahia 1998). Fruit stored at 10 °C (50 °F), 98% RH, and low pressure of 20 mm Hg ripened more slowly than fruit at normal atmospheric pressure. Low-pressure storage appears to suppress disease development (Alvarez 1980, Chau and Alvarez 1983).

Retail Outlet Display Considerations

The optimum temperature for fruit ripening is 23 to 28 °C (73 to 82 °F), with fruit taking 10 to 16 days to reach full skin yellowing from the color-break stage (An and Paull 1990). Severe weight loss and external abnormalities become significant at temperatures higher than 28 °C (82 °F). Display temperatures should not be less than 10 °C (50 °F) if fruit are not fully ripe. Fully ripe fruit at the edible stage can be held at 1 to 3 °C (34 to 37 °F). Fruit should not be stacked more than two or three deep in racks, and wicker baskets with uneven bottoms and sides should be avoided; or at least a layer of protection should be placed between racks and fruit (Paull et al. 1997). Loss of about 8% of weight from color break produces rubbery, low-gloss, unmarketable fruit (Paull and Chen 1989). Diseased and bruised fruit should be removed from display and used immediately, if possible, in salads or mixed fruit cocktails. Papaya should not be misted.

Chilling Sensitivity

Chilling injury symptoms include skin scald, hard lumps in the pulp around vascular bundles, and water-soaking of flesh (Thompson and Lee 1971, El-Tomi et al. 1974, Chen and Paull 1986). Fruit become progressively less susceptible to chilling stress as they ripen (Chen and Paull 1986). Symptoms of chilling injury occur after 14 days at 5 ºC (41ºF) in mature green fruit and 21 days in 60% yellow fruit. Skin scald can be induced in color-break fruit after chilling at 1 ºC (34 ºF) for 24 h. At a storage temperature of 7 ºC (45 ºF) for 14 days, storage decay is less than when fruit are held at 12 to 13 ºC (54 to 55 ºF) (Arisumi 1956, El-Tomi et al. 1974).

Ethylene Production and Sensitivity

Ethylene rates in ripening fruit are 6 to 10 µL kg^{-1} h^{-1} (Paull and Chen 1983, Paull 1993). Ethylene-treated papaya ripen faster and more uniformly in terms of skin degreening, softening, and flesh color (An and Paull 1990). Since papaya ripen from the inside outwards, the effect of ethylene treatment is to accelerate the rate of ripening of the mesocarp tissue nearer the skin that has not started to soften. Ethylene is not recommended commercially, as rapid softening severely limits available marketing time (An and Paull 1990).

Respiration Rates

Papaya are climacteric and begin to yellow from the blossom end (Akamine 1966).

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	4 to 6
15 °C	15 to 22
20 °C - color break	9 to 18
20 °C - ripe	70 to 90

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

A number of nonpathological disorders are seen in marketed fruit (Paull et al. 1997). Green, slightly sunken areas on ripe yellow fruit are caused by abrasion injury when fruit were still green (Quintana and Paull 1993). Unsightly skin freckles (small, brown, slightly raised areas) that are more common on the side of the fruit exposed to the sun is seasonal, developing when rainfall and low temperatures occur 2 mo before harvest (Reyes and Paull 1994). This disorder is nonpathogenic and does not influence ripening or flavor. Sunscald, a dark-olive-brown discoloration, occurs on fruit developing on trees with very sparse foliage, on trees that are leaning over with fruit directly exposed to the sun, and where harvested fruit are left exposed to the sun.

Blossom end defect can be severe at some times of the year (Zee et al. 1989). It leaves an open channel at the blossom end to the fruit seed cavity. Fruit with this disorder are prone to bacterial diseases in the fruit seed cavity before harvest.

Hard lumps in the flesh occur infrequently in otherwise ripe, non-heat-treated fruit (Magalona 1963, Cavaletto 1989). The lumps are thought to be associated with insect injury, disease, or other foreign material in the flesh. The condition can also occur in heat-treated fruit. Premature ripening of fruit, referred to as “soft fruit,” is related to low calcium content. This condition is more common following periods of heavy rainfall 2 to 3 mo before harvest, at the start of the final phase of fruit growth (Qiu et al. 1995).

Intra-ovarian ovaries are common in some strains of papaya (Nakasone and Arkle 1971). These ovaries occur as a proliferation of tissue in the seed cavity and can be a threadlike appendage to round or elongated structures of various sizes and shapes. A few fill the entire seed cavity of the fruit and have their own seed cavity.

Sunken, dry, brownish-grey areas are caused by mites feeding on skin during early fruit growth. The red and black mite (*Brevipalpus phoenicis* [Geijskes]) generally causes this damage in Hawaii.

Postharvest Pathology

The major postharvest diseases are anthracnose and stem end rot. Postharvest diseases, especially anthracnose, become a problem when fruit have 25% or more skin yellowing (Wardlaw et al. 1939, Alvarez and Nishijima 1987). Papaya diseases greatly increase in severity and incidence following 4 weeks storage at 10 °C (50 °F). Mechanical injury and chilling injury can enhance development of postharvest diseases (Somner and Mitchell 1978, Alvarez and Nishijima 1987, Nishijima et al. 1990). *Rhizopus* requires breaks in the cuticle for the disease to develop (Nishijima et al. 1990). Cuticle disruption occurs as latex vessels break down, when the fruit is 40 to 60% yellow (Paull and Chen 1989). Fruit fly punctures can also increase *Rhizopus* rot (Hunter and Buddenhagen 1972), as can mechanical injuries and lesions caused by fungi such as anthracnose and *Cercospora* black spot (Nishijima et al. 1990). Postharvest diseases are effectively controlled by hot water at 49 °C (120 °F) for 20 min (Akamine and Arisumi 1953, Couey et al. 1984, Glazener et al. 1984) and fungicide treatment (Couey and Farias 1979).

Quarantine Issues

Fruit fly infestation becomes a problem with papaya after fruit have 25% skin yellowing (Seo et al. 1982). The damage caused by fruit flies include small surface blemishes, destruction of the edible flesh, and spoilage from decay. Heat treatments and irradiation are used for fruit fly disinfestation (Couey 1989, Paull 1990, Armstrong 1994). Occasionally, heat treatment can cause internal injury and scald (Paull 1995), limit postharvest life, and reduce quality (Paull 1990). Papaya can tolerate insecticidal atmospheres (0.17 to 0.35% O_2, balance N_2) at 20 °C (68 °F) for up to 5 days (Yahia et al. 1989), though its disinfestation potential has not been shown.

Suitability as Fresh-Cut Product

Fruit are prepared as deseeded, halved fruit, slices, and chunks. Fresh-cut products made from 60 to 80% yellow-skinned fruit, overwrapped with plastic film, can be held for up to 3 weeks at 0 to 4 °C (32 to 39 °F) (Paull and Chen 1997). Powrie et al. (1990) patented a procedure in which pieces dipped in citric acid held in multilayer bags with 15 to 20% O_2 and 3% helium had little loss in taste and texture after 16 weeks at 1 ºC (34 °F).

References

Akamine, E.K. 1959. Effects of carbon dioxide on quality and shelf life of papaya. Tech. Progr. Rpt. 120, Hawaii Agricultural Experiment Station, Honolulu, HI.

Akamine, E.K. 1966. Respiration of fruits of papaya (*Carica papaya* L. var. Solo) with reference to effect of quarantine disinfestation treatments. Proc. Amer. Soc. Hort. Sci. 89:231-236.

Akamine, E.K., and T. Arisumi. 1953. Control of postharvest storage decay of papaya (*Carica papaya* L.) with special reference to the effect of hot water. Proc. Amer. Soc. Hort. Sci. 61:270-274.

Akamine, E.K., and T. Goo. 1969. Effects of controlled atmosphere storage of fresh papaya (*Carica papaya*, L. var. Solo) with special reference to shelf life extension of fumigated fruit. Res. Bull. 144, Hawaii Agricultural Experiment Station, Honolulu, HI.

Akamine, E.K., and T. Goo. 1971. Relationship between surface color development and total soluble solids in papaya. HortScience 6:567-568.

Alvarez, A.M. 1980. Improved marketability of fresh papaya by shipment in hypobaric containers. HortScience 15:517-518.

Alvarez, A.M., and W.T. Nishijima. 1987. Postharvest diseases of papaya. Plant Dis. 71:681-686.

An, J.F., and R.E. Paull. 1990. Storage temperature and ethylene influence on ripening of papaya fruit. J. Amer. Soc. Hort. Sci. 115:949-953.

Arisumi, T. 1956. Test shipments of papaya with special reference to storage decay control. Tech. Bull. 29, Hawaii Agricultural Experiment Station, Honolulu, HI.

Armstrong, J.W. 1994. Tropical and subtropical fruits. *In* R.E. Paull and J.W. Armstrong, eds., Insect Pests and Fresh Horticultural Products: Treatments and Responses, pp. 275-290. CAB Intl., Wallingford, U.K.

Cavaletto, C.G. 1989. Quality of high temperature forced air treated papaya. *In* Proceedings of the 25th Annual Papaya Industry Association Conference, Sept. 1989, Hilo, HI, pp. 10-15.

Cenci, S.A., A.G. Soares, J.M.S. Bibino, and M.L.M. Soiya. 1997. Study of the storage of 'Sunrise' and 'Solo' papaya fruits under control atmospheres. Abstract no. 112. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 4, University of California, Davis, CA.

Chau, K.F., and A.M. Alvarez. 1983. Effects of low-pressure storage on *Colletotrichum gloeosporioides* and postharvest infection of papaya. HortScience 18:953-955.

Chen, N.M., and R.E. Paull. 1986. Development and prevention of chilling injury in papaya fruit. J. Amer. Soc. Hort. Sci. 111:639-643.

Couey, H.M. 1989. Heat treatment for control of postharvest diseases and insect pests of fruits. HortScience 24:198-202.

Couey, H.M., A.M. Alvarez, and M.G. Nelson. 1984. Comparison of hot-water spray and immersion treatments for control of postharvest decay of papaya. Plant Dis. 68:436-437.

Couey, H.M., and G. Farias. 1979. Control of postharvest decay of papaya. HortScience 14:719-721.

El-Tomi, A.L., A.B. Abon-Aziz, A.S. Abdel-Kader, and F.K. Abdel-Wahab. 1974. The effect of chilling and non-chilling temperatures on quality of papaya fruit. Egypt. J. Hort. 1:179-185.

Glazener, J.A., H.M. Couey, and A. Alarez. 1984. Effect of postharvest treatments on stemphyllium rot of papaya. Plant Dis. 68:986-988.

Hatton, T.T., and W.F. Reeder. 1969. Controlled atmosphere storage of papaya. Proc. Trop. Reg. Amer. Soc. Hort. Sci. 13:251-256.

Hawaii Department of Agriculture. 1990. Standards for Hawaii-Grown Papaya. Hawaii Department of Agricuture, Marketing Division, Honolulu, HI.

Hunter, J.E., and I.W. Buddenhagen. 1972. Incidences, epidemiology and control of fruit disease of papaya in Hawaii. Trop. Ag. 49:61-71.

Magalona, N. 1963. Artificial Induction of Lumps in the Fruit of Papaya (*Carica papaya* L.) M.Sc. Thesis, University of Hawaii, Honolulu, HI.

Nakasone, H.Y. 1986. Papaya. *In* S.P. Monselise, ed., CRC Handbook of Fruit Set and Development, pp. 277-301. CRC Press, Boca Raton, FL.

Nakasone, H.Y., and T.D. Arkle. 1971. Development of intra-ovarian ovaries in *Carica papaya* L. J. Amer. Soc. Hort. Sci. 96:550-553.

Nazeeb, M., and W.J. Broughton. 1978. Storage conditions and ripening of papaya 'Bentong' and 'Taiping.' Sci. Hort. 9:265-277.

Nishijima, W.T., S. Ebersole, and J.A. Fernandez. 1990. Factors influencing development of postharvest incidence of *Rhizopus* soft rot of papaya. Acta Hort. 269:495-502.

Paull, R.E. 1990. Postharvest heat treatments and fruit ripening. Postharv. News Info. 1:355-363.

Paull, R.E. 1995. Preharvest factors and the heat sensitivity of field grown ripening papaya fruit. Postharv. Biol. Technol. 6:167-175.

Paull, R.E. 1993. Pineapple and papaya. *In* G. Seymour, J. Taylor, and G. Tucker, eds., Biochemistry of Fruit Ripening, pp. 291-323. Chapman & Hall, London, U.K.

Paull, R.E., and N.J. Chen. 1983. Postharvest variation in wall degrading enzymes of papaya fruit during ripening. Plant Physiology 72:131-138.

Paull, R.E., and N.J. Chen. 1989. Waxing and plastic wraps influence water loss from papaya fruit during storage and ripening. J. Amer. Soc. Hort. Sci. 114:937-942.

Paull, R.E., and N.J. Chen. 1997. Minimal processing of papaya (*Carica papaya* L.) and the physiology of halved fruit. Postharv. Biol. Technol. 12:93-99.

Paull, R.E., W. Nishijima, M. Reyes, and C. Cavaletto. 1997. A review of postharvest handling and losses during marketing of papaya (*Carica papaya* L). Postharv. Biol. Tech. 11:165-179.

Powrie, W.D., R. Chiu, H. Wu, and B.J. Skura. 1990. Preservation of cut and segmented fresh fruit pieces. U.S. Patent No. 4,895,729.

Qiu, Y., M.S. Nishina, and R.E. Paull. 1995. Papaya fruit growth, calcium uptake and fruit ripening. J. Amer. Soc. Hort. Sci. 120:246-253.

Quintana, M.E.G., and R.E. Paull. 1993. Mechanical injury during postharvest handling of 'Solo' papaya fruit. J. Amer. Soc. Hort. Sci. 118:618-622.

Reyes, M.E.Q., and R.E. Paull. 1994. Skin freckles on 'Solo' papaya fruit. Sci. Hort. 58:31-39.

Seo, S.T., G.B. Farias, and E.J. Harris. 1982. Oriental fruit fly: ripening of fruit and its effect on index of infestation of Hawaiian papayas. J. Econ. Ent. 75:173-178.

Sommer, N.F., and F.G. Mitchell. 1978. Relation of chilling temperatures to postharvest *Alternaria* rot of papaya fruit. Proc. Trop. Reg. Amer. Soc. Hort. Sci. 22:40-47.

Thompson, A.K., and G.R. Lee. 1971. Factors affecting the storage behaviour of papaya fruit. J. Hort. Sci. 46:511-516.

Wardlaw, C.W., R.E.D. Baker, and S.H. Crowdy. 1939. Latent infections in tropical fruits. Trop. Ag. 16:275-276.

Yahia, E. 1998. Modified and controlled atmospheres for tropical fruits. Hort. Rev. 22:123-183.

Yahia, E., F. Medina, and M. Rivera. 1989. Tolerance of mango and papaya to atmospheres containing very high levels of CO_2 and/or very low levels of O_2 as a possible insect control treatment. *In* E. Kupferman, and M. Patterson, eds., 5th International Controlled Atmosphere Research Conference, Wenatchee WA, June 14-16, 1989, vol. 2, pp. 77-89.

Zee, F.T., M.S. Nishina, H.T. Chan, and K.A. Nishijima. 1989. Blossom end defects and fruit fly disinfestation in papayas following hot water quarantine treatment. HortScience 24:323-325.

Parsley

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Scientific Name and Introduction

Petroselinum crispum (Mill.) Nyman ex A.W. Hill—parsley—is a member of the Apiaceae family. The edible foliage is grown as an annual and used as a garnish and food ingredient. Both curly-leaved (such as ‘Deep Green,’ ‘Forest Green,’ and ‘Moss Curled’) cultivars and flat-leaved (such as Plain, Plain Italian Dark Green, and Deep Green Italian) types are available. There is a subspecies, *P. crispum* subsp. *tuberosum*, Hamburg parsley, that has an edible root. Parsley has very high vitamin and nutrient content. It is highest in calcium, iron, and folate of all vegetables studied (Athar et al. 1999) and has among the highest contents of β-carotene, thiamin, riboflavin, and vitamins C and E. A high proportion of the carotene is 9-cis β-carotene, possibly active against cancer and cardiovascular disease (Benamotz and Fishler 1998).

Quality Characteristics and Criteria

The quality criteria for parsley are freshness, green color, freedom from defects or seed stems, and freedom from decay (AMS 2002).

Horticultural Maturity Indices

Parsley can be harvested progressively or cut all at one time. Long petioles are desirable for bunching. Most of the U.S. crop is harvested by hand.

Grades, Sizes, and Packaging

Only one grade is available (U.S. No. 1), which consists of parsley that meet quality criteria and have similar varietal characteristics; that is, curly-leaf and flat-leaf varieties are not mixed. Parsley is usually packaged in cartons or jumbo crates of 60 bunches, 9 to 11 kg (20 to 25 lb).

Precooling Conditions

Rapid removal of field heat without excessive drying helps retain green color and freshness. Parsley can be precooled with ice (package icing or liquid-icing [Cantwell and Reid 1992]) or by vacuum-cooling (Aharoni et al. 1989). Forced-air cooling or hydrocooling are commonly practiced (Joyce et al. 1986).

Optimum Storage Conditions

The recommended conditions for commercial storage of parsley are 0 °C (32 °F) with 95 to 100% RH (Cantwell 2002). Parsley can be stored for 1 to 2 mo under these conditions, compared to only 3 days at 18 to 20 °C (64 to 68 °F) with 85 to 90% RH (Lisiewska et al. 1997). The endpoint of storage at 0 °C (32 °F) occurs when parsley wilts, at around 20% weight loss (Hruschka and Wang 1979). MAP is effective in extending storage life, but temperature changes and condensation must be avoided. Aharoni et al. (1989) showed that nonperforated polyethylene liners delayed yellowing and decay at low temperature. Park et al. (1999) achieved 77 days of storage at 0 °C (32 °F) and 35 days at 5 °C (41 °F) with good retention of firmness and vitamin C content by using a 40 μm-thick ceramic film. A preharvest spray with gibberellic acid may extend storage life (Lers et al. 1998). Hamburg parsley roots (without leaves) can be stored at 0 °C (32 °F) for several months (Bakowski et al. 1994, Elkner et al. 1998).

Controlled Atmosphere (CA) Considerations

Parsley can tolerate 8 to 10% O_2 and 8 to 10% CO_2 (Saltveit 1997), but this may be of little benefit at 0 °C (32 °F). An atmosphere of 10% O_2 and 11% CO_2 was optimal for delaying yellowing in parsley stored at 5 °C (41 °F) (Apeland 1971). Storage in 10% O_2 and 10% CO_2 (Yamauchi and Watada 1993) or 10% CO_2 (Lers et al. 1998) delayed yellowing at room temperature.

Retail Outlet Display Considerations

Parsley is often sold in unsealed bunches. Light reduces yellowing, but levels in retail shelves are too low to have a significant effect. Use of ice or water sprays is acceptable. If MAP is used during storage, care must be taken to prevent condensation during the retail period.

Chilling Sensitivity

Parsley is not chilling sensitive. It should be stored as cold as possible without freezing, which occurs at -1.1 °C (30 °F).

Ethylene Production and Sensitivity

Parsley leaves produce very little ethylene but are very sensitive to it (Joyce et al. 1986, Tsumura et al. 1993). Cantwell and Reid (1993) observed that parsley leaves produced 0.08, 0.44 and 0.80 µL kg^{-1} h^{-1} at 0, 10 and 20 °C (32, 50, 68 °F). As little as 0.4 µL L^{-1} is enough to accelerate yellowing if parsley is stored above 0 °C (32 °F) (Cantwell and Reid 1993). Ethylene application does not stimulate respiration in parsley (Inaba et al. 1989).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	22 to 38
5 °C	49 to 70
10 °C	78 to 150
15 °C	131 to 168
20 °C	176 to 221
25 °C	259 to 289

Data from Apeland (1971), Hruschka and Wang (1979), and Cantwell and Reid (1986).

Rates were measured 3 days after harvest.

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Wilting and yellowing signal the end of shelf-life. No particular disorders are described for parsley.

Postharvest Pathology

Both *Erwinia* and *Botrytis* can cause postharvest damage from rots and mold (Ryall and Lipton 1979).

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Parsley's flavor and aroma were retained better in perforated film packages than in sealed film packs (Manzano et al. 1995). Food safety is a major concern. Chlorinated water is somewhat beneficial in reducing contamination (Park and Sanders 1992), but personal hygiene of the staff is paramount. Parsley has been implicated as a source of the infectious *Shigella* (Crowe et al. 1999) and *Citrobacter freundii*, causing gastroenteritis and hemolytic uremic syndrome (Tschape et al. 1995), and thermotolerant campylobacters (Park and Sanders 1992).

Special Considerations

Parsley has an extremely high respiration rate. Young leaves respire at a higher rate than old leaves at harvest, but the respiration rate does not decrease as much after harvest in older leaves as in younger leaves, so younger leaves store better (Apeland 1971).

Parsley contains furocoumarins, including psoralen (Manderfeld et al. 1997), which are effective antimicrobial agents but can act as phototoxins, inducing dermatitis (Lagey et al. 1995). Parsley is used as a medicinal plant to treat hypertension in Morocco (Ziyyat et al. 1997) and diabetes in Turkey (Tunali et al. 1999).

References

Aharoni, N., A. Reuveni, and O. Dvir. 1989. Modified atmospheres in film packages delay senescence and decay of fresh herbs. Acta Hort. 258:255-262.

Apeland, J. 1971. Factors affecting respiration and color during storage of parsley. Acta Hort. 20:43-52.

Athar, N., T.W. Spriggs, and P. Liu. 1999. The Concise New Zealand Food Composition Tables, 4th ed. New Zealand Institute for Crop & Food Research, Palmerston North, N.Z.

Bakowski, J., H. Michalik, and L. Umiecka. 1994. Effect of sowing and harvest date on the quality of root parsley and its storability. Biuletyn Warzywniczy 41:157-167.

Benamotz, A., and R. Fishler. 1998. Analysis of carotenoids with emphasis on 9-cis β-carotene in vegetables and fruits commonly consumed in Israel. Food Chem. 62:515-520.

Cantwell, M. 2002. Properties and recommended conditions for storage of fresh fruits and vegetables. *At* http://postharvest.ucdavis.edu/produce_information/storagefreshproduce.

Cantwell, M.I., and M.S. Reid. 1986. Postharvest handling of fresh culinary herbs. II. Respiration and ethylene production. Perishables Handling Quarterly 60:2-5.

Cantwell, M.I., and M.S. Reid. 1992. Postharvest handling systems: fresh herbs. *In* A.A. Kader, ed., Postharvest Technology of Horticultural Crops, 2nd ed., pp. 211-213. DANR Pub. no. 3311, University of California, Oakland, CA.

Cantwell, M.I., and M.S. Reid. 1993. Postharvest physiology and handling of fresh culinary herbs. J. Herbs, Spices and Medicinal Plants 1:93-127.

Crowe, L., W. Lau, and L. McLeod. 1999. Outbreaks of *Shigella sonnei* infection associated with eating fresh parsley—United States and Canada, July-August 1998. J. Amer. Med. Assoc. 281:1785-1787.

Elkner, K., M. Horbowicz, and R. Kosson. 1998. Effect of storage on contents of dietary fibre and its composition in some cultivars of red beet, root parsley and carrot. Veg. Crops Res. Bull. 49:107-120.

Hruschka, H.W., and C.Y. Wang. 1979. Storage and shelf life of packaged watercress, parsley and mint. Marketing Research Report 1102, U.S. Department of Agriculture, Washington, DC.

Inaba, A., Y. Kubo, and R. Nakamura. 1989. Effect of exogenous ethylene on respiration in fruits and vegetables with special reference to temperature. J. Jap. Soc. Hort. Sci. 58:713-718.

Joyce, D., M.S. Reid, and P. Katz. 1986. Postharvest handling of fresh culinary herbs. Perishables Handling Quarterly 58:1-4.

Lagey, K., L. Duinslaeger, and A. Vanderkelen. 1995. Burns induced by plants. Burns 21:542-543.

Lers, A., W.B. Jiang, E. Lomanies, and N. Aharoni. 1998. Gibberellic acid and CO_2 additive effect in retarding postharvest senescence of parsley. J. Food Sci. 63:66-68.

Lisiewska, Z., W. Kmiecik, and A. Budnik. 1997. Effect of conditions and time of storage on technological quality changes of parsley leaves. Folia Hort. 9:21-29.

Manderfeld, M.M., H.W. Schafer, P.M. Davidson, and E.A. Zottola. 1997. Isolation and identification of antimicrobial furocoumarins from parsley. J. Food Protect. 60:72-77.

Manzano, M., B. Citterio, M. Maifreni, et al. 1995. Microbial and sensory quality of vegetables for soup packaged in different atmospheres. J. Sci. Food Agric. 67:521-529.

Park, C.E., and G.W. Sanders. 1992. Occurrence of thermotolerant campylobacters in fresh vegetables sold at farmers outdoor markets and supermarkets. Can. J. Microbiol. 38:313-316.

Park, K.W., H.M. Kang, E.M. Yang, and J.C. Jung. 1999. Effects of film package and storage temperature on quality of parsley in modified atmosphere storage. Acta Hort. 483:291-298.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation, and Storage of Fruits and Vegetables, 2nd ed., vol. 1. AVI, Westport CT.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 4, pp. 98-117. University of California, Davis CA.

Tschape, H., R. Prager, W. Streckel, et al. 1995. Verotoxinogenic *Citrobacter freundii* associated with severe gastroenteritis and cases of hemolytic uraemic syndrome in a nursery school—green butter as the infection source. Epidem. Inf. 114:441-450.

Tsumura, F., Y. Ohsako, Y. Haraguchi. 1993. Rapid changes in parsley leaves during storage in controlled or ethylene-containing atmosphere. J. Food Sci. 58:619-625.

Tunali, T., A. Yarat, R. Yanardag, et al. 1999. Effect of parsley *(Petroselinum crispum)* on the skin of STZ-induced diabetic rats. Phytotherapy Res. 13:138-141.

AMS [USDA Agricultural Marketing Service]. 2002. Quality Standards—Fresh Fruits and Vegetables. *At* http://www.ams.usda.gov/AMSv1.0/standards.

Yamauchi, N., and A.E. Watada. 1993. Pigment changes in parsley leaves during storage in controlled or ethylene-containing atmosphere. J. Food Sci. 58:616-618, 637.

Ziyyat, A., A. Legssyer, H. Mekhfi, et al. 1997. Phytotherapy of hypertension and diabetes in oriental Morocco. J. Ethnopharmacol. 58:45-54.

Parsnip

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Scientific Name and Introduction

The parsnip (*Pastinaca sativa* L.) is a native of Europe and Asia. The plant is a biennial, belonging to the Apiaceae (Umbelliferae), or parsley, family. The crop is grown as an annual, and the thickened, cream-colored root is the edible portion. It is a long-season crop (~100 days) and thrives best in cool growing climates. Parsnips are generally available from mid August to March.

Quality Characteristics and Criteria

A high-quality parsnip will be firm, reasonably clean, and fairly smooth-surfaced (not deeply ridged, no secondary rootlets). Parsnips are topped after harvesting but should not be trimmed into the crown.

Horticultural Maturity Indices

Parsnips are harvested when root diameter is between 2.5 and 7.6 cm (1 and 3 in) at the shoulder.

Grades, Sizes, and Packaging

There are two grades, U.S. No. 1 and U.S. No. 2, based on shape, external appearance, and size. Parsnips are commonly packaged in 11.4-kg (25-lb) perforated polyethylene bags or 5.5-kg (12-lb) cartons holding 12 cello bags of 0.5 kg (1 lb) each.

Precooling Conditions

Parsnips are similar to carrots in requirements and should be cooled using hydrocooling or package-icing. Rapid cooling to 5 °C (41 °F) or below immediately after harvest is essential to minimize decay and moisture losses during extended storage.

Optimum Storage Conditions

Parsnip roots can be stored 4 to 6 mo at 0 to 1 °C (32 to 34 °F) with 98% RH (van den Berg and Lentz 1973). Only healthy roots with no damage should be placed in storage.

Controlled Atmosphere (CA) Considerations

Little work has been done, but limited results suggest that there are no benefits to controlled-atmosphere storage (Stoll and Weichmann 1987).

Retail Outlet Display Considerations

Water sprinklers and top-icing are acceptable for nonpackaged product. Packaged products should be held in a cold display case with no ice or water sprinklers.

Chilling Sensitivity

Parsnips are not chilling sensitive.

Ethylene Production and Sensitivity

Parsnips produce very little ethylene: <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F). Exposure to low levels of ethylene in cold storage causes bitterness, likely due to accumulation of xanthotoxin (8-methoxypsoralen) (Johnson et al. 1973, Shattuck et al. 1988).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	8 to 16
5 °C	8 to 18
10 °C	19 to 25
15 °C	30 to 43

Data from Smith (1957) and van den Berg and Lentz (1972).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Surface browning is a significant problem that is largely associated with bruising and abrasion injury during harvest (Kaldy et al. 1976, Toivonen 1992). Crops grown on coarse sandy soils are more susceptible, and there are cultivars resistant to browning (Kaldy et al. 1976, Toivonen 1992). Surface browning also increases with length of storage (Kaldy et al. 1976). Postharvest dips reduce browning during storage (Toivonen 1992). Waxing parsnips, to reduce moisture loss, will increase browning (Plantenius 1939).

Postharvest Pathology

Diseases of importance during storage, transit, and marketing are parsnip canker (*Itersonilia perplexans* Derx.), gray mold rot (*Botrytis cinerea* Pers.:Fr.), bacterial soft rot (*Erwinia carotovora* (Jones) Bergey et al.) and watery soft rot (*Sclerotinia sclerotiorum* [Lib.] de Bary) (Smith et al. 1982). Some cultivars are resistant to parsnip canker (Davis et al. 1989).

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

No potential exists.

Special Considerations

The highest freezing temperature is -0.9 °C (30.4 °F). An important component of parsnip quality is sweetness, which is enhanced if exposed to fall frosts before harvest. However, early-harvested parsnips can also be induced to sweeten using short-term cold storage (Shattuck et al. 1989).

Acknowledgments

Some information in this chapter is from the Oregon State University website "Commercial Vegetable Production Guides" (http://horticulture.oregonstate.edu/content/vegetable-production-guides) and the British Columbia Vegetable Marketing Commission website (http://www.bcveg.com).

References

Davis, D.W., F.L. Pfleger, and M.A. Shehata. 1989. 'Andover' parsnip. HortScience 24:521-522.

Johnson, C., D.R. Brannon, and J. Kuc. 1973. Xanthoxin: A phytoalexin of *Pastinaca sativa* root. Phytochemistry 12:2961-2962.

Kaldy, M.S., J.F. Dormaar, S.A. Molnar, and P. Ragan. 1976. Browning of parsnips as related to varieties, soil conditions and length of storage. *In* 55th Annual Report of the Canadian Horticultural Council, pp. 101-102.

Plantenius, H. 1939. Wax emulsions for vegetables. Bull. 723, New York University Agricultural Experiment Station, Geneva, NY.

Shattuck, V.I., Y. Kakuda, and R. Yada. 1989. Sweetening of parsnip roots during short-term cold storage. Can. Inst. Food Sci. Technol. J. 22(4):378-382.

Shattuck, V.I., R. Yada, and E.C. Lougheed. 1988. Ethylene-induced bitterness in stored parsnips. HortScience 23:912.

Smith, H. 1957. The production of carbon dioxide and metabolic heat by horticultural produce. Modern Refrig. 60:493-496.

Smith, M.A., L.P. McColloch, and B.A. Friedman. 1982. Market Diseases of Asparagus, Onions, Beans, Peas, Carrots, Celery, and Related Vegetables. Agriculture Handbook 303, U.S. Department of Agriculture, Washington, DC.

Stoll, K., J. Weichmann. 1987. Root vegetables. *In* J. Weichmann, ed., Postharvest Physiology of Vegetables, pp. 541-553. Marcel Dekker, New York, NY.

Toivonen, P.M.A. 1992. The reduction of browning in parsnips. J. Hort. Sci. 67:547-551.

van den Berg, L., and C.P. Lentz. 1972. Respiratory heat production of vegetables during refrigerated storage. J. Amer. Soc. Hort. Sci. 97:431-432.

van den Berg, L., and C.P. Lentz. 1973. High humidity storage of carrots, parsnips, rutabagas and cabbage. J. Amer. Soc. Hort. Sci. 98:129-132.

Passion Fruit

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Scientific Name and Introduction

Purple passion fruit (*Passiflora edulis* Sim.) and yellow passion fruit (*P. edulis* f. *flavicarpa* Deg.) should more correctly be referred to as the passion flower fruit, but the trade more commonly uses passion fruit. Hybrids of the two subspecies form freely and have characteristics between the two parents. A tough outer skin surrounds a fleshy, acidic, yellow pericarp and aril surrounding small edible black seeds (Pruthi 1963). The yellow, egg-shaped type of passion fruit is 6 to 8 cm (2.5 to 3 in) wide by 7 cm (2.7 in) long and weighs 50 to 150 g (1.8 to 5.3 oz). The smaller purple fruit weighs 25 to 50 g (1 to 2 oz).

Quality Characteristics and Criteria

Size, shape, skin color, acidity, and SSC are the major criteria used to evaluate quality. Fruit should be free of blemishes. SSC is 10 to 18% in yellow fruit and 10 to 20% in the purple type, with the yellow type having a more acidic flavor.

Horticultural Maturity Indices

Fruit are harvested when ≥75% are turning yellow or purple (Chan 1980). Purple passion fruit at the light-purple stage is more suitable for long distance transport. Normally, the respiratory climacteric occurs on the vine. Fruit harvested earlier have an unripe flavor (Campbell and Knight 1983). In some cases, fruit are allowed to abscise and fall and are then picked up from the ground.

Grades, Sizes, and Packaging

Fruit should have a diameter of 5 to 8 cm (2 to 3 in) for purple and 6 to 8 cm (2.5 to 3 in) for yellow. Skin color should be full yellow or purple, unless a hybrid. Fruit are packed in 6-kg (13.2-lb) and 4.5-kg (9.9-lb) fiberboard cartons, sometimes in one- or two-layer trays or cell packs.

Precooling Conditions

Room-cooling or forced-air cooling to 10 °C (50 °F) is desirable.

Optimum Storage Conditions

Yellow passion fruit should be stored at 7 to 10 °C (45 to 50 °F) with 90 to 95% RH. They will have a potential storage life of 2 weeks (Arjona et al. 1992). Purple passion fruit are chilling tolerant and can be stored at 3 to 5 °C (37 to 41 °F) for 3 to 5 weeks.

Controlled Atmosphere (CA) Consideration

Modified atmospheres (MA) have been tested on yellow passion fruit, and a fungicide treatment before storage is desirable. Film-bagging and various coatings reduce water loss in yellow and purple passion fruit (Arjona et al. 1992, Mohammed 1993, Bepete et al. 1994). Response to coatings and film bagging may be associated with control of water loss, rather than MA effects.

Retail Outlet Display Considerations

Fruit should be displayed at ambient temperature and not misted or iced.

Chilling Sensitivity

Symptoms of chilling injury on yellow passion fruit are skin discoloration, pitting, water-soaked areas, uneven ripening, and increased decay. Discoloration can penetrate skin into the exocarp.

Ethylene Production and Sensitivity

Passion fruit produce very high levels of ethylene: 160 to 400 µL kg^{-1} h^{-1} at 20 °C (68 °F) at their climacteric peak (Shiomi et al. 1996). Exposure to 100 µL L^{-1} ethylene for 24 h accelerates ripening (Akamine et al. 1957, Arjona and Matta 1991).

Respiration Rates

The climacteric of this fruit normally occurs on the vine (Biale 1975).

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	29 to 58
10 °C	39 to 78
20 °C	87 to 194
25 °C	175 to 349

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Shrivel, pulp fermentation, and fungal attack are the major postharvest problems (Pruthi 1963). Shrivel is caused by moisture loss without initially significantly affecting pulp quality.

Postharvest Pathology

Postharvest disease is normally a minor problem. Most common is brown spot *(Alternaria passiflorae),* whose symptoms include circular, sunken, light-brown spots on ripening fruit (Inch 1978). This disease is most severe following warm, wet periods. Septoria spot *(Septoria passiflorae)* infects fruit in the field and leads to uneven ripening of the skin. Phytophthora fruit rot (*Phytophthora* spp.) causes water-soaked, dark-green patches that dry up on the skin. Orchard sanitation, reduction of high RH by pruning to open the canopy, and application fungicides can minimize these diseases.

Quarantine Issues

Fruit are a fruit fly host and may require treatment. Irradiation has been successful.

Suitability as Fresh-Cut Product

No potential currently exists.

References

Akamine, E.K., R.E. Young, and J.B. Biale. 1957. Respiration and ethylene production in the purple passion fruit. Proc. Amer. Soc. Hort. Sci. 69:221-225.

Arjona, H.E., and F.B. Matta. 1991. Postharvest quality of passion fruit as influenced by harvest time and ethylene treatment. HortScience 26:1297-1298.

Arjona, H.E., F.B. Matta, and J.O. Garner. 1992. Temperature and storage time affect quality of yellow passion fruit. HortScience 27:809-810.

Biale, J.B. 1975. Synthetic and degrading process in fruit ripening. *In* N.F. Haard and D.K. Salunkhe, eds., Symposium: Postharvest Biology and Handling of Fruits and Vegetables, pp. 5-18. AVI, Westport, CT.

Bepete, M., N. Nenguwo, and J.E. Jackson. 1994. The effect of sucrose coating on ambient temperature storage of several fruits. *In* B.R. Champ, E. Highley and G.I. Johnson, eds., Proceedings of the International Conference on Postharvest Handling of Tropical Fruits, pp. 427-429. Chiang Mai, Thailand, July 1993. The Australian Centre for International Agricultural Research Proceedings no. 50, Canberra, Australia

Campbell, C.W., and R.J. Knight. 1983. Production de Gandadilla, pp. 223-231. Ministerio de Agricultura, Pesca y Alimentacion, Canary Islands, Spain.

Chan, H.T. 1980. Passion fruit. *In* S. Nagy and P.E. Shaw, eds., Tropical and Subtropical Fruits: Composition, Properties and Uses, pp. 300-315. AVI, Westport, CT.

Inch, A.J. 1978. Passion fruit diseases. Queensland Ag. J. 104:479-484.

Mohammed, M. 1993. Storage of passion fruit in polymeric films. Proceedings of the Interamerican Society for Tropical Horticulture 37:85-88.

Pruthi, J.S. 1963. Physiology, chemistry, and technology of passion fruit. Adv. Food Res. 12:203-282.

Shiomi, S., L.S. Wamocho, and S.G. Agong. 1996. Ripening characteristics of purple passion fruit on and off the vine. Postharv. Biol. Technol. 7:161-170.

Pea

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Specific Name and Introduction

There are three types of edible peas (*Pisum sativum* L.) from the family Fabaceae (also called Leguminosae). The most common is the garden or green pea *P. sativum* var. *sativum* L. This pea has a tough pod that is discarded prior to eating (Basterrechea and Hicks 1991, Snowdon 1991). Most often these peas are frozen or processed. The success of the frozen pea industry in the United States has resulted in a decline in the sale of peas sold in the pods (Basterrechea and Hicks 1991). The other two types of peas have soft, edible pods and belong to the subspecies *P. sativum* var. *macrocarpon* Ser. The snow or sugar pea has a flat pod with minimal development of the seeds, while the sugar snap pea or snap pea has well developed seeds and is fully rounded (Hocking 1997, Suslow and Cantwell 1998). The sugar snap pea is the result of a cross between the snow pea and an unusual tightly podded pea with thick walls. All of these peas grow best under cool, moist conditions.

Quality Characteristics and Criteria

Good-quality peas are uniformly bright green, fully turgid, and free from defects and mechanical damage. Stems and calyxes should be green.

Grades, Sizes, and Packaging

Grades include U.S. No. 1 and U.S. Fancy, based primarily on external appearance. They should exhibit similar varietal characteristics and be not overmature or excessively small, not badly misshapen or water-soaked, fairly well filled, fresh, and free from decay and from damage caused by black calyxes, freezing, splitting, hail, dirt, leaves or other foreign matter, mildew or other diseases, insects, or mechanical or other means. There are no USDA grades for snow or snap peas, but best-quality snow peas are 7.6 to 9 cm (3 to 3.5 in) long and 1.9 cm (0.75 in) wide, while snap peas should be 6.4 to 7.6 cm (2.5 to 3 in) long. Green peas are shipped in 13.6-kg (30-lb) bushel baskets, or crates. Snow and sugar snap peas are shipped in 4.5-kg (10-lb) cartons.

Harvest Maturity Indices

For best quality, both edible podded peas and green peas should be harvested before physiological maturity; that is, before peas deform the hull (Basterrechea and Hicks 1991). Snow peas should be harvested when the pods are maximum size but before any visible seed development; frequent harvesting is necessary. Sugar snap peas should be harvested after they have developed seeds, as with garden peas (Hocking 1997).

Precooling Conditions

Sugar content and flavor decrease rapidly after harvest unless green peas are promptly cooled to 0 °C (32 °F). Therefore, they must be promptly precooled after harvest by forced-air cooling, hydrocooling, or vacuum-cooling. If vacuum-cooling is used, it is important that the peas are prewet to ensure rapid cooling (Ryall and Lipton 1979). Forced-air cooling is the preferred method of cooling for edible podded peas (NWREC 1998).

Optimum Storage Conditions

All three types of peas can be stored for 1 to 2 weeks at 0 °C (32 °F) with 95 to 98% RH (Wager 1964, Suslow and Cantwell 1998). Garden peas store better unshelled than shelled, possibly because shelling damages the peas (Basterrechea and Hicks 1991). If there is surface moisture on peas, it is essential that they be stored below 2 °C (36 °F).

Controlled Atmosphere (CA) Considerations

Little work has been done on CA storage of peas. Green pea quality was maintained better for 20 days in 5 to 7% CO_2 at 0 °C (32 °F) than in air (Tomkins 1957). Snow and snap peas respond moderately to CA of 2 to 3% O_2 and 2 to 3% CO_2, though not all research has found CA to be beneficial (Suslow and Cantwell 1998).

Retail Outlet Display Considerations

Storage with crushed ice can be beneficial, and water sprays are acceptable for garden and snow peas, but these methods should be avoided for snap peas (Suslow and Cantwell 1998).

Chilling Sensitivity

Peas are not sensitive to low temperature and should be stored as close to 0 °C (32 °F) as possible without freezing.

Ethylene Production and Sensitivity

Peas produce very low levels of ethylene: <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F). However, they are moderately sensitive to ethylene after harvest, which results in yellowing and increased decay. The calyx is more sensitive to ethylene than the pod (Suslow and Cantwell 1998).

Respiration Rates

Temperature	Garden Peas	Edible-pod peas (estimated)
	mg CO_2 kg^{-1} h^{-1}	
0 °C	30 to 46	30 to 48
5 °C	55 to 72	53 to 74
10 °C	63 to 108	65 to 112
15 °C	165 to 185	165 to 187
20 °C	220 to 322	221 to 324
25 °C	298 to 327	—

Data from ASHRAE (1985) and Suslow and Cantwell (1998).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Freezing may start at -0.6 °C (31 °F). Freezing causes water-soaked areas followed by rapid decay from soft rot bacteria (Suslow and Cantwell 1998). Edible podded peas are susceptible to premature senescence resulting in yellowing, color changes in the calyx, and loss of tenderness and flavor (Suslow and Cantwell 1998). Storage at >5 °C (41 °F) and exposure to ethylene can accelerate this problem.

Postharvest Pathology

Because of high respiration rate, the heat generated by unrefrigerated peas will promote decay. Blemishes that reduce quality can be caused by alternaria blight *(Alternaria alternata)*, anthracnose *(Colletotrichum)*, ascochyta pod spot (*Ascochyta pisi* Lib), and powdery mildew (*Erysiphe* spp.) (Snowdon 1991). Common diseases for edible podded peas are gray mold *(Botrytis cinerea)*, watery soft rot *(Sclerotinia sclerotiotorum)*, rhizopus rot, and bacterial soft rot. Botrytis gray mold can be a problem at the blossom-end of fresh-cut pods.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Edible podded peas are suitable for use in fresh-cut mixtures.

Special Considerations

Keeping peas cold is critical for retaining quality. Surface moisture should be avoided unless the marketing chain is short and temperatures are kept <2 °C (<36 °F).

References

ASHRAE [American Society of Heating, Refrigerating, and Air-Conditioning Engineers]. 1985. ASHRAE Handbook—1985 Fundamentals. ASHRAE, Atlanta, GA.

Basterrechea, M., and J.R. Hicks. 1991. Effect of maturity on carbohydrate changes in snap pea pods during storage. Sci. Hort. 48:1-8.

Hocking, D.F. 1997. Snow peas and sugar snap peas. Agfact H8.1.35, New South Wales Agriculture, Sydney, Australia.

NWREC [North Willamette Research and Extension Center]. 1998. Edible pod peas. *At* http://horticulture.oregonstate.edu/content/vegetable-production-guides.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transport and Storage of Fruits and Vegetables, 2nd ed., vol. 1, Vegetables and Melons. AVI Pub., Westport, CT.

Snowdon, A.L. 1991. A Colour Atlas of Postharvest Diseases and Disorders of Fruit and Vegetables, vol. 2, Vegetables, pp. 97-138. Wolfe Scientific, London, U.K.

Suslow, T.V., and M. Cantwell. 1998. Peas—Snow and Snap Pod Peas. Perishables Handling Quarterly 93:15-16

Tomkins, R.G. 1957. Peas kept for 20 days in gas store. Grower (U.K.) 48:226-227.

Wager, H.G. 1964. Physiological studies of the storage of green peas. J. Sci. Food Agr. 15:245-252.

Peach

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Scientific Name and Introduction

The peach, *Prunus persicae*, is native to China and Persia (Iran); at one time it was called “Persian apple.” Chinese literature dates its cultivation in China to 1,000 B.C. Carried from China to Persia, the peach quickly spread from there to Europe. In the 16th century, it was established in Mexico, probably by the Spanish. Spanish missionaries introduced the peach to California in the 18th century.

California is a major producer and shipper of peaches in the United States. The development of white-fleshed peach cultivars is important. Current fresh peach shipments approach 19 million 10-kg (22-lb) packages from more than 155 cultivars. In the San Joaquin Valley, harvest of early cultivars starts in mid May, and harvest of late cultivars is completed in early October. The United States exports mainly to Canada, Taiwan, Hong Kong, Mexico, and South America.

Quality Characteristics and Criteria

There is high consumer acceptance of peaches with high SSC. TA and SSC:TA are also important factors in consumer acceptance. For mid-season peaches, a minimum of 11% SSC with TA $\leq$0.7% is required to satisfy about 80% of consumers. Fruit with 9 to 13.5 N (2 to 3 lb-force) flesh firmness are considered ready to eat. Fruit with firmness below about 30 N (7 lb-force) measured on the fruit cheek have high consumer acceptance.

Horticultural Maturity Indices

In California, harvest date of most cultivars is determined by change in skin ground color from green to yellow. A color chip guide is used to determine maturity of each cultivar except white-fleshed cultivars. A two-tier maturity system is used in California: (1) U.S. Mature (minimum maturity) and (2) Well-Mature or Tree Ripe. Well-Mature and Tree Ripe are the same according to the California Department of Food and Agriculture, Division of Inspection Services.

Measurement of fruit firmness is recommended for cultivars in which skin ground color is masked by full red color development before maturation. In these cases, a maximum maturity index can be applied. Maximum maturity is defined as the minimum flesh firmness (measured with a penetrometer with an 8-mm tip) at which fruit can be handled without bruising damage. Bruising susceptibility varies among cultivars.

Grades, Sizes, and Packaging

Fruit are hand-picked into bags, baskets, or totes. Fruit are then dumped into bins on trailers between tree rows in the orchard. If fruit are picked into totes, the totes are usually placed directly inside the bins. Peaches are transported from orchard to packinghouse and cooled as soon as possible after harvest.

At the packinghouse, fruit are dumped (mostly using dry bin dumps) and cleaned. Sorting is done to eliminate fruit with visual defects and sometimes to divert fruit of high surface color to a high-quality pack. Attention to details in sorting line efficiency is especially important with peaches, which have a range of colors, sizes, and shapes. Sizing segregates fruit by either weight or dimensions.

Most yellow-flesh peaches are packed into 2-layer (tray) boxes. Small yellow-flesh peaches are generally volume-fill packed. Most white-flesh and tree-ripe peaches are packed into 1-layer (tray) boxes. Limited volumes of high-maturity fruit are "ranch-packed" at the point of production. In a typical tree-ripe operation, high-maturity or high-quality fruit are picked into buckets or totes that are carried by trailer to the packing area. Packers work directly from buckets to select, grade, size, and pack fruit into plastic trays.

Precooling Conditions

Fruit can be cooled in field bins using forced-air cooling or hydrocooling. Forced-air cooling in side-vented bins can be accomplished by either the tunnel or the serpentine method. Hydrocooling is normally done by a conveyor-type hydrocooler or *in situ*. Fruit in field bins can be cooled to intermediate temperatures of 5 to 10 °C (41 to 50 °F), provided packing will occur the next day. If packing is to be delayed beyond the next day, fruit should be thoroughly cooled in the bins to near 0 °C (32 ºF). In cultivars susceptible to internal breakdown, fast cooling (within 8 h), as well as maintaining fruit temperature near 0 °C (32 °F), is recommended. Peaches in packed containers should be cooled by forced-air cooling to near 0 °C (32 °F). Even peaches that were thoroughly cooled in the bins will warm substantially during packing and should be thoroughly recooled after packing.

Optimum Storage Conditions

Optimum temperature for storage is -1 to 0 °C (31 to 32 °F). The freezing point varies, depending on SSC, from -3 to -1.5 °C (27 to 30 °F). RH should be 90 to 95%, and an air velocity of approximately 50 ft^3 min^{-1} is recommended during storage.

Controlled Atmosphere (CA) Considerations

The major benefits of CA during storage and shipment are retention of fruit firmness and ground color. CA of 6% O_2 and 17% CO_2 at 0 °C is recommended for reducing internal breakdown during shipping, but the efficacy is related to cultivar, preharvest factors, temperature, market life, and shipping time. Large-sized 'Elegant Lady' and 'O'Henry' peaches stored at 0 °C benefit from an atmosphere of 6% O_2 and 17% CO_2.

Fruit size, storage atmosphere, and temperature all affect development of chilling injury. Small peaches stored in air at 0 °C have a longer market life than large fruit. At both temperatures, large-sized 'Elegant Lady' and 'O'Henry' fruit have a longer market life under CA than under air storage. However, at 3 °C (38 ºF) small-sized 'Elegant Lady' in CA showed flesh browning.

Retail Outlet Display Considerations

If fruit firmness is <27 N (6 lb-force), fruit should be displayed on a cold table. If firmness is >27 N (6 lb-force), fruit should be displayed on a dry table.

Chilling Sensitivity

Most mid-season and late peach cultivars are susceptible to chilling injury or internal breakdown. Chilling injury develops faster and more intensely in fruit stored at 2 to 7 °C (36 to 45 °F) than in those stored at 0 °C (32 °F) or below.

Ethylene Production and Sensitivity

The lower end of this range is for mature but unripe fruit; higher values are for ripe fruit:

Temperature	µL C_2H_4 kg^{-1} h^{-1}
0 °C	0.01 to 5
5 °C	0.02 to 10
10 °C	0.05 to 50
20 °C	0.10 to 160

In general, peaches harvested at Well Mature (higher than U.S. Mature) will ripen properly without exogenous ethylene application. In most cultivars, ethylene application to fruit harvested at U.S. Mature will ripen the fruit more uniformly without speeding up the rate of ripening.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	4 to 6
10 °C	16 to 24
20 °C	64 to 110

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

The major physiological cause of deterioration is a low-temperature or chilling injury problem generically called *"internal breakdown" (IB).* The disorder can manifest itself as dry, mealy, woolly, or hard-textured fruit; flesh or pit cavity browning; or flesh translucency usually radiating through the flesh from the pit. An intense red color development of the flesh ("bleeding") usually radiating from the pit may be associated with this problem in some peach cultivars. In all cases, flavor is lost before visual symptoms are evident. However, there is large variability in IB susceptibility among peach cultivars. In general, peach cultivars are more susceptible to IB than nectarine and plum cultivars. At the shipping point, fruit should be cooled and held near or below 0 °C (32 °F). If IB-susceptible cultivars are exposed to 5 °C (41 °F) during transportation, their postharvest life can be significantly reduced. Several treatments to delay and limit IB have been tested. Among them, preripening fruit before storage is being used successfully in California. The success of CA (17% CO_2 and 6% O_2) depends on cultivar market life, shipping time, and fruit size.

Inking (black staining) is a cosmetic problem affecting only the skin. This disorder is characterized by black-brown spots or stripes. These symptoms appear generally 24 to 48 h after harvest. Inking occurs as a result of abrasion damage in combination with contamination by heavy metals (iron, copper, and aluminum). It occurs usually during harvesting and hauling, though it may occur in other steps of postharvest handling. Gentle handling of fruit, short hauling, avoiding foliar nutrient sprays within 15 days of harvest, and following suggested guidelines for preharvest fungicide spray intervals will reduce inking.

Postharvest Pathology

Brown rot, caused by *Monilinia fructicola*, is the most important postharvest disease of peaches. Infection begins during flowering. Fruit rot may occur before harvest but often appears after harvest. Orchard sanitation to minimize infection sources, preharvest fungicide application, and prompt cooling after harvest are among the control strategies. Also, postharvest fungicide treatment may be used.

Gray mold is caused by *Botrytis cinerea*. It can be a serious problem during wet spring weather. It can occur during storage if fruit have been contaminated through harvest and handling wounds. Avoiding mechanical injuries and good temperature management are effective controls.

Rhizopus rot is caused by *Rhizopus stolonifer*. It can occur in ripe or near-ripe peaches kept at 20 to 25 °C (68 to 77 °F). Cooling and keeping fruit below 5 °C (41 °F) is an effective control.

Quarantine Issues

Because some insects, such as *Conotracherlus nenuphar* (plum curculio), *Cydia pomonella* (codling moth), *Rhagoletis pommonella* (apple maggot), and *Tetranychus pacificus* are not present in some of our import markets, phytosanitary restrictions have been established. Issues associated with exotic pest quarantines, addressing either imported or exported peaches, can change rapidly. APHIS issues rules regarding import requirements. This agency provides information to assist exporters in targeting markets and defining countries' entry requirements. APHIS, in cooperation with State plant boards, developed a database called “Excerpt” to track phytosanitary requirements for each country. APHIS also provides phytosanitary inspections and certifications that declare peaches free of pests to facilitate compliance with foreign regulatory requirements.

For peaches, there are three main ways to deal with these phytosanitary requirements: inspection prior to shipment (including use of screened crates transported in sealed containers), methyl bromide fumigation, and a systems approach. A phytosanitary certificate (PC) is required to import California peaches into Taiwan. Peaches must be free of *Anarsia ineatella* (peach twig borer), *Conotracherlus nenuphar* (plum curculio), *Cydia pomonella* (codling moth), *Erwinia amylovora* (fire bright), *Rhagoletis pomonella* (apple maggot), *Tetranychus pacificus* (Pacific spider mite), and *Ceratitis capitata* (Mediterranean fruit fly). If these conditions are not met, fruit must receive an appropriate treatment prior to shipment. Details of the treatment must be recorded on the PC.

A phytosanitary certificate is required to import California peaches into British Columbia. The PC should state that fruit are free of *Cydia molesta* (oriental fruit moth). Also, it should clearly state that fruit were produced and inspected in accordance with the systems approach guidelines agreed to by APHIS and the Canadian Food Inspection Agency. Fruit imports are unrestricted to all other Canadian provinces.

A similar program between APHIS and several Mexican agencies exists to facilitate import and assure that peaches and nectarines are free of *Cydia molesta* (oriental fruit moth), *Conotracherlus nenuphar* (plum curculio), *Rhagoletis pomonella* (apple maggot), and fruit flies (Tephritdae). Peaches imported into the United States from other parts of the world are sometimes fumigated with methyl bromide, at shipping or arrival point, following treatment schedules issued by APHIS, to prevent entry of insect pests.

Suitability as Fresh-Cut Product

The optimal ripeness for preparing fresh-cut peach slices is a flesh firmness of 13 to 27 N (3 to 6 lb-force). These slices can be kept while retaining good eating quality for 2 to 8 days (depending on cultivar) at 5 °C (41 °F) with 90 to 95% RH. Postcutting dips in ascorbate and calcium lactate, or use of MAP, may slightly prolong shelf-life.

Special Considerations

Because peaches area a climacteric fruit, they are harvested after they reach a minimum maturity but before they are completely ripe (that is, ready to eat). Ripening must be initiated before consumption in order to satisfy consumers. Detailed ripening protocols for shippers, retail handlers, warehouse managers, and produce managers have been developed.

Acknowledgments

Some of the information in this chapter is from the University of California, Davis, website on “Produce Facts” at http://postharvest.ucdavis.edu/produce_information.

Further Reading

Ceponis, M.J., R.A. Cappellini, J.M. Wells, and G.W. Lightner. 1987. Disorders in plum, peach and nectarine shipments to the New York market, 1972-1985. Plant Dis. 71:947-952.

Crisosto, C.H. 1994. Stone fruit maturity indices: a descriptive review. Postharv. News Info. 5(6):65N-68N.

Crisosto, C.H., F.G. Mitchell, and S. Johnson. 1995. Factors in fresh market stone fruit quality. Postharv. News Info. 6(2):17N-21N.

Crisosto, C.H., F.G. Mitchell, and Z. Ju. 1999. Susceptibility to chilling injury of peach, nectarine, and plum cultivars grown in California. HortScience 34:1116-1118.

Kader, A.A., and F.G. Mitchell. 1989. Postharvest physiology. *In* J.H. LaRue and R.S. Johnson, eds., Peaches, Plums, Nectarines: Growing and Handling for Fresh Market, pp. 154-164. Pub. no. 3331, University of California, Davis, CA.

Gorny, J.R., B. Hess-Pierce, and A.A. Kader. 1998. Effect of fruit ripeness and storage temperature on the deterioration rate of fresh-cut peach and nectarine slices. HortScience 33:110-113.

Gorny, J.R., B. Hess-Pierce, and A.A. Kader. 1999. Quality changes in fresh-cut peach and nectarine slices as affected by cultivar, storage atmosphere and chemical treatments. J. Food Sci. 64:429-432.

LaRue, J.H., and R.S. Johnson, eds., 1989. Peaches, plums, nectarines: growing and handling for fresh market. Pub. no. 3331, University of California, Davis, CA.

Lill, R.E., E.M. O'Donoghue, and G.A. King. 1989. Postharvest physiology of peaches and nectarines. Hort. Rev. 11:413-452.

Mitchell, F.G. 1987. Influence of cooling and temperature maintenance on the quality of California grown stone fruit. Intl. J. Refrig. 10:77-81.

Pear

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Scientific Name and Introduction

Pyrus communis L., the pear, is a member of the family Rosaceae. The fleshy part of pear fruit consists of the fused base of the calyx (sepals), corolla (petals), and stamens, which are interpreted by one school of anatomists as being the "receptacle." Therefore, pears are also a pome fruit (Hulme and Rhodes 1971). Commercial pear production on the Pacific Coast is largely confined to nine districts including the Wenatchee and Yakima Valley areas in central Washington, the Hood River Valley in north central Oregon, and the Rogue River Valley around Medford in southern Oregon. In California, production is mainly in the foothill district of Eldorado, Placer, and Nevada counties; the Sacramento River district; the coast district north of San Francisco Bay known as the Santa Clara Valley district; and the southern California acreage mostly in the Antelope Valley in Los Angeles County (Childers 1949).

Pears rank third among the most important tree fruits grown in the world and fourth among all fruits for which statistics are available (Childers 1949). All important pear varieties grown in the United States belong to the European species, and commercial pear production is confined to six main varieties—'Bartlett,' 'Beurré d'Anjou,' 'Beurré Bosc,' 'Beurré Hardy,' 'Doyenne' du Comice,' and 'Seckel.' Other minor varieties include 'Winter Nelis,' 'El Dorado,' 'Kieffer,' and 'Packham's Triumph.'

Quality Characteristics and Criteria

A properly ripened pear is buttery with juicy texture and the aroma and taste distinct to each cultivar. Pear fruit require a period of cold storage at -1 °C (30 °F) to induce normal ripening and develop high dessert quality upon ripening. When pear fruit meet the chilling requirement after a period of cold storage, they should be ripened at 20 °C (68 °F) in air for 4 to 7 days depending on the variety for the development of high dessert quality.

Horticultural Maturity Indices

Pear fruit are capable of developing good dessert quality upon ripening only if they are harvested at proper maturity. Pear fruit harvested at improper maturity are more susceptible to physiological disorders and have a shorter storage life. Immature pear fruit are more susceptible to superficial scald, shriveling, and friction discoloration, while overmature fruit tend to have higher incidence of core breakdown and CO_2 injury (Hansen and Mellenthin 1962, Fidler et al. 1973, Mellenthin and Wang 1974).

One of the most satisfactory and easiest ways of determining proper harvest maturity is to measure fruit firmness. A pressure test using a penetrometer on the pear surface gives an indication of flesh firmness. Firmness decreases with maturation. Different varieties have different firmness at maturity. Recommended ranges of firmness for harvesting different pear varieties as measured using a 8-mm plunger tip are as follows (Williams et al. 1978, Hansen and Mellenthin 1979):

	N
'd'Anjou'	57.8 to 66.7
'Bartlett'	66.7 to 84.3
'Bosc'	62.7 to 71.6
'Comice'	49.0 to 57.8
'Hardy'	41.2 to 49.0
'Kiefer'	52.9 to 66.7
'Seckel'	57.8 to 66.7
'Packham'	57.8 to 66.7
'El Dorado'	57.8 to 66.7
'Winter Nelis'	57.8 to 66.7

(1 N = 0.225 lb-force)

Heat units accumulated during the 9 weeks following full bloom provide an accurate prediction of maturity and harvest date. The equation (for Fahrenheit) can be expressed as—

Daily Heat Unit = [(Maximum Temp. + Minimum Temp.)/2] - 45

Heat units accumulated during the 9 weeks following full bloom have been developed at the Mid-Columbia Agricultural Research and Extension Center to provide an accurate prediction of the commercial harvest date for 'd'Anjou' and 'Bartlett' pear cultivars. The 50-yr record (1944 to 1994) at this Center has shown that correlation coefficients between the number of days from full bloom (DFFB) until harvest and the accumulated heat units (AHU) are -0.9213 for 'd'Anjou' pears and -0.8300 for 'Bartlett' pears. The linear equations between DFFB and AHU are—

'd'Anjou'	DFFB = 177.5472 - 0.0481 × AHU
'Bartlett'	DFFB = 147.5377 - 0.0353 × AHU

In Oregon's Hood River Valley district, the entire pear-producing area covers elevations between 500 ft (152 m) and 2,000 ft (610 m). The dates of full bloom or the dates of first commercial harvest between the lower and higher elevations could be as much as 3 weeks apart. Predictive models for the harvest maturity of 'd'Anjou' and 'Bartlett' pears grown in 14 orchards representing the entire Hood River Valley district have been developed (Varga and Chen 1995). Other predictive methods such as days from full bloom, SSC, and starch-iodine test are quite variable from season to season and have not been adopted for routine practice by the pear industry.

Grades, Sizes, and Packaging

Grades include Extra Fancy, U.S. No. 1, Fancy, and Unclassified (or Third Grade) for all winter pear cultivars, and U.S. No. 1 and Fancy for 'Bartlett.' Grading is based primarily on external appearance. Size categories are 50, 60, 70, 80, 90, 100, 110, 120, 135, 150, 165, and 180 fruit per standard 20-kg box.

Precooling Conditions

Rapid removal of field heat and prompt cooling of harvested pears are essential for long-term storage. During the pull-down period, room temperatures of -3.5 to -2.0 °C (26 to 28 °F) can be used, but the environment should be raised to -1 °C (30 °F) as the fruit temperatures approach this temperature (Hansen and Mellenthin 1979). Delay in cooling shortens storage life. It has been suggested that the core temperature should be reduced to near the holding temperature in 4 days (Porritt 1965). When pears are packed in cartons before cooling, cartons should be stacked to provide exposure of the sides to airflow (Sainsbury and Schomer 1957).

Optimum Storage Conditions

Pears are very sensitive to temperature. The storage life of 'd'Anjou' and 'Bartlett' pears has been reported to be 35 to 40% longer at -1 °C (30 °F) than at 0 °C (32 °F) (Porritt 1964). Most pears in the Pacific Northwest are stored at -1 °C (30 °F) with RH of 90 to 94% (Hansen and Mellenthin 1979). Many operators of pear storage rooms use thermocouples in the air and in fruit to determine temperatures at selected areas in the storage. Precise temperature control is needed to prevent freezing when pears are stored at these low temperatures (Hartman 1931). Intermediate temperatures of 2.5 to 10 °C (37 to 50 °F) are harmful to some pear cultivars. 'Bartlett' pears stored at this temperature have dry texture and inferior flavor (Porritt 1964). Pears lose moisture rapidly; hence, it is advisable to hold RH at >90%. Polyethylene liners are effective in controlling moisture loss.

Controlled Atmosphere (CA) Considerations

CA storage has been used successfully to extend the storage life of pears and to maintain greater capacity for ripening. The optimum and safe CA for commercial use is 2 to 2.5% O_2 and 0.8 to 1% CO_2 (Hansen and Mellenthin 1979). Use of short-term high-CO_2 treatment improves keeping quality of ‘d’Anjou’ pears (Wang and Mellenthin 1975). Treatment with 12% CO_2 for 2 weeks immediately after harvest has a beneficial effect on retention of ripening capacity. Keeping ‘d’Anjou’ pears in a low-O_2 atmosphere (1.0%) with ≤0.1% CO_2 can also maintain higher dessert quality and reduce incidence of superficial scald after long-term cold storage (Hansen 1957, Mellenthin et al 1980).

Pear Ripening in Storage

Most pear cultivars require a period of cold storage before they will ripen normally at room temperature (Leblond and Ularic 1973, Drouet and Hartmann 1979, Blankenship and Richardson 1985, Morin et al. 1985, Knee 1987). Most cultivars do not soften appreciably during cold storage; hence, they require a period of ripening at warm temperature to develop good flavor and texture for eating. The best ripening temperature after storage is about 15 to 21 °C (59 to 70 ºF). Higher temperatures may result in poor quality or decay. Most cultivars fail to soften at 30 °C (86 ºF). It is generally recognized that ethylene induces ripening.

A striking characteristic of climacteric fruits is their autocatalytic ethylene production; that is to say, ethylene stimulates its own synthesis (Pech et al. 1994). During storage at -1 °C (30 °F), 1-aminocyclopropane-1-carboxylic acid (ACC; the immediate ethylene precursor) starts to accumulate; as a consequence, pear fruit begin to produce ethylene and ripen normally upon exposure to room temperature. Exposure of pear fruit to a storage temperature of -1 to 0 °C (30 to 32 ºF) stimulates synthesis of ACC and ethylene because low temperature induces biosynthesis of ACC oxidase and ACC synthase (Blankenship and Richardson 1985, Wang et al. 1985, Leliévre at al. 1997, Agar et al. 2000). The duration of chilling required for proper ripening is cultivar-dependent (Wang et al. 1985) and varies with storage temperature (Sfakiotakis and Dilley 1974, Gerasopoulos and Richardson 1995). Storage duration at -1 °C (30 °F), which is required to induce normal ripening of pear fruit, is 2 to 4 weeks for ‘Bartlett’ (Puig et al. 1996, Agar et al. 1999), 2 to 3 weeks for ‘Bosc’ (Chen et al. 1982), and 7 to 8 weeks for ‘d’Anjou’ (Chen et al. 1982).

Exogenous ethylene, at 100 µL L^{-1}, has been used commercially to precondition underchilled ‘Bartlett’ and ‘d’Anjou’ pears at 20 °C (68 °F) for 2 to 3 days before shipment. Preconditioned pear fruit are capable of ripening normally and uniformly upon reaching the retail markets or for the canning process (Chen et al. 1996, Puig et al. 1996, Agar et al. 1999, 2000).

Ethylene Production and Sensitivity

Ethylene production rates are low at harvest: <0.1 µL kg^{-1} h^{-1}; but rates gradually increase during air storage at -1.1°C (30 °F). After 3 mo of air storage at -1.1 °C (30 °F) and 1 day at 20 °C (68 °F), ethylene production of ‘d’Anjou’ was 0.5 µL kg^{-1} h^{-1}; of ‘Bosc,’ 30 µL kg^{-1} h^{-1}; and of ‘Comice,’ 30 µL kg^{-1} h^{-1}.

Most pear cultivars will exhibit climacteric-like ethylene production during the ripening period at 20 °C (68 °F) when optimally mature fruit have satisfied their chilling requirement at -1.1 °C (30 °F). The chilling requirement of optimally mature pears stored at -1.1 °C (30 °F) for induction of normal ripening capacity is about 60 days for ‘d’Anjou,’ 30 days for ‘Bosc,’ 30 days for ‘Comice,’ and 15 days for ‘Bartlett.’ The magnitude of ethylene production at the climacteric-like peak is 10 to 20 µL kg^{-1} h^{-1} for ‘d’Anjou,’ 40 to 80 µL kg^{-1} h^{-1} for ‘Bosc,’ 80 to 200 µL kg^{-1} h^{-1} for ‘Bartlett,’ and 60 to 80 µL kg^{-1} h^{-1} for ‘Comice.’

Unripe pear fruit are somewhat sensitive to ethylene, depending on the cultivar. ‘Bartlett’ pears are most sensitive to ethylene, ‘Bosc’ and ‘Comice’ fruit are moderately sensitive, and ‘d’Anjou’ fruit are least sensitive to ethylene for induction of ripening. Nevertheless, it is best to avoid storing pear fruit near ripe fruit or other fresh produce that produces appreciable levels of ethylene. Preconditioning of pear fruit with 100 μL L^{-1} ethylene at 20 °C (68 °F) for 72, 48, or 24 h will induce ripening within 3 to 6 days, depending on the cultivar (Wang and Mellenthin 1972, Chen et al. 1982, Elgar et. al. 1997).

Respiration Rates

Temperature	*'d'Anjou'* Days in Storage						*'Bartlett'* Days in Storage				
°C	1	25	50	100	150	200	1	10	20	90	120
	mg CO_2 kg^{-1} h^{-1}										
-2	5.0	2.0	2.0	2.3	2.4	2.7	—	1.5	2.2	3.2	3.8
-1	5.0	2.0	2.0	2.4	2.5	2.8	—	2.2	2.4	3.6	4.2
0	5.0	2.4	2.5	3.2	4.1	4.5	—	2.5	2.6	5.6	5.9
2	5.0	3.1	3.6	5.1	—	—	—	3.2	4.5	—	—
10	9.0	6.0	7.0	—	—	—	16.0	8.1	24.0	—	—
21	17.0	7.0	7.0	—	—	—	16.0	38.0	—	—	—

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Superficial scald, also called storage scald, is a cosmetic condition of surface browning affecting only a few layers of cells beneath the skin. Eating quality of fruit is not affected. Frequently, fruit appear normal after several months in cold storage but then develop scald symptoms after a few days at room temperature. The unpleasant brown appearance makes fruit difficult to market.

Superficial scald affects 'd'Anjou' pears and other pear cultivars. The cause of superficial scald is conjugated trienes, the oxidative products of the naturally occurring terpene α-farnesene, which are toxic to the epidermal and endodermic cells of the fruit peel (Chen et al. 1990b). Factors that usually increase the severity of the disorder include immaturity, high fruit nitrogen, low fruit calcium, warm preharvest weather, delayed cold storage, high storage temperatures, and high RH during cold storage.

Conventional control method: The primary method of controlling superficial scald on 'd'Anjou' pears at present is a postharvest treatment of ethoxyquin, an antioxidant (Hansen 1964, Hansen and Mellenthin 1967, 1979). Ethoxyquin is recommended at a concentration of 2,700 μL L^{-1}, which can be applied to the fruit either as a drench, as a line spray, or by impregnating it into paper wraps (Hansen and Mellenthin 1979). Drenching fruit is done as soon as possible after harvest, usually no later than 2 days. Unfortunately, this treatment often causes considerable phytotoxicity when the ethoxyquin solution becomes more concentrated at contact points between fruit or between fruit and wooden bins. Fruit at these contact points develop pinkish (or blackened) ring markings during storage (Porritt et al. 1982), and the injured fruit become unmarketable. Ethoxyquin treatment as a line spray or a paper wrap is carried out during commercial packing. Because it usually takes about 3 mo to pack all fruit stored in air, fruit may receive ethoxyquin protection as early as 1 week after harvest or as late as 3 mo after storage using either of these methods. Though neither method causes any phytotoxicity to fruit, delay in ethoxyquin application has resulted in significant incidence of scald disorder at terminal markets. Current recommended ethoxyquin treatments are inadequate.

Split application of ethoxyquin control method: Drenching 'd'Anjou' fruit with 1,000 µL L^{-1} ethoxyquin within 2 days after harvest controlled scald development for 4 mo in air storage without causing phytotoxicity to fruit. Drenching fruit with 1,000 µL L^{-1} ethoxyquin within 2 days after harvest plus an additional line spray of 1,700 µL L^{-1} ethoxyquin within 3 mo of harvest controlled scald development for 5 mo in air storage (Chen et al. 1990a).

Nonchemical control method: A short-term (3- to 4-mo) CA storage of 'd'Anjou' pears at -1 ºC in 0.8% O_2 and <0.1% CO_2 (denoted as low O_2) effectively controls development of superficial scald without inducing black speck and pithy brown core (Chen and Varga 1997a, 1997b). Fruit stored in a short-term low-O_2 regime remain free from scald after 8 weeks in air at -1 ºC. These fruit can be safely packed without antioxidant treatment and marketed after 2 mo of air storage.

Combined ethoxyquin/CA control method (Chen and Varga 1997a): For 'd'Anjou' fruit destined for mid-term (5- to 6-mo) or long-term (7- to 8-mo) CA storage, a prestorage drench of fruit with 1,000 µL L^{-1} ethoxyquin within 2 days after harvest was necessary in order to control superficial scald disorder. The concentrations of O_2 and CO_2 in CA storage must be kept at 1.5% and <0.5%, respectively, throughout the entire storage period to minimize development of black speck and pithy brown core. An alternative method would be to store field-run 'd'Anjou' pears in low O_2 (0.8% O_2 and <0.03% CO_2) at -1 °C (30 °F) for 90 days until qualified. Low-O_2 stored fruit can be either presized or packed with in-line spray of 2,700 µL L^{-1} ethoxyquin within 2 weeks after being returned to air storage. Treated fruit can be further stored in regular CA storage (2% O_2 and 1% CO_2) for another 3 to 4 mo at -1 °C (30 °F) for late season marketing.

Pithy brown core (PBC) affects 'd'Anjou' pears stored in either sealed polyethylene box liners or CA storage with elevated CO_2. It is characterized by pithy, brown areas in the core region of the fruit. It may be restricted to brown flecks between the carpels, or it may encompass the entire core and extend into the surrounding flesh. In some instances, the tissues collapse, producing cavities. The affected tissues are dry and pithy, in contrast to the soft, watery texture resulting from core breakdown. The disorder is associated with high CO_2 in atmospheres of sealed box liners or CA storage and is considered to be a form of CO_2 injury. It is aggravated by the combination of low O_2 and high CO_2 levels in CA storage. Susceptibility to PBC increases with factors that induce fruit senescence, such as late harvesting, delayed storage, slow cooling, high storage temperatures, and extended CA storage (Hansen and Mellenthin 1962). Fruit from trees with low vigor and fruit grown in cool seasons are more susceptible to PBC (Hansen and Mellenthin 1962).

For fruit stored loose in bins—field-run fruit—CO_2 should be maintained at <0.03% when O_2 in CA storage is 0.8 to 1.0% (Chen and Varga 1997b). The maximum storage length of 'd'Anjou' fruit stored under low O_2 should be no more than 120 days. For fruit stored loose in bins, CO_2 should be maintained at <0.5% when O_2 in CA storage is 1.5 to 1.8%. The maximum storage time of fruit stored in the CA regime described above should be no longer than 8 mo. For fruit stored loose in bins, CO_2 should be maintained at <1.0% when O_2 in CA storage 2.0 to 2.5%. The maximum storage time of fruit stored in the CA regime described above should also be no longer than 8 mo (Chen and Varga 1997b).

For fruit stored in packed boxes, only the CA regime with 2.0 to 2.5% O_2 and <1.0% CO_2 gives minimal risk for ‘d’Anjou’ pears to develop PBC after prolonged CA storage (6 to 8 mo) (Chen and Varga 1997b).

Black speck (BS), or “skin speckling,” of ‘d’Anjou’ pears becomes an economic problem after prolonged CA storage. It has been observed frequently in commercial CA storage. It is a physiological disease and is suspected to be closely associated with PBC. Kupferman (1988) reported that BS could develop on ‘d’Anjou’ pears with or without PBC. Similarly to PBC, ‘d’Anjou’ fruit develop BS only in CA storage. The unbalanced O_2:CO_2 ratio in CA storage must be an initial factor in causing skin injury of fruit. It was confirmed that BS was induced by ≤1.0% O_2 in CA storage for longer than 4 mo and was not affected by <1% CO_2 (Chen and Varga 1989). Each BS spot consists of several hundred epidermal cells discolored to dark brown. The distinct specks scatter randomly on the peel tissue and are not restricted to around the lenticels. It affects only five to six layers of hypodermal cells of the skin (Kupferman 1988, Chen and Varga 1989, Lee et al. 1990).

Since BS is associated with low O_2 (≤1%), a CA regime with O_2 at 1.5% or higher will alleviate the disorder after prolonged CA storage. For ‘d’Anjou’ pears, low-O_2 (0.8 to 1.0% O_2) storage should not exceed 120 days (Chen and Varga 1997b).

Black end of ‘d’Anjou’ pears begins with symptoms appearing when fruit are one-third to one-half full size. It is a protrusion of the calyx due to the retarded development of tissues around the calyx. As the disorder progresses, the calyx lobes turn black, the tissues surrounding the calyx opening become hard, and a brownish discoloration forms. This discoloration may appear first in separate spots, which later coalesce; or there may be a large area completely and uniformly discolored from the beginning. The final color of affected tissues is black, and cracks up to 3 cm in length may appear in the blackened area. The affected area is usually confined to approximately 1 to 2 cm around the calyx, but it may cover the entire lower half of fruit in severe cases. Discoloration usually does not extend deep into the flesh, sometimes only affecting the skin.

Black end is believed to be caused by water imbalance stemming from a restricted root system. Excessive subsoil moisture in spring damages feeder roots, inducing development of the disorder. Fruit grown on trees with Asian rootstocks (*Pyrus serotina* Rehder) are highly susceptible to black end. Fruit grown on trees with French rootstocks (*Pyrus communis* L.) are generally free from the disorder (Heppner 1928, Davis and Tufts 1932).

Core breakdown has been referred to in different investigations as “internal breakdown,” “core rot,” “brown heart,” and “mealy core.” As the names imply, this disorder of pears is characterized by the softening and browning of tissues in the region of the core. The breakdown may be closely confined to the core or may extend into the surrounding flesh. In the early stages, the affected tissues are soft and watery; they later become dark brown. The disorder is often associated with an external skin discoloration resembling senescent scald.

Overmature fruit are more susceptible to core breakdown in storage and in the market. Late-harvested pears are unable to slow their metabolic activities sufficiently for successful storage at -1 °C (30 ºF). Serious breakdown can occur in storage or after pears are removed to ripen at 20 °C (68 ºF). Late-harvested pears show an increase in CO_2 in the tissues around the core area until the onset of core breakdown. Such fruit produce an abnormally high amount of acetaldehyde until core breakdown is advanced. ‘Bartlett,’ ‘Bosc,’ and ‘Comice’ pears are highly susceptible to core breakdown, whereas ‘d’Anjou’ pears are somewhat resistant. Harvesting fruit at optimum maturity and rapidly precooling fruit before storage are essential to reduce core breakdown (Hartman 1925, Harley 1929).

Senescent scald occurs differently in various pears. Pears can be classified broadly into two groups based on their storage behavior. One group, including 'd'Anjou,' 'Winter Nelis,' 'Packham's Triumph,' and 'Hardy,' senesce very slowly in cold storage and generally do not lose their capacity for normal ripening at room temperature as a result of extended storage. These pears are subject to storage scald, called "Anjou scald" or "superficial scald." The other group of pears, which includes 'Bartlett,' 'Bosc,' 'Howell,' 'Comice,' 'Sierra,' and 'Flemish Beauty,' show a higher rate of senescence during cold storage; fruit lose their ability for normal ripening at room temperature after prolonged storage. As storage length is extended, fruit become yellow and ultimately develop a dark brown discoloration of the skin called "senescent scald." This may occur in cold storage or after fruit are removed from cold storage and subjected to higher temperatures. Fruit remain firm, but the skin sloughs off easily (Porritt et al. 1982).

Methods of treating senescent scald are similar to those used to reduce core breakdown disorder, with overmature fruit more susceptible in storage and in the market. Pears that are harvested late do not exhibit a decrease in metabolic activity necessary for storage at -1 °C (30 ºF). There are no control measures other than harvesting pears at optimum maturity, reducing the storage period, and improving postharvest handling with methods such as fast cooling of pears immediately after harvest and maintaining constant temperature at -1 °C (30 ºF) throughout storage (Porritt et al. 1982).

Postharvest Pathology

A detailed description of pear diseases and control measures can be found in "Compendium of Apple and Pear Diseases" (Jones and Aldwinckle 1990). The cause of postharvest decay in pear fruit is often difficult to identify through symptoms alone. Many decay pathogens do not sporulate on fruit in cold or CA storage. The only reliable method for identifying the cause of decay is to isolate and identify the causal agent. Isolations are easily accomplished by removing the fruit skin over the margin of a decayed area and plating some of the decayed flesh on potato-dextrose agar.

Fungi causing postharvest decay in pome fruits can be subdivided into two broad groups: those that cause primarily postharvest decay and those that also cause fruit decay in the field. Postharvest decay attributable to fungi in the latter group usually result from infections that occurred in the field but were quiescent or otherwise escaped notice at harvest. Control measures for these diseases are based on the protection of fruit from preharvest infections. Control measures broadly applicable to many postharvest diseases include both sanitation and harvesting, as well as handling methods that maintain the integrity of harvested fruit. Sanitation measures are especially important for reducing exposure of fruit to spores of wound pathogens, such as *Penicillium* and *Botrytis*. Harvesting and handling methods are important because wounded, bruised, or overmature fruit are more susceptible to many postharvest decay fungi. Rapid cooling after harvest reduces the incidence of decay in storage, because low temperatures reduce both the rate of fungal growth and fruit senescence. Low temperature prevents development of incipient infections by some fungi in storage, such as those causing white rot and brown rot.

Postharvest decay pathogens infecting pears in the field and causing symptoms in stored pears as a result of incipient or quiescent infections are *Botryosphaeria dothidea* (white rot), *B. obtusa* (black rot), *Glomerella cingulata* (bitter rot), *Monilinia fructicola* (brown rot), *M. fructigena* (brown rot), *M. laxa* (brown rot), and *Phytophthora cactorum* (phytophthora fruit rot).

Postharvest diseases commonly found in pears after storage are blue mold (*Penicillium* spp.), gray mold (*Botrytis cuberea* Per.), bull's-eye rot (*Pezicula malicorticis* [H. Jacks.] Nannf.), alternaria rot (*Alternaria alternata* [Fr.] Keissler), mucor rot (*Mucor piriformis* E. Fischer), side rot (*Phialophora malorum* [Kidd & Beaumont] McColloch), cladosporium rot (*Cladosporium herbarum* [Pers.] Link), coprinus rot (*Coprinus psychromorbidus* Redhead & Traquair), fisheye rot

(*Butlerelfia eustacei* Weresub & Illman), pink rot (*Trichothecium roseum* [Pers.] Link), and rhizopus rot (*Rhizopus stolonifer* [Ehrenb.] Vuill.).

References

Agar, I.T., W.V. Biasi, and E.J. Mitcham. 1999. Exogenous ethylene accelerates ripening responses in 'Bartlett' pears regardless of maturity or growing region. Postharv. Biol. Technol. 17:67-68.

Agar, I.T., W.V. Biasi, and E.J. Mitcham. 2000. Cold storage duration influences ethylene biosynthesis and ripening of 'Bartlett' pears. HortScience 35:687-690.

Blankenship, S.M., and D.G. Richardson. 1985. Development of ethylene biosynthesis and ethylene induced ripening in 'd'Anjou' pears during the cold requirement for ripening. J. Amer. Soc. Hort. Sci. 110:520-523.

Chen, P.M., S.R. Drake, D.M. Varga, and L. Puig. 1996. Precondition of 'd'Anjou' pears for early marketing by ethylene treatment. J. Food Qual. 19:375-390.

Chen, P.M., D.G. Richardson, and W.M. Mellenthin. 1982. Differences in biochemical composition between 'Beurre d'Anjou' and 'Bosc' pears during fruit development and storage. J. Amer. Soc. Hort. Sci. 107:807-812.

Chen, P.M., and D.M. Varga. 1989. Black speck. A superficial disorder of 'd'Anjou' pears after prolonged CA storage. *In* J.K. Fellman, ed., 5th International Controlled Atmosphere Research Conference, vol 1, Wenatchee, WA, pp. 145-156.

Chen, P.M., and D.M. Varga. 1997a. CA regimes for control of superficial scald of 'd'Anjou' pears. *In* G. Kupferman, ed., 13th Annual Washington Tree Fruit Postharvest Conference, Wenatchee WA, pp, 17-26.

Chen, P. M., and D.M. Varga. 1997b. Determination of optimum controlled atmosphere regimes for the control of physiological disorders of 'd'Anjou' pears after short-term, mid-term or long-term storage. *In* E.J. Mitcham, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 2, pp. 85-90. University of California, Davis CA.

Chen, P.M., D.M. Varga, E.A. Mielke, et al. 1990a. Control of superficial scald on 'd'Anjou' pears by ethoxyquin: effect of ethoxyquin concentration, time and method of application, and a combined effect with controlled atmosphere storage. J. Food Sci. 55:167-170.

Chen, P.M., D. Varga, E. Mielke, et al. 1990b. Control of superficial scald on 'd'Anjou' pears by ethoxyquin: oxidation of α-farnesene and its inhibition. J. Food Sci. 55:171-175, 180.

Childers, N.F. 1949. Pear and quince culture. *In* R.W. Gregory, ed., Fruit Science, Orchard and Small Fruit Management, pp. 248-273. J.B. Lippincott, New York, NY.

Davis, L.D., and W.P. Tufts. 1932. Black end and its occurrence in selected pear orchards. Proc. Amer. Soc. Hort. Sci. 28:634-638.

Drouet, A., and C. Hartmann. 1979. Ployribosomes from pear fruit. Plant Physiol. 64:1104-1108.

Elgar, H.J., C.B. Watkins, S.H. Murray, and F.A. Gunson. 1997. Quality of 'Buerre Bosc' and 'Doyenne du Comice' pears in relation to harvest date and storage period. Postharv. Biol. Technol. 10:29-37.

Fidler, J.G., B.G. Wilkinson, K.L. Edney, and R.O. Sharples. 1973. The Biology of Apple and Pear Storage. Commonwealth Agricultural Bureaux, Farnham Royal, U.K.

Gerasopoulos, D., and D.G. Richardson. 1995. Changes in fatty acids of ‘d’Anjou’ pears in relation to storage temperature and calcium. Acta Hort. 379:459-466.

Hansen, E. 1957. Reactions of anjou pears to carbon dioxide and oxygen content of the storage atmosphere. Proc. Amer. Soc. Hort. Sci. 69:110-115.

Hansen, E. 1964. Control of anjou pear scald improves market appeal and quality. Oreg. State Hort. Soc. Ann. Rpt. 56:29.

Hansen, E., and W.M. Mellenthin. 1962. Factors influencing susceptibility of pears to carbon dioxide injury. Proc. Amer. Soc. Hort. Sci. 80:146-153.

Hansen, E., and W.M. Mellenthin. 1967. Chemical control of superficial scald on Anjou pears. Proc. Amer. Soc. Hort. Sci. 91:860-864.

Hansen, E., and W.M. Mellenthin. 1979. Commercial handling and storage practices for winter pears. Spec. Rpt. 550, Oregon Agricultural Experiment Station, Corvallis, OR.

Harley, C.P. 1929. Relation of picking time to acetaldehyde content and core breakdown of ‘Bartlett’ pears. J. Agric. Res. 39:483-493.

Hartman, H. 1925. The control of core breakdown in pears. Bull. 216, Oregon State University Agricultural Experiment Station, Corvallis, OR.

Hartman, H. 1931. A peculiar freezing trouble of pears in cold storage. Bull. 282, Oregon State University Agricultural Experiment Station, Corvallis, OR.

Heppner, M.J. 1928. Pear black-end and its relation to different rootstocks. Proc. Amer. Soc. Hort. Sci. 24:139-142.

Hulme, A.C., and M.J.C. Rhodes. 1971. Pome fruits. *In* A.C. Hulme, ed., The Biochemistry of Fruits and Their Products, vol. 2, pp. 333-373. Academic Press, New York, NY.

Jones, A.L., and H.S. Aldwinckle, eds. 1990. Compendium of Apple and Pear Diseases. Amer. Phytopath. Soc. Press, St. Paul, MN.

Knee, M. 1987. Development of ethylene biosynthesis in pear fruit at -1 °C. J. Exp. Bot. 38:1724-1733.

Kupferman, E.M. 1988. Research on skin speckling and pithy brown core of ‘d’Anjou’ pears reported. Good Fruit Grower 39(16):17-18.

Leblond, C., and R. Ularich. 1973. Controle de l’evolution de la maturation par divers traitements theriques et gazeux chez la poire “Passe-Crassane.” Bull. Inst. Intl. Froid. 3:69-74.

Lee, S.P., P. Chen, T.H.H. Chen, et al. 1990. Differences of biochemical components between the skin tissues of normal and black-speckled ‘d’Anjou’ pears after prolonged low oxygen storage. J. Amer. Soc. Hort. Sci. 115:784-788.

Leliévre, J.M., L. Tichit, P. Dao, et al. 1997. Effects of chilling on the expression of ethylene biosynthetic genes in ‘Passe-Crassane’ pear (*Pyrus communis* L.) fruit. Plant Mol. Biol. 33:847-855.

Mellenthin, W.M., P.M. Chen, and S.B. Kelly. 1980. Low oxygen effects on dessert quality, scald prevention, and nitrogen metabolism of ‘d’Anjou’ pear fruit during long-term storage. J. Amer. Soc. Hort. Sci. 105:522-527.

Mellenthin, W.M., and C.Y. Wang. 1974. Friction discoloration of ‘d’Anjou’ pears in relation to fruit size, maturity, storage and polyphenoloxidase activities. HortScience 9:592-593.

Morin, F., C. Rigault, and C. Hartmann. 1985. Consequences d’un sejour au froid sur le metabolisme de l’ethylene au cours de la maturation de la poire Passe Crassane apres recolte. Physiol. Veg. 23:353-359.

Pech, J., C. Balagué, A. Latche, and M. Bouzayen. 1994. Postharvest physiology of climacteric fruits: recent developments in the biosynthesis and action of ethylene. Sci. Des Aliment. 14:3-15.

Porritt, S.W. 1964. The effect of temperature on postharvest physiology and storage-life of pears. Can. J. Plant Sci. 44:568-579.

Porritt, S.W. 1965. Effect of cooling rate on storage-life of pears. Can. J. Plant Sci. 45:90-97.

Porritt, S.W., M. Meheriuk, and P.D. Lidster. 1982. Postharvest disorders of apples and pears. Agric. Can. Pub. no. 1737/E.

Puig, L., D.M. Varga, P.M. Chen, and E.A. Mielke. 1996. Synchronizing ripening in individual ‘Bartlett’ pears with ethylene. HortTechnology 6:24-27.

Sainsbury, G.F., and H.A. Schomer. 1957. Influence of carton stacking patterns on pear cooling rates. Marketing Research Report 171, U.S. Department of Agriculture, Washington, DC.

Sfakiotakis, E.M., and D.R. Dilley. 1974. Induction of ethylene production in ‘Bosc’ pears by postharvest stress. HortScience 9:336-338.

Varga, D.M., and P.M. Chen. 1995. Predicting optimum maturity essential for pears. Good Fruit Grower 46:39-40.

Wang, C.Y., and W.M. Mellenthin. 1972. Induction period and threshold temperatures for premature ripening in ‘Bartlett’ pears. J. Amer. Soc. Hort. Sci. 97:557-560.

Wang, C.Y., and W.M. Mellenthin. 1975. Effect of short-term high CO_2 treatment on storage response of ‘d’Anjou’ pears. J. Amer. Soc. Hort. Sci. 100:492-495.

Wang, C.Y., C.E. Sams, and K.C. Gross. 1985. Ethylene, ACC, soluble polyuronide, and cell wall noncellulosic neutral sugar content in ‘Eldorado’ pears during cold storage and ripening. J. Amer. Soc. Hort. Sci. 110:687-691.

Williams, M.W., H.M. Couey, H. Moffitt, and D.L. Coyier. 1978. Pear Production. Agriculture Handbook 526, U.S. Department of Agriculture, Washington, DC.

Pepper

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Scientific Name and Introduction

Pepper (*Capsicum annul* L.), also called bell pepper, chili, chilies, aji, pimiento, paprika, and capsicum, is a warm-season crop that is a member of the Solanaceae family. Sweet bell peppers are green at the immature stage (when most are sold) and turn red, gold, purple, orange, or brown as they ripen. Because sugar content increases as they ripen, colored peppers tend to be sweeter than green peppers. The most notable feature of peppers is flavor, which can be sweet, mild, or strongly pungent. Sweet bell peppers are available year round, with 'California Wonder' being the most common cultivar.

Chili peppers include a number of varieties: ancho, anaheim, cayenne, cherry hot pepper, cheese, fresno (red and green), habanero (red, green, and orange), jalapeno, poblano, serrano (green and red), yellow, chiltepin, cuban, long wax, new mexican, tabasco, thai, etc. Chili peppers vary greatly from mild to very hot. Heat is determined by capsaicin content. Some chili peppers are dried and sold individually or tied together in ornamental arrangements.

Peppers are eaten raw in salads and salsa; processed by canning, freezing, or pickling; and dehydrated and powdered to produce paprika and chili powder. Unlike in the United States, most European paprika is mildly pungent. Chili powder prepared at different levels of pungency is usually composed of ground, dried, pungent peppers mixed with other spices, such as oregano, cumin, and garlic. Various pepper forms, usually chili types, are extensively used in combination with other spices such as turmeric, cumin, and coriander to produce curry powder, the pungency of which depends on the pepper cultivars used. For instance, cayenne powder is a high-pungency condiment produced from dried mature fruit of cayenne-type cultivars

Quality Characteristics and Criteria

Good-quality sweet bell peppers are uniform in shape and are the size and color typical of the variety. The flesh (pericarp) should be firm and relatively thick with a bright skin color and sweet flavor; it should be free from defects such as cracks, decay, and sunburn. Peppers should not be shriveled and dull-looking or pitted. The same quality criteria apply to fresh chili peppers. Dry lines or striations across the skin are not an indication of poor quality—they indicate a hotter pepper.

Horticultural Maturity Indices

Criteria for the maturity of green peppers include fruit size, firmness, and color. For colored peppers the additional criteria of having a minimum of 50% coloration is important.

Chili peppers are harvested by hand. They are generally picked when ripe and then dried and allowed to equilibrate in moisture content in covered piles. The major dried peppers are hot red peppers for cayenne and occasionally pimientos for paprika. The pods may be sliced before drying to shorten drying time and improve color and flavor. Seeds may be removed by screening and water sprays.

Grades, Sizes, and Packaging

Grades for fresh sweet bell peppers include U.S. Fancy, U.S. No.1, and U.S. No. 2. Not all sweet peppers are graded; ungraded peppers are "unclassified." Differences between grades are based primarily on external appearance. Sizes include Small, Medium, Large, and Extra Large/ Jumbo. Cardboard boxes commonly hold 6.8 to

15.9 kg (15 to 35 lb) of randomly packed peppers. Very high quality peppers are often marketed in 5-kg (11-lb) flat cartons with one or two layers of fruit.

There are no U.S. grades for chili peppers.

Precooling Conditions

After harvest, fresh market peppers should be rapidly cooled to no lower than 7 °C (45 °F) at high RH to reduce water loss and shrivel. Precooling can be done using forced-air cooling, hydrocooling, or vacuum-cooling. Properly vented cartons are required to facilitate forced-air cooling. If hydrocooling is used, care should be taken to prevent development of decay. High RH is necessary to avoid desiccation. Waxing has been used to reduce desiccation, but it tends to increase bacterial soft rot. Shelf-life varies among different pod types. Deterioration is often due to moisture loss, with some pod types more prone to desiccation than others.

Optimum Storage Conditions

Fresh peppers can be kept for 2 to 3 weeks at 7 °C (45 °F) with 90 to 95% RH. Storage life can be extended another week by packaging in moisture-retentive films at 7 to 10 °C (45 to 50 °F). Peppers are subject to chilling injury when stored below 7 °C (45 °F) and to accelerated ripening and bacterial soft rot when stored above 13 °C (55 °F). Storage at 5 °C (41 °F) reduces water loss and ripening, but after 2 weeks chilling injury will appear. Some pepper cultivars can be sensitive to chilling if stored at 7 °C (45 °F), so a good storage temperature range is 7 °C (45 °F) to 13 °C (55 °F).

Controlled Atmosphere (CA) Considerations

Peppers derive a slight benefit from CA storage (Saltveit 1997). Low-O_2 atmospheres (2 to 5% for bell peppers and 3 to 5% for chilies) retard ripening and respiration during transit and storage and benefit quality slightly. At 10 °C (50 °F), high CO_2 (>5%) can cause calyx discoloration, skin pitting, and discoloration and softening in both bell and chili peppers. An atmosphere of 3% O_2 and 5% CO_2 is more beneficial for red than for green peppers stored at 5 to 10 °C (41 to 50 °F) for 3 to 4 weeks. Before processing, chili peppers can be stored under 3 to 5% O_2 and 15 to 20% CO_2 for up to 3 weeks at 5 °C (41 °F) without appreciable chilling injury or quality loss. Freshly harvested chili or other hot peppers should be stored under the same temperature and RH conditions as sweet peppers.

Retail Outlet Display Considerations

Fresh bell and chili peppers should be displayed at 7 °C (45 °F). They should not be sprinkled or top iced. Dried chili peppers should be kept dry.

Chilling Sensitivity

Peppers are sensitive to chilling injury when stored below 7 °C (45 °F). Symptoms include surface pitting, water-soaked areas, decay (especially *Alternaria*), and discoloration of the seed cavity. Symptoms can appear after a few days at 0 °C (32 °F) or a few weeks at 5 °C (41 °F). Sensitivity varies with cultivar; ripe or colored peppers are less chilling sensitive than green peppers.

Ethylene Production and Sensitivity

Peppers are nonclimacteric and produce very low levels of ethylene: 0.1 and 0.2 $\mu L\ kg^{-1}\ h^{-1}$ at 10 and 20 °C (50 and 68 °F), respectively. The use of ethylene to enhance ripening or color change is not recommended because it stimulates respiration and softening more than coloration. The most effective way to color peppers is to hold partially colored fruit at 20 to 25 °C (68 to 77 °F) with RH >95%. To maintain quality, store them away from ethylene-producing fruits and ripening rooms.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	7 to 8
10 °C	10 to 15
15 °C	24 to 30
20 °C	32 to 36

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Blossom end rot is characterized by a slightly discolored or dark sunken lesion at the blossom end of the fruit. It is caused by calcium deficiency during growth. Pepper speck appears as spotlike lesions that penetrate the fruit wall. The cause is unknown; some varieties are more susceptible. Chilling injury is described above.

Postharvest Pathology

The most common decay microorganisms are *Botrytis*, *Alternaria*, and soft rots of fungal and bacterial origin. *Botrytis* (grey mold) is a common organism on peppers. Field sanitation and prevention of wounds on the fruit reduce its incidence. *Botrytis* grows well at the recommended pepper storage temperatures. High CO_2 levels (>10%) can control *Botrytis* but damages peppers. Hot water dips at 53 to 55 °C (126 to 130 °F) for 4 min can effectively control botrytis rot without causing fruit injury. The presence of alternaria black rot, especially on the stem end, is a symptom of chilling injury. The best control is to store peppers at 7 °C (45 °F). Bacterial soft rot is caused by several bacteria that attack damaged tissue. Soft rots can occur on washed or hydrocooled peppers when water sanitation is inadequate. Peppers are also affected by many of the disease, virus, insect, and nematode pests that affect tomato.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Before cutting, peppers should be stored at 7 to 10 °C (45 to 50 °F). After cutting, fresh-cut peppers should be held at 0 to 5 °C (32 to 41 °F). Pepper slices (red and green) can be stored for up 12 days at 5 °C (41 °F) using a CA of 3% O_2 and 10% CO_2.

Special Considerations

Mechanically harvested peppers are usually unsuitable for fresh market because of extensive injuries but can be used for processing. Peppers must be handled with care to avoid mechanical damage that may cause discoloration and pathological problems. Before packaging, peppers can be washed with 300 µL L^{-1} chlorine to reduce disease. Waxing with fungicides reduces water loss and disease.

After drying, chili peppers are packaged tightly into sacks holding ≥200 lb (≥91 kg) and are generally stored in nonrefrigerated warehouses for up to 6 mo. The temperature of the warehouse depends on its construction and the way it is managed, but mainly on ambient outdoor temperature. Insect infestation is a major storage problem. In Southern States, chili and other hot peppers are dried, packaged, and stored at 0 to 10 °C (32 to 50 °F). Storage at low temperature retards loss of red color and slows insect activity.

Moisture content of chili and other hot peppers during storage should be low (10 to 15%) to prevent mold growth. A RH of 60 to 70% is desirable. With a high moisture content, pods may be too pliable for grinding and may have to be redried. With lower moisture content (<10%), pods may be so brittle they shatter during handling, causing loss and release of dust, which is irritating to the skin and respiratory system.

The use of polyethylene film liners within bags allows better storage and reduces dust. The liners ensure that the pods maintain constant moisture content during storage until the time of grinding. Thus, they permit successful storage or shipment under a wide RH range. Peppers can be stored 6 to 9 mo at 0 to 4 °C when packed in this manner.

Manufacturers of hot-pepper products hold part of their raw material in cold storage at 0 to 10 °C but prefer to grind peppers immediately and store the dried product in air-tight containers.

Whole peppers are also dried until they are brittle and the seeds and pulp are completely dry. The dried product is used in flavoring and improving the appearance of various products, including canned products. Some sliced peppers are partially dried and mixed with salt for preservation for ultimate use in various processed products.

References

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. In M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 4, pp. 98-177. University of California, Davis, CA.

Further Reading

Ben-Yehoshua, S., B. Shapiro, J. Chen, and S. Lurie. 1983. Mode of action of plastic film in extending life of lemon and bell pepper fruits by alleviation of water stress. Plant Physiol. 73:87-93.

Brackett, R.E. 1990. Influence of modified atmosphere packaging on the microflora and quality of fresh bell peppers. J. Food Prot. 53:255-257.

Cantwell, M. 1998. Bell peppers. Recommendations for maintaining postharvest quality. University of California, Davis, CA. At http://postharvest.ucdavis.edu/produce_information.

Gonzalez-Aguilar, G.A., and M. Tiznado. 1993. Postharvest physiology of bell peppers stored in low density polyethylene bags. Lebensm-Wiss. U-Thechnol. 26(5):450-455.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agricultural Handbook 66, U.S. Department of Agriculture, Washington, DC.

Miller, W.R., and L.A. Risse. 1986. Film wrapping to alleviate chilling injury of bell peppers during cold storage. HortScience. 21:467-468.

Miller, W.R., L.A. Risse, and R.E. McDonald. 1986. Deterioration of individually wrapped and non-wrapped bell peppers during long term storage. Trop. Sci. 26:1-8.

Meir, S., Y. Rosenberger, Z. Aharon, et al. 1995. Improvement of the postharvest keeping quality and color development of bell pepper (cv. ‘Maor’) by packaging with polyethylene bags at reduced temperature. Postharv. Biol. Technol. 5:303-309.

Mercado, J.A., M.A. Quesada, V. Valpuerta, et al. 1995. Storage of bell peppers in CA at chilling and non-chilling temperatures. Acta Hort. 412:134-142.

Rodov, V., S. Ben-Yehoshua, T. Fierman, and F. Fang. 1995. Modified-humidity packaging reduces decay of harvested red bell pepper fruit. HortScience 30:299-302.

Wang, C.Y. 1977. Effect of CO_2 treatment on storage and shelf life of sweet peppers. J. Amer. Soc. Hort. Sci. 102:808-812.

Perennial Culinary Herbs

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Scientific Names and Introduction

Perennial culinary herbs include chives (*Allium schoenoprasum* L.), Chinese chives (*A. tuberosum* Rottler), marjoram (*Origanum hortensis*), oregano (*O. vulgare* L.), peppermint (*Mentha piperita* L.), spearmint (*M. spicata* L.), rosemary (*Rosmarinus officinalis* L.), sage (*Salvia officinalis* L.), tarragon (*Artemesia dracunculus* L.), and thyme (*Thymus vulgaris* L.). The leaves are the part primarily used in foods and cooking. Due to their strong flavors and aromas, these culinary herbs are generally used in small quantities.

Quality Characteristics and Criteria

Herbs should appear fresh and green, with no yellowing, decay, insect damage, or mechanical damage. Leaves should be uniform in size. Flavor and aroma should be strong and characteristic of the herb.

Horticultural Maturity Indices

Most herbs for fresh culinary use are best if harvested before flowering. Exceptions are marjoram and oregano (sometimes sold with flower buds) and chive blossoms (sometimes used in salads or as edible garnishes).

Grades, Sizes, and Packaging

There are no market grades or sizes for fresh herbs. They are bunched and tied with twist-ties or rubberbands, packaged in plastic bags or clamshell containers, and then packed in corrugated cartons. Perforated polyethylene liners should be used.

Precooling Conditions

Herbs should be cooled to just above 0 °C (32 °F) immediately after harvest.

Optimum Storage Conditions

Chives and mint can be stored for 2 to 3 weeks at 0 °C (32 °F) with 95 to 100% RH; Chinese chives last for 1 to 2 weeks. Top icing is sometimes used for mint. Marjoram, oregano, and tarragon can be stored at 0 °C (32 °F) with 90 to 95% RH for 1 to 2 weeks; rosemary, sage, and thyme will last for 2 to 3 weeks (Hruschka and Wang 1979, Cantwell 1997).

Controlled Atmosphere (CA) and Modified Atmosphere Packaging Considerations

Because of their short postharvest life, CA is generally not used for fresh herbs. MAP has been shown to retard yellowing in chives (Aharoni et al. 1993).

Retail Outlet Display Considerations

Use of water sprinklers is acceptable.

Chilling Sensitivity

These perennial herbs are not chilling sensitive and should be stored as close to 0 °C (32 °F) as possible without freezing.

Ethylene Production and Sensitivity

Ethylene production is low, but sensitivity is high. Low levels of ethylene can result in leaf abscission, epinasty, and yellowing. Storage at 0 °C (32 °F) minimizes effects of ethylene on visual quality (Cantwell and Reid 1993, Cantwell 1997).

Respiration Rates

	0 °C	10 °C	20 °C
	mg CO_2 kg^{-1} h^{-1}		
Chives	22	110	540
Chinese chives	54	99	432
Marjoram	28	68	—
Mint	20	76	252
Oregano	22	101	176
Sage	36	103	157
Tarragon	40	99	234
Thyme	38	82	203

Data from Cantwell and Reid (1993) and Peiris et al. (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Yellowing and leaf abscission may occur due to ethylene exposure, especially if held at ≥10 °C (≥50 °F).

Postharvest Pathology

Molds and bacterial decay may develop, especially on mechanically damaged leaves or cut ends of stems. Mints are subject to rust caused by *Puccinia menthae* Pers., which causes small brown pustules to form on leaves (Snowdon 1992). It is important that low temperatures be maintained during storage and distribution to slow the rate of decay.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Perennial herbs are not currently used in fresh-cut products.

References

Aharoni, N., O. Dvir, D. Chalupowicz, and Z. Aharon. 1993. Coping with postharvest physiology of fresh culinary herbs. Acta Hort. 344:69-78.

Cantwell, M. 1997. Properties and recommended conditions for storage of fresh fruits and vegetables. *At* http://postharvest.ucdavis.edu/produce_information/storagefreshproduce.

Cantwell, M.I., and M.S. Reid. 1993. Postharvest physiology and handling of fresh culinary herbs. J. Herbs, Spices and Medicinal Plants 1:93-127.

Hruschka, H.W., and C.Y. Wang. 1979. Storage and shelf life of packaged watercress, parsley and mint, p. 19. Marketing Research Report 1102, U.S. Department of Agriculture, Washington, DC.

Peiris, K.H.S., J.L. Mallon, and S.J. Kays. 1997. Respiratory rate and vital heat of some specialty vegetables at various storage temperatures. HortTechnology 7:46-49.

Snowdon, A.L. 1992. A color atlas of post-harvest diseases and disorders of fruits and vegetables, vol. 2, Vegetables. CRC Press, Boca Raton, FL.

Persimmon

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Scientific Name and Introduction

Persimmon is the species *Diospyros kaki*, a tree belonging to the family Ebenaceae and native to the Far East. Originally cultivated in China and Japan, it is also known as Chinese date plum. Fruit are grown throughout warmer parts of the world, including southern France, other Mediterranean countries, and the United States. Fruit are a good source of carotenoids, dietary fiber, and vitamins A and C.

The fruit is a berry, but the seeds are large, almond-shaped, and few in number. The epidermis is thin, and an enlarged calyx adheres to the base of the fruit. Persimmon has a delicious flavor and may be eaten fresh as a dessert or may be consumed dried or candied. In the United States, a native species—*Diospyros virginiana*—occurs, but its fruit are inferior to *D. kaki*. Another well known species is *D. lotus*, which yields fruit called date plums and is grown in Asia and Italy.

Quality Characteristics and Criteria

High-quality persimmons are medium to large in size, with uniform skin color from yellow to orange. Fruit should be firm, (penetration force [8-mm tip] >22.2 N [5 lb-force] for 'Fuyu' and similar cultivars). Fruit should be free from growth cracks, mechanical injuries, and decay. Recommended SSC is 21 to 23% in 'Hachiya' and 18 to 20% in 'Fuyu' and similar nonastringent cultivars. Astringent cultivars must be treated to remove astringency by polymerizing tannins.

Horticultural Maturity Indices

Minimum maturity is based on change in skin color from green to orange or reddish-orange ('Hachiya') or to yellow or yellowish-green ('Fuyu,' 'California Fuyu,' 'Jiro'). In California, the minimum maturity indicators for 'Hachiya' persimmon are a blossom-end color of orange or reddish equal to or darker than Munsell color chart 6.7YR 5.93/12.7 on at least one-third of the fruit's length with the remaining two-thirds a green color equal to or lighter than Munsell 2.5GY 5/6. For other varieties, fruit must have attained a yellowish-green color equal to or lighter than Munsell 10Y 6/6.

Optimum Storage Conditions

The optimum temperature for storing persimmons is 0±1 °C (32±2 °F). The freezing point is -2 °C (28.4 °F), but may vary depending on SSC. RH should be maintained at 90 to 95%.

Controlled Atmosphere (CA) Considerations

Low O_2 of 3 to 5% delays ripening; CO_2 at 5 to 8% helps retain firmness and can reduce chilling injury symptoms on 'Fuyu' and similar cultivars. Postharvest life under optimum temperature and RH in ethylene-free air is 3 mo, whereas fruit can be stored up to 5 mo using ethylene-free CA (3 to 5% O_2 and 5 to 8% CO_2).

Retail Outlet Display Considerations

Cold-table display is recommended.

Chilling Sensitivity

Sensitivity varies by cultivar. 'Hachiya' is not chilling sensitive while 'Fuyu' and similar nonastringent cultivars are sensitive at temperatures between 5 ºC and 15 ºC (41 ºF and 59 ºF); they will exhibit flesh browning and softening. Exposure to ethylene aggravates chilling injury at these temperatures.

Ethylene Production and Sensitivity

Persimmons produce <0.1 µL kg^{-1} h^{-1} at 0 °C (32 °F) and 0.1 to 0.5 µL kg^{-1} h^{-1} at 20 °C (68 °F). They are very sensitive to ethylene. Exposure to 1 and 10 µL L^{-1} ethylene at 20 °C (68 °F) accelerates softening to less than 4 lb-force (17.8 N), the limit of marketability, after 6 and 2 days, respectively. Thus, removing or excluding ethylene from transport and storage facilities is recommended.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	4 to 8
20 °C	20 to 24

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Chilling injury is the main physiological disorder. The incidence and severity depend on temperature, cold temperature duration, and the cultivar. For example, 'Fuyu' is chilling sensitive while 'Hachiya' is not. Chilling injury can be a major cause of deterioration of 'Fuyu' persimmons during marketing. Symptom development is greatest at 5 to 7 °C (41 to 45 °F) and slowest at 0 °C (32 °F), which is the recommended storage and transport temperature for persimmons. 'Fuyu' fruit exhibit symptoms if held between 2 °C (36 °F) and 15 °C (59 °F). On transfer to higher temperatures, symptom severity (flesh softening, browning, and water-soaked appearance) increases and renders fruit unmarketable. Respiration and ethylene production rates of chilled 'Fuyu' persimmons are higher than those of nonchilled fruits. Exposure to ethylene at 0.1 µL L^{-1} or higher aggravates chilling symptoms of 'Fuyu' persimmons, while CA ameliorates symptoms. Chilling injury is controlled by avoiding exposure of 'Fuyu' fruit to temperatures between 2 °C (36 °F) and 15 °C (59 °F). The optimum storage and transport temperature is 0 °C (32 °F). Exposure to ethylene >1 µL L^{-1} during postharvest handling should also be avoided. CA of 3 to 5% O_2 and 5 to 8% CO_2 at temperatures <5 °C (<41 °F) reduces chilling injury.

Exposure to O_2 levels <3% during storage for longer than 1 mo can result in failure of fruit to ripen and development of off flavors. *Exposure to CO_2 >10%* during storage for longer than 1 mo can cause brown discoloration of the flesh and lead to development of off flavors.

Calyx separation is a problem with some cultivars. It has caused losses in New Zealand. Growing conditions are all-important, and excessive nitrogen fertilization should be avoided. Thinning trees early in the season will enhance calyx growth and help prevent this disorder.

Postharvest Pathology

Alternaria rot is caused by *Alternaria alternata,* which attacks developing fruits. Infections remain quiescent until after harvest, when black spots become apparent during ripening. Wound infection results in earlier appearance of symptoms. Other causes of decay in persimmons include species of *Botrytis, Cladosporium, Colletotrichum, Mucor, Penicillium, Phoma,* and *Rhizopus.*

Quarantine Issues

Currently, there is a limited trade exchange for persimmons. The United States exports persimmons to the Middle East and Mexico and imports persimmons from Chile without specific requirements. APHIS issues rules regarding import requirements and provides information to assist exporters in targeting markets and defining what entry requirements a particular country has. APHIS, in cooperation with State plant boards, developed a database called “Excerpt” to track phytosanitary requirements for each country. APHIS also provides phytosanitary inspections and certifications that declare fruit are free of pests to facilitate compliance with foreign regulatory requirements.

Suitability as a Fresh-Cut Product

Nonastringent persimmon cultivars can be prepared as fresh-cut wedges or slices. Wright and Kader (1997) reported that the shelf-life of ‘Fuyu’ persimmon slices was 7 days in air and 8 days in a CA of 2% O_2 and 12% CO_2 at 5 °C (41 °F). A longer shelf-life can be expected at 0 to 2 °C (32 to 36 °F). Protecting slices from ethylene helps firmness retention.

Special Considerations

The best method of harvesting fruit is to cut them from the tree, leaving the calyx attached to the fruit. It is possible to snap fruit from the tree by hand, but this practice is not recommended as it can injure the fruit and adjoining shoot. Fruit must be handled very carefully to avoid bruising, which is likely to become unsightly as fruit ripen. Two or three harvests are usually required, depending on fruit size and color. A desirable size for ‘Fuyu’ is 230 to 250 g; 200 g is the minimum marketable size.

Astringency can be removed from ‘Hachiya’ persimmons using 10 µL L^{-1} ethylene at 20 °C (68 ºF), but the excessive softening that results can make marketing the fruit difficult. Exposure to air enriched with 80% CO_2 for 24 h at 20 °C (68 ºF) is also effective, and fruit maintain firmness.

References

Wright, K.P., and A.A. Kader. 1997. Effect of slicing and controlled-atmosphere storage on the ascorbate content and quality of strawberries and persimmons. Postharv. Biol. Technol. 10:39-48.

Further Reading

Beede, R.H. 1983. The Storage Performance of the Fuyu Persimmon and Its Susceptibility to Chilling Injury. M.S. thesis, Department of Pomology, University of California, Davis, CA.

Collins, R.J., and J.S. Tisdell. 1995. The influence of storage time and temperature on chilling injury in ‘Fuyu’ and ‘Suruga’ persimmon (*Diospyros khaki* L.) grown in subtropical Australia. Postharv. Biol. Technol. 6:149-157.

Crisosto, C.H., E.J. Mitcham, and A.A. Kader. 1995. Produce Facts: Persimmons. Perishables Handling Quarterly 84:19-20. *At* http://postharvest.ucdavis.edu/produce_information.

Glucina, P.G. 1987. Calyx separation: a physiological disorder of persimmons. Orchardist of New Zealand 60:161-163.

Ito, S. 1971. The persimmon. *In* A.C. Hulme, ed., The Biochemistry of Fruits and Their Products, vol. 2, pp. 281-301. Academic Press, New York, NY.

Ito, S. 1980. Persimmon. *In* S. Nagy and P.E. Shaw, eds., Tropical and Subtropical Fruits: Composition, Properties and Uses, pp. 442-468. AVI, Westport, CT.

Kitagawa, H., and P.G. Glucina. 1984. Persimmon Culture in New Zealand, ch. 6-7. Science Information Publishing Center, Wellington, N.Z.

MacRae, E.A. 1987. Development of chilling injury in New Zealand grown ‘Fuyu’ persimmon during storage. N.Z. J. Exp. Agric. 15:333-344.

Prusky, D., R. Ben-Arie, and S. Guelfat-Reich. 1981. Etiology and histology of *Alternaria* rot of persimmon fruits. Phytopathology 71:1124-1128.

Snowdon, A.L. 1990. A Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 1, General Introduction and Fruits. CRC Press, Boca Raton, FL.

Pineapple

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Scientific Name and Introduction

Pineapple (*Ananas comosus* L. Merr.) is a terrestrial member of the diverse *Bromeliaceae* family. The pineapple fruit has the distinction of being selected, developed, and domesticated by peoples in tropical America in prehistoric times (Collins 1968). Of the many pineapple cultivars, 'Smooth Cayenne' is the major commercial cultivar. Other cultivars grown on a smaller scale include 'Red Spanish,' 'Queen,' 'Pernambuco,' 'Sugarloafs,' and 'Cabaiani.' Low acid 'Smooth Cayenne' varieties are also available (Nakasone and Paull 1998).

Quality Characteristics and Criteria

Pineapple fruit must have a desirable size and shape, with flat "eyes" (individual fruitlets) and deep-green crown leaves that look fresh. High shell color is not always a good measure of sweetness. Negative characteristics include dry, brown crown leaves; dull, yellow skin; presence of mold on the surface or cut stem; and an unfirm feel.

Horticultural Maturity Indices

Pineapple fruit maturity is evaluated on the extent of fruit "eye" flatness and skin yellowing. Consumers similarly judge fruit quality by skin color and aroma. A minimum of 12% SSC is required for fresh fruit in Hawaii (Hawaii Department of Agriculture 1968). A SSC:TA ratio of 0.9 to 1.3 is recommended (Soler 1992b). Fruit do not continue to ripen or sweeten after harvest. Fully ripe yellow fruit are unsuitable for transporting to distant markets, so slightly less mature fruit are selected for this purpose (Akamine 1963, Cancel 1974). Immature fruit should not be shipped, since they do not develop good flavor, have low Brix, and are more prone to chilling injury (Rohrbach and Paull 1982).

Grades, Sizes, and Packaging

Pineapples are graded by degree of skin coloration, size (weight), absence of defects and disease, and uniformity of these characteristics before packing. Other characteristics include maturity, firmness, nice shape, flat eyes, well-cured broken stem (peduncle), and a minimum SSC of 12% in Hawaii (Hawaii Department of Agriculture 1968). Crown size is a crucial grade component, with a minimum size and minimum ratio of crown:fruit length (0.33 to 1.5) for higher grades. Crowns developed during summer in Hawaii tend to be larger and may require gouging (removal of the crown center) at harvest to meet the standard.

Pineapples are normally packed into cartons of two different sizes and on the basis of color and size: (1) a large telescoping fiberboard carton holding 18 kg (40 lb) and containing 8 to 10 fruit in two layers, flat or upright, for surface and air shipment and (2) a smaller container of 9 kg (20 lb) with five to six fruit in a single layer laid flat for air shipment. Tourist packs of two to four fruit are also prepared. Absorbent pads are used at the bottom of the carton and between layers if fruit are placed horizontally within the carton. In other packs, fruit are placed vertically.

Precooling Conditions

Room-cooling or forced-air cooling should be used.

Optimum Storage Conditions

Temperatures of 7 to 12 °C (45 to 55 °F) are recommended for storage of pineapples for 14 to 20 days, provided fruit are at the color break stage

(Paull 1993). RH of 85 to 95% is recommended; high RH significantly reduces water loss. Ripe fruit can be held at 7 °C (45 °F) for about 7 to 10 days. Pineapples may be stored at 0 to 4 °C (32 to 39 °F) for weeks, but upon removal fruit fail to continue ripening and show severe chilling injury. Quarter-yellow fruit at harvest gain about 1 additional week of storage for every 6 °C (11 °F) decrease in storage temperature (Dull 1971). The maximum storage life at 7 °C (45 °F) is about 4 weeks (Paull and Rohrbach 1985); however, when the fruit are removed, chilling-injury-induced internal browning develops within 2 to 3 days.

Controlled Atmospheres (CA) Consideration

Modifying O_2 levels is only minimally effective at extending pineapple shelf-life (Dull et al. 1967, Akamine and Goo 1971). Some benefit is gained from CA (4% O_2) treatments in reducing chilling injury development (Paull and Rohrbach 1982). The fruit waxes currently used generate high internal concentrations of CO_2 (up to 5%) and reduced O_2 (Paull and Rohrbach 1982). Low O_2 has no effect on crown condition or decay but does delay shell color development and reduce superficial mold growth (Akamine and Goo 1971). Subjecting fruit to 1 to 2% O_2 and 0 to 10% CO_2 after shipment from Mexico to England at 8 ºC did delay chilling injury (Haruenkit and Thompson 1994). Polyethylene bagging, though difficult to perform commercially on individual fruit, results in atmosphere of 8 to 10% O_2 and 7% CO_2, and fruit waxing delays appearance of chilling-induced internal browning (Paull and Rohrbach 1982, Rohrbach and Paull 1982, Abdullah et al. 1985). The tentative recommendation is 2 to 5% and 5 to 10% CO_2 (Yahia 1998).

Retail Outlet Display Considerations

Whole fruit should be displayed refrigerated at 10 to 13 °C (50 to 55 °F) and should not be misted or iced.

Chilling Sensitivity

Symptoms of chilling injury include wilting, drying and discoloration of crown leaves, failure of green-shelled fruit to yellow, browning and dulling of yellow fruit, and internal flesh browning (Lim 1985, Paull and Rohrbach 1985). Preharvest shading, as well as preharvest and postharvest low temperature, are the major factors increasing symptom intensity (Akamine et al. 1975, Akamine 1976, Keetch and Balldorf 1979, Smith 1983). Chilling injury symptoms include endogenous brown spot, physiological breakdown, blackheart, and internal browning. Symptoms develop after fruit are returned to physiological temperatures of 15 to 30 °C (59 to 86 °F) (Paull and Rohrbach 1985). Susceptible fruit are generally lower in ascorbate and sugar and are opaque (Abdullah and Rohaya 1983, Abdullah et al. 1985, Paull and Rohrbach 1985, Swete Kelly and Bragshaw 1993).

Ethylene Production and Sensitivity

The ethylene production rate of this nonclimacteric fruit is low: 0.1 to 1.0 µL kg^{-1} h^{-1}. Postharvest use of ethephon to degreen the shell has been tested in the Ivory Coast (Poignant 1971, Crochon et al. 1981), Hawaii (Paull 1985), and Australia (Smith 1991). Treated fruit show more rapid uniform skin degreening and little change in quality. However, shelf-life is slightly shortened (Paull 1985, unpublished data; Smith 1991, Soler 1992a). There is no recommendation for use of ethephon; it is not approved for postharvest use.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	2
10 °C	4 to 7
15 °C	10 to 16
20 °C	19 to 29

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Flesh translucency, also called porosity, is associated with greater fruit sensitivity to mechanical injury, indicated by leakage and oozing of cellular fluids. This condition begins before harvest and continues after (Bowden 1969, Rohrbach and Paull 1982, Paull and Reyes 1996). Fruit with increased translucency also have increased pH, a higher SSC:acid ratio, higher fruit weight, higher total esters, and lower acidity. SSC, flesh pigments, and palatability increase to a maximum at about 60% translucency, then decline in fruit with higher translucency (Bowden 1969).

Bruising by impact damage is a major problem during harvesting, packing, and shipping of pineapple. Mechanical injury of translucent fruit can lead to leakage of cell contents and loss of marketable fruit. Injury can be avoided by careful handling and avoiding impacts and bruising.

Sunburned, or sun-scorched, pineapples show a bleached, yellow-white skin that turns pale gray-brown with damage to the flesh underneath. Damaged areas are more susceptible to disease. It is common during hot periods (>35 °C [95 ºF]) (Keetch and Balldorf 1979).

Malformations, or pineapple fruit with pronounced eyes or fruitlets, are normally not acceptable in Fancy grades of fruit, and the thicker skin results in lower flesh recovery. This condition is common in fruits that flower during cool weather. Some Spanish varieties are susceptible to broken core, in which the central core has a transverse break leading to the upper part of the fruit ripening ahead of the bottom (Lim 1985).

Postharvest Pathology

Black rot, also called thielaviopsis fruit rot, water blister, soft rot, or water rot, is a universal fresh pineapple problem characterized by a soft watery rot (Rohrbach 1983). Diseased tissue turns dark in the later stages of the disease because of the dark mycelium and spores. Black rot is caused by the fungus *Chalara paradoxa* (De Seynes) Sacc. Red Spanish types are more resistant than 'Smooth Cayenne.' Infection occurs within 8 to 12 h following harvest and enters through the point of detachment or wounds. The severity of the problem depends on the degree of bruising or wounding during harvesting and packing, the level of inoculum on the fruit, and storage temperature during transportation and marketing (Rohrbach and Schmitt 1994). The rot is commercially controlled by minimizing bruising of fruit during harvest and handling, refrigerating the fruit, and applying postharvest fungicides (Rohrbach and Phillips 1990).

Fruitlet core rot, black spot, fruitlet brown rot, and *eye rot* describe the brown to black color of the central part of an individual fruitlet. Epidemic levels are rare in the major commercial pineapple-producing areas of the world (Rohrbach and Schmitt 1994). Low-acid cultivars being grown commercially are most susceptible (Rohrbach and Schmitt 1994). This disease is caused by a complex of fungi (Rohrbach and Schmitt 1994). Infection frequently can lead to misshapen fruit that are culled before packing and shipping.

Yeasty fermentation arises due to the fact that fruit are not sterile inside, containing many nongrowing but viable yeasts and bacteria. In damaged, overripe fruit and fruit with interfruitlet cracking, resident yeasts begin to grow or new yeasts invade. This growth leads to fermentation and bubbles of gas and juice through cracks in the skin. The skin turns brown and leathery and fruit become spongy with bright yellow flesh.

Saprophytes (*Penicillium* sp.) growing on the broken end of the peduncle and fruit surface are nonpathogenic but are unsightly and therefore a marketing problem (Rohrbach 1989). The condition is more common on highly translucent fruit.

Quarantine Issues

Pineapple fruit that are >50% 'Smooth Cayenne' are not regarded a host for tephritid fruit flies.

Thus, insect disinfestation is not required for import into fly-free countries (Armstrong 1994).

Pineapple caterpillars (*Thecla basilides* Geyer, *Metamasius ritchiei* Marchall, *Batrachedre methesoni* Busch, and *Paradiophorus crenatus* Billbarg) are exotic and limited to Central America, South America, and the Caribbean (Harris 1927, Rohrbach 1983). The adult oviposits on the inflorescence prior to anthesis. Larvae then infest fleshy parts of the bracts and feed inside the developing inflorescence, exuding gum from the feeding chambers. Control with insecticides is relatively easy if flowering is induced uniformly with forcing agents. *T. basilides* is a tropical species that could cause problems if imported into Southern States such as Florida, as it can feed on corn, cacao, heliconia, and several other bromeliads (Rohrbach 1983).

Pineapple scale, *Diaspis bromeliea* Kerner, occurs wherever pineapple is grown. Normally, in Hawaii pineapple scale is not a major problem in fields, probably because of scale parasites and predators. However, because of the quarantine requirement to have fruit insect-free, even low levels of pineapple scale at harvest present quarantine problems. Scale are controlled by preharvest insecticide applications, taking into account "last-application-to-harvest" time.

The pineapple fruit mite, *Steneotarsonemus ananas* Tryon, occurs universally on the growing plant, developing in the inflorescence, fruit, and crown. Fruit mites feed on developing trichomes on the white basal leaf tissue and flower bracts and sepals, causing light brown necrotic areas. The pineapple red mite, *Dolichotetranychus floridanus* Banks, feeds on the white basal leaf tissue, particularly of the crown. Severe damage occurs when the fruit mature under drought conditions. Red mites may cause death of basal crown leaves, affecting quality (Rohrbach and Schmitt 1994).

Mealybugs are removed from the surface by brushing. Preharvest insecticide and ant control almost eliminate mealybugs (Soler 1992b). Crickets and locusts may feed on bracts before harvest.

Suitability as Fresh-Cut Product

Fresh-cut pineapple is readily prepared at a central plant or in-store for ready-to-use consumer pack. Packs contain fresh-cut cylinders with the core removed or spears, chunks, or wedges. The product has a shelf-life of at least 7 days at proper temperature. A patent has been issued for the use of pouches flushed with 15 to 20% O_2 and 3% argon and held at 1 °C (34 °F) for 10 weeks (Powrie et al. 1990) for fresh-cut pineapple pieces.

Special Considerations

Ease of removal of crown leaves, full skin yellowing, or the sound produced by tapping the fruit are not signs of ripeness or quality. Fruit are picked at the ripe stage and are ready-to-eat, even if there is a little skin yellowing.

References

Abdullah, H., and M.A. Rohaya. 1983. The development of black heart disease in Mauritius pineapple (*Ananas comosus* cv. Mauritius) during storage at lower temperatures. MARDI Res. Bull. 11:309-319.

Abdullah, H., M.A. Rohaya, and M.Z. Zaipun. 1985. Effect of modified atmosphere on black heart development and ascorbic acid contents in 'Mauritius' pineapple (*Ananas comosus* cv. 'Mauritius') during storage at low temperature. ASEAN Food J. 1:15-18.

Akamine, E.K. 1963. Fresh pineapple storage. Hawaii Farm Sci. 12:1-4.

Akamine, E.K. 1976. Postharvest control of endogenous brown spot in fresh Australian pineapples with heat. HortScience 11:586-588.

Akamine, E.K., and T. Goo. 1971. Controlled atmosphere storage of fresh pineapples (*Ananas comosus* [L.] Merr. 'Smooth Cayenne'). Res. Bull. 152, Hawaii Agricultural Experiment Station, Honolulu, HI.

Akamine, E.K., T. Goo, T. Steepy, et al. 1975. Control of endogenous brown spot of pineapple in postharvest handling. J. Amer. Soc. Hort. Sci. 100:60-65.

Armstrong, J.W. 1994. Tropical and subtropical fruits. *In* R.E. Paull and J.W. Armstrong, eds., Insect Pests and Fresh Horticultural Products: Treatments and Responses, pp. 275-290. CAB Intl., Wallingford, U.K.

Bowden, R.P. 1969. Further studies on ripeness in pineapple. Food Tech. Australia. 21:160-163.

Cancel, H.L. 1974. Harvesting and storage conditions for pineapples of the ‘Red Spanish’ variety. J. Agric., Puerto Rico 58:162-169.

Collins, J.L. 1968. The Pineapple. Leonard Hill, London, U.K.

Crochon, M., R. Tisseau, C. Teisson, and R. Huet. 1981. Effet d’une application d’Ethrel avant la recolte sur la qualite gustative de ananas de Cote d’Ivoire. Fruits 36:409-415.

Dull, G.G. 1971. The pineapple: general. *In* A.C. Hulme, ed., The Biochemistry of Fruits and Their Products, vol. 2, pp. 303-331. Academic Press, London, U.K.

Dull, G.C., R.E. Young, and J.B. Biale. 1967. Respiratory patterns in fruit of pineapple, *Ananas comosus*, detached at different stages of development. Physiol. Plant. 20:1059-1065.

Harris, W.V. 1927. On a lycaenid butterfly attacking pineapple in Trinidad, British West Indies. Bull. Ent. Res. 18:183-188.

Haruenkit, R., and A.K. Thompson. 1994. Storage of fresh pineapple. *In* B.R. Champ, E. Highley and G.I. Johnson, eds., Proceedings of the International Conference on Postharvest Handling of Tropical Fruits, pp. 422-426. Chiang Mai, Thailand, July 1993. Australian Centre for International Agricultural Research, Proceedings no. 50, Canberra, Australia.

Hawaii Department of Agriculture. 1968. Wholesale standards for Hawaiian-grown pineapple. Hawaii Department of Agriculture, Marketing Division, Honolulu, HI.

Keetch, D.P., and D. B. Balldorf. 1979. The incidence of certain pineapple fruit blemishes in the eastern cape and border. Citrus Subtrop. Fruit J. 551:12-15.

Lim, W.H. 1985. Diseases and Disorders of Pineapples in Peninsular Malaysia. Report 97, MARDI, Kuala Lumpur, Malaysia.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K.

Paull, R.E. 1993. Pineapple and papaya. *In* G. Seymour, J. Taylor, and G. Tucker, eds., Biochemistry of Fruit Ripening, pp. 291-323. Chapman & Hall, London, U.K.

Paull, R.E., and K.G. Rohrbach. 1982. Juice characteristics and internal atmosphere of waxed ‘Smooth Cayenne,’ pineapple fruit. J. Amer. Soc. Hort. Sci. 107:448-452.

Paull, R.E., and K.G. Rohrbach. 1985. Symptom development of chilling injury in pineapple fruit. J. Amer. Soc. Hort. Sci. 110:100-105.

Paull, R.E., and M.E.Q. Reyes. 1996. Preharvest weather conditions and pineapple fruit translucency. Sci. Hort. 66:59-67.

Poignant, A. 1971. La maturation controlee de l’ananas II-L’ethrel et son action au cours des phases ascendante et descendarte de la maturite. Fruits 26:23-35.

Powrie, W.D., R. Chiu, H. Wu, and B.J. Skura. 1990. Preservation of cut and segmented fresh fruit pieces. U.S. Patent 4,895,729.

Rohrbach, K.G. 1983. Exotic pineapple diseases and pests and their potential for spread. *In* K.G. Singh, ed., Exotic Plant Quarantine Pests and Procedures for Introduction of Plant Materials, pp. 145-171. ASEAN Plant Quarantine Centre and Training Institute, Selangor, Malaysia.

Rohrbach, K.G. 1989. Unusual tropical fruit diseases with extended latent periods. Plant Dis. 73:607-609.

Rohrbach, K.G., and R. E. Paull. 1982. Incidence and severity of chilling induced browning of waxed ‘Smooth Cayenne’ pineapple. J. Amer. Soc. Hort. Sci. 107:453-457.

Rohrbach, K., and D.J. Phillips. 1990. Postharvest diseases of pineapple. Acta Hort. 269:503-508.

Rohrbach, K., and D.P. Schmitt. 1994. Pineapple. *In* R.C. Ploetz, G.A. Zentmyer, W.T. Nishijima, et al., eds., Compendium of Tropical Fruit Diseases, pp. 45-55. Amer. Phytopath. Soc., St. Paul, MN.

Smith, L.G. 1983. Causes and development of black heart in pineapples. Trop. Agric. (Trinidad) 60:31-35.

Smith, L.G. 1991. Effects of ethephon on ripening and quality of fresh market pineapples. Austr. J. Exp. Agric. 31:123-127.

Soler, A. 1992b. Metabolism de l’ethephon dans l’epiderme de l’ananas (*Ananas comosus*, L. Merr). Fruits 47:471-477.

Soler, A. 1992a. Pineapple. CIRAD-IRFA, Paris, France.

Swete Kelly, D., and J. Bragshaw. 1993. Effect of fruit handling and fruit coatings on black heart (internal brown spot) and other aspects of fresh pineapple quality. Acta Hort. 334:305-316.

Yahia, E. 1998. Modified and controlled atmospheres for tropical fruits. Hort. Rev. 22:123-183.

Plum and Fresh Prune

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Scientific Name and Introduction

Plums *(Prunus salicina)* are mainly marketed for fresh consumption and not for drying. They are also used for canning, freezing, and making jam and jelly. The Japanese plum (*P. salicina*) is native to China but was domesticated in Japan 400 years ago. It was first brought to California from Japan in 1870 by John Kelsey. In 1885, Luther Burbank imported about 12 seeds from Japan and used them to breed many cultivars. The plum industry has increased throughout California (mainly in the central San Joaquin Valley) where most Japanese plums in the United States are grown.

Prunes are cultivars of the European plum (*Prunus domestica*, L.) that can be dried whole. Like plums, prunes can be eaten fresh (if a very sweet fruit is desired), but they also have the high sugar content necessary for successful drying. The European plum, believed to have originated in the Near East, has been grown in parts of Europe for many centuries. Through its culture in France, the prune ‘d’Agen’ was introduced to California from France by Louis Pellier, a French horticulturist who had come to California seeking gold.

Quality Characteristics and Criteria

Consumer acceptance is high for fruit with high SSC. Fruit TA, SSC:TA, and phenolic content (astringency) are also important factors in consumer acceptance. However, there is no established minimum quality standard based on these factors. Plums with about 10 N (1 kg-force) flesh firmness (8-mm tip) are considered ready to eat.

Horticultural Maturity Indices

In most of the plum cultivars grown in California, harvest date is determined by skin color changes specific to each cultivar. A color chip guide is used to determine maturity for some cultivars. Firmness, measured by squeezing fruit in the palm of the hand (“spring”), is also a useful maturity index for a few cultivars.

A two-tier maturity system is currently used in California: U.S. Mature (minimum maturity) and California Well-Mature. Measurement of fruit firmness is recommended for plum cultivars in which skin ground color is masked by development of full red or dark color before maturation. Flesh firmness, measured using a penetrometer (8-mm tip), can be used to determine a maximum maturity index, which is the stage at which fruit can be harvested without suffering bruising damage during postharvest handling. Plums are less susceptible to bruising than most peach and nectarine cultivars at comparable firmness.

Fresh prunes are picked on the basis of color: at least 50% of the fruit surface is red or purple and SSC is at least 16% in ‘Moyer’ and 19% in ‘French’ prunes.

Grades, Sizes, and Packaging

Plums and fresh prunes are hand-picked into bags, then dumped in bins that are moved on trailers between tree rows in the orchard. At the packinghouse, plums are dumped (mostly using dry bin dumps) and washed. Sorting is done to eliminate fruit with visual defects and sometimes to divert fruit of high surface color to a high-quality pack. Sizing segregates fruit either by weight or dimension. In general, plums and fresh prunes are packed into 12.6-kg (28-lb) volume-filled containers.

Precooling Conditions

Plums and fresh prunes can be cooled in field bins using forced-air cooling, hydrocooling, or room-cooling prior to packing. Packed plums and fresh prunes should be cooled by forced-air cooling to near 0 °C (32 °F).

Optimum Storage Conditions

A storage temperature of -1.1 to 0 °C (30 to 32 °F) with 90 to 95% RH should be used. An air circulation velocity of approximately 15 m^3 min^{-1} is suggested. The freezing point varies from -2 to -1 °C (28 to 30 °F) depending on SSC.

In late-season plums and in fresh 'French' and 'Moyer' prunes, internal breakdown (IB) has been delayed by storing IB-susceptible cultivars at -1.1 °C (30 °F). However, to store fruit at this low a temperature, high SSC and excellent thermostatic control are essential to avoid freeze damage.

Controlled Atmosphere (CA) Considerations

The major benefits of CA during storage and shipment are retention of fruit firmness and delay of changes in ground color. Decay incidence is reduced by CA of 1 to 2% O_2 and 3 to 5% CO_2. Currently, CA has a limited use for storage longer than 1 mo of some cultivars such as 'Angeleno,' 'Casselman,' 'Santa Rosa,' 'Laroda,' and 'Queen Ann.'

Retail Outlet Display Considerations

If fruit firmness is <22 N (2.3 kg-force [5 lb-force]), plums should be displayed on a cold table. If fruit firmness is >22 N (2.3 kg-force [5 lb-force]), they should be displayed on a dry table.

Chilling Sensitivity

Postharvest life varies among cultivars and is strongly affected by temperature management. Most plum and fresh prune cultivars are susceptible to chilling injury when stored at 5 °C (41 °F). Market-life of 'Blackamber,' 'Fortune,' and 'Angeleno' plums at 0 °C (32 °F) was >5 weeks. 'Show Time,' 'Friar,' and 'Howard Sun' plums developed chilling injury symptoms within 4 weeks, even when stored at 0 °C (32 °F). In all plum cultivars, a much longer market life was achieved when stored at 0 °C (32 °F) than at 5 °C (41 °F).

Ethylene Production and Sensitivity

Ethylene production rates are 0.01 to 5 µL kg^{-1} h^{-1} at 0 °C, 0.02 to 15 µL kg^{-1} h^{-1} at 5 °C, 0.04 to 60 µL kg^{-1} h^{-1} at 10 °C, and 0.1 to 200 µL kg^{-1} h^{-1} at 20 °C. The lower end of this range is for mature but unripe fruit; higher values are for ripe fruit.

Most plums harvested at the California Well-Mature stage (higher than U.S. Mature stage) will ripen properly without exogenous ethylene. However, for slow-ripening cultivars, such as 'Black Beaut,' 'Casselman,' 'Late Santa Rosa,' 'Kelsey,' 'Nubiana,' 'Queen Ann,' and 'Roysum,' application of 100 µL L^{-1} for at least 24 h at 20 °C (68 °F) is needed for faster and more uniform ripening.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	2 to 3
10 °C	8 to 12
20 °C	16 to 24

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Chilling injury (CI) is a concern with most plum and fresh prune cultivars. It is expressed as flesh translucency associated with flesh browning. Late plum cultivars also develop lack of juiciness in addition to these symptoms. In previous publications from South Africa, flesh translucency, specifically in some plum cultivars, has been called "gel breakdown" (Dodd 1984). In the United States, these symptoms are reported under "internal breakdown," or CI (Kader and Mitchell 1989, Crisosto et al. 1999). CI symptoms normally appear after placing fruit at ripening temperatures following cold storage at 2 to 8 °C (36 to 46 °F).

Internal browning is a physiological disorder of 'Italian' and other cultivars of prunes. It originates before harvest. It is associated with high temperatures during fruit maturation and delayed harvest.

Postharvest Pathology

Brown rot is caused by *Monilia fructicola* and is the most important postharvest disease of stone fruits. Infection begins during flowering. Fruit rot may occur before harvest but often develops during postharvest handling. Orchard sanitation to minimize infection sources, preharvest fungicide application, and prompt precooling after harvest are control strategies. Fruit cracking makes late season cultivars more prone to decay. Postharvest fungicide treatments may be used to limit decay.

Gray mold is caused by *Botrytis cinerea*. This rot can be serious during wet spring weather. It can develop during storage if fruit have been contaminated through harvest and handling wounds. Avoiding mechanical injuries, effective temperature management, and postharvest fungicide treatments are effective control measures.

Rhizopus rot is caused by *Rhizopus stolonifer*. This rot can occur in ripe or near-ripe stone fruits kept at 20 to 25 °C (68 to 77 °F). Precooling fruit and storing them below 5 °C (41 °F) is effective in controlling this fungus.

Quarantine Issues

A phytosanitary certificate is required to import California plums into Taiwan. Plums must be free of *Anarsia lineatella* (peach twig borer), *Conotracherlus nenuphar* (plum curculio), *Cydia pomonella* (codling moth), *Erwinia amylovora* (fire blight), *Rhagoletis pomonella* (apple maggot), *Tetranychus pacificus* (Pacific spider mite), and *Ceratitis capitata* (Mediterranean fruit fly). If these conditions cannot be met, fruit must be treated appropriately prior to shipment. Details of the treatment must be recorded on the phytosanitary certificate.

A phytosanitary certificate is required to import California plums into British Columbia. The certificate should state that fruit are free of *Cydia molesta* (oriental fruit moth), and it should clearly advertise that the fruit in the shipment were produced and inspected in accordance with the "systems approach guidelines" agreed to by APHIS and the Canadian Food Inspection Agency. Fruit imports to all of the other Canadian provinces are unrestricted.

A similar systems approach, between APHIS and Mexican agencies, facilitates import and assures plums are free of *Cydia molesta* (oriental fruit moth), *Conotracherlus nenuphar* (plum curculio), *Rhagoletis pomonella* (apple maggot), and fruit flies (*Tephritidae*).

Suitability as Fresh-Cut Product

Fresh-cut plums are best kept at 0 °C (32 °F) in packages that minimize water loss. Marketing life of fresh-cut plums ranges from 2 to 5 days, depending on cultivar and stage of ripeness (firmness) at the time of slicing.

Acknowledgments

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References

Crisosto, C.H., F.G. Mitchell, and Z. Ju. 1999. Susceptibility to chilling injury of peach, nectarine, and plum cultivars grown in California. HortScience 34:1116-1118.

Dodd, M.C. 1984. Internal breakdown in plums. Deciduous Fruit Grower, August, pp. 255-256.

Kader, A.A., and F.G. Mitchell. 1989. Postharvest physiology. *In* J.H. LaRue and R.S. Johnson, eds., Peaches, Plums, Nectarines: Growing and Handling for Fresh Market, pp. 154-164. Pub. no. 3331, University of California, Davis, CA.

Further Reading

Ben, J., and M. Gaweda. 1992. Effect of increasing concentrations of CO_2 in controlled atmosphere storage on the development of physiological disorders and fungal diseases in plums (*Prunus domestica* L.). Folia Hort. 4:87-100.

Ceponis, M.J, R.A. Cappellini, J.M. Wells, and G.W. Lightner. 1987. Disorders in plum, peach and nectarine shipments to the New York market, 1972-1985. Plant Dis. 71:947-952.

Combrink, J.C. 1996. Integrated Management of Postharvest Quality. INFRUITEC, Stellenbosch, South Africa.

Couey, H.M. 1960. Effect of temperature and modified atmosphere on the storage-life, ripening behavior, and dessert quality of 'El Dorado' plums. Proc. Amer. Soc. Hort. Sci. 75:207-215.

Couey, H.M. 1965. Modified atmosphere storage of 'Nubiana' plums. Proc. Amer. Soc. Hort. Sci. 86:166-168.

Crisosto, C.H. 1994. Stone fruit maturity indices: a descriptive review. Postharv. News Info. 5(6):65N-68N.

Eksteen, G.J., T.R. Visagie, and J.C. Laszlo. 1986. Controlled atmosphere storage of South African grown nectarines and plums. Deciduous Fruit Grower 36(4):128-132.

Gerdts, D., F.G. Mitchell, and G. Mayer. 1987. Extended storage of late season plum varieties. California Tree Fruit Agreement Report, CTFA, Sacramento CA.

Mitchell, F.G. 1987. Influence of cooling and temperature maintenance on the quality of California grown stone fruit. Intl. J. Refrig. 10:77-81.

Mitchell, F.G., G.S. Sibbett, and G. Mayer. 1981. Cold storage of 'French' prunes may expand dehydrator capacity. Calif. Agr. 35(1&2):20-22.

Proebsting, E.L. Jr., G.H. Carter, and H.H. Mills. 1974. Interaction of low temperature storage and maturity on quality of 'Early Italian' prunes. J. Amer. Soc. Hort. Sci. 99:117-121.

Streif, J. 1989. Storage behaviour of plum fruits. Acta Hort. 258:177-183.

Truter, A.G., J.C. Combrink, and L.J. von Mollendorff. 1994. Controlled-atmosphere storage of plums. Deciduous Fruit Grower 44:373-375.

Wells, J.M., J.E. Butterfield, and M.J. Ceponis. 1994. Diseases, physiological disorders, and injuries of plums marketed in metropolitan New York. Plant Dis. 78:642-644.

Pomegranate

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Scientific Name and Introduction

Punica granatum L., the pomegranate, belongs to the Punicacea family and is one of the oldest known edible fruits. It is sometimes called Chinese apple and has been cultivated extensively in Mediterranean countries (Tunisia, Turkey, Israel, Egypt, Spain, and Morocco), Iran, Afghanistan, India, and to some extent in the United States (California), China, Japan, and Russia. The pomegranate requires a long, hot summer for fruit to mature, but it can withstand low temperatures in winter and is drought- and salt-tolerant.

Pomegranate fruit is nearly round with a prominent attached calyx and a hard, leathery skin. Surface color varies among commercial cultivars from yellow with a crimson cheek to solid brownish-red and also bright-red. The edible portion is the bright-red pulp (aril) surrounding the individual seed. The fruit is consumed fresh, or it can be processed into juice, syrup, jams, or wine. Fruit of the wild-type pomegranate is acidic, but cultivated cultivars bear fruit with a sweet-sour or sweet flavor. There are several types of edible pomegranate, and there are ornamental types with double flowers, largely sterile, which are not grown for edible fruit. Several cultivars are grown commercially around the world, including 'Wonderful' in California and Israel, 'Mollar' and 'Tendral' in Spain, 'Schahvar' and 'Robab' in Iran, 'Hicaznar' and 'Beynar' in Turkey, and 'Zehri' and 'Gabsi' in Tunisia (LaRue 1980, Onur and Kaşka 1985, Morton 1987, Patil and Karale 1990, Llacer et al. 1994, Mars 1994).

Quality Characteristics and Criteria

Fruit quality depends largely on sugar and acid content of the juice. A high-quality pomegranate should also have an attractive skin and small seeds in the aril and should be free from sunburn, growth cracks, cuts, bruises, and decay. Skin color and smoothness are also quality indices. Sour and sour-sweet pomegranates have reddish skin, in contrast to sweet pomegranates which have yellowish-green skin. Skin thickness varies from 1.5 to 4.24 mm (Küpper 1995). Skin contains 30% tannin, which is used in medical and dye industries.

Pomegranates are low in vitamin C, an important nutritional quality component, compared to many other fruits. Vitamin C content ranges from 0.49 to 30 mg per 100 g juice depending on cultivar (Hussein and Hussein 1972, Küpper 1995). Juice content of pomegranates is 45 to 65% of the whole fruit or 76 to 85% of the aril.

Horticultural Maturity Indices

Pomegranates can be harvested when they reach a certain size and skin color. Other maturity indices are TA and SSC. Each pomegranate type requires a certain TA:SSC at harvest. TA of pomegranates varies between 0.13 and 4.98% at harvest (Küpper 1995). The TA is $<1\%$ in sweet cultivars, 1 to 2% in sweet-sour cultivars, and $>2\%$ in sour cultivars (Onur and Kaşka 1985). SSC of pomegranates varies from 8.3 to 20.5% at harvest (Küpper 1995). Thus, maturity indices depend on cultivar. For example, TA $<1.85\%$ and SSC $\geq 17\%$ are recommended for California-grown 'Wonderful' fruit (Ben-Arie et al. 1984, Elyatem and Kader 1984). Juice tannin content $<0.25\%$ is preferred, and red juice color equal to or darker than Munsell color chart 5R 5/12 is desirable (Crisosto et al. 1996).

Grades, Sizes, and Packaging

There are no U.S. grades. Only a small number of pomegranates have been grown historically in the U.S., mostly in California and Arizona. Therefore, most fruit are imported for the U.S. market. Pomegranates are classified into four groups based on size. Under Turkish standards, sizes are defined as—

Small	150 to 200 g	65 to 74 mm diameter	25 to 34 fruit per 5-kg carton
Medium	201 to 300 g	75 to 84 mm diameter	17 to 25 fruit per 5-kg carton
Large	301 to 400 g	85 to 94 mm diameter	13 to 17 fruit per 5-kg carton
Extra large	401 to 500 g	94 to 104 mm diameter	10 to 13 fruit per 5-kg carton

Fruit are generally packed into two-layer tray packs or bulk cartons.

Optimum Storage Conditions

Optimum storage temperature varies by cultivar, production area, and postharvest treatment (Mercantilia 1989, Hardenburg et al. 1990, Köksal 1989, Snowdon 1990, SeaLand 1991, Onur et al. 1995). The recommended conditions for storage of 'Hicaznar' are 6 °C (43 °F) with 90% RH (Onur et al. 1992, 1995, Pekmezci et al. 1998). Storage of 'Wonderful' at <5 °C (41 °F) resulted in chilling injury, and severity of symptoms increased with time and temperature below 5 °C (Elyatem and Kader 1984). Control of RH is critical in storage because skin desiccates readily at low RH, resulting in hard, darkened rinds, which are unattractive and reduce marketability. RH of 90 to 98% is preferred for storage (Salunkhe and Desai 1984). Waxing fruit and storage in plastic liners can reduce weight loss (Küpper 1995).

Controlled Atmosphere (CA) Considerations

CA storage has the advantage of reducing loss of TA and vitamin C (Küpper et al. 1995). Optimal CA levels for pomegranate storage are 3% O_2 and 6% CO_2 (Küpper et al. 1995). 'Hicaznar' fruit can be stored for 6 mo at 6 °C (43 °F) under CA (Pekmezci et al. 1998).

Retail Outlet Display Considerations

Pomegranates should not be water-sprinkled or top-iced.

Chilling Sensitivity

Pomegranates are susceptible to chilling injury and should not be stored at <5 °C (41 °F). External symptoms include rind pitting, brown discoloration of the skin, and increased susceptibility to decay. Internal symptoms include a pale aril color and brown discoloration of the white segments separating the arils (Elyatem and Kader 1984).

Ethylene Production and Sensitivity

Pomegranates produce very low amounts of ethylene: <0.1 $\mu L\ kg^{-1}\ h^{-1}$ at up to 10 °C (50 °F) and <0.2 $\mu L\ kg^{-1}\ h^{-1}$ from 10 to 20 °C (50 to 68 °F) (Elyatem and Kader 1984). Fruit are not particularly sensitive to ethylene exposure, though ethylene at ≥1 $\mu L\ L^{-1}$ stimulates respiration and autocatalytic ethylene. Ben-Arie et al. (1984) reported that ethylene treatment of 'Wonderful' pomegranates caused a rapid but transient rise in CO_2 but no change in SSC, TA, or fruit and juice color. Pomegranates do not ripen after harvest and must be picked fully ripe.

Respiration Rates

Pomegranate is a nonclimacteric fruit and has a very low respiration rate that declines with time in storage.

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	4 to 8
10 °C	8 to 16
20 °C	16 to 36

Data from Crisisto et al. (1996).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Chilling injury (CI) is the most common physiological disorder during storage. Incidence and severity of CI depend on temperature and duration. Symptoms are especially apparent upon removal of fruit from cold storage to 20 °C (68 °F). External CI symptoms include surface pitting, skin discoloration, scald, and dead skin tissues. Internal symptoms include dead tissues, brown discoloration of the white segments separating the arils, and pale aril color (Elyatem and Kader 1984). Husk scald (brown superficial discoloration) is another manifestation of CI in pomegranate; it is a restricted to the husk. At advanced stages, scalded areas became moldy. Scald symptoms become evident after 8 weeks of storage at 2 °C (36 °F).

Splitting and cracking occur in fruit on the tree. The rind shows various degrees of cracking, which often serves as entry points for decay organisms (Salunkhe and Desai 1984). Splitting and cracking can be prevented by using regular irrigation; the last irrigation must be done 15 to 20 days before harvest.

Internal breakdown is another physiological disorder in pomegranate fruit. The pulp-bearing seeds (arils) do not develop their typical red color and are somewhat flattened rather than plump (Ryall and Pentzer 1974).

Postharvest Pathology

Gray mold rot *(Botrytis cinerea)*, green mold rot *(Penicillium digitatum)*, and *Cladosporium* spp. are the main postharvest diseases of pomegranate fruit. Gray mold usually starts at the calyx. As it progresses, the skin becomes light-brown, tough, and leathery. Heart rot is another disorder; it may be caused by *Aspergillus* spp. and *Alternaria* spp. Affected fruit show slightly abnormal skin color and a mass of blackened arils; disease develops while fruit are on the tree (Salunkhe and Desai 1984).

Quarantine Issues

There are no known quarantine issues.

Suitability as a Fresh-Cut Product

Possibly, but none are fresh-cut at this time.

Special Considerations

Pomegranates do not ripen after harvest and must be picked fully ripe to ensure the best eating quality.

References

Ben-Arie, R., N. Segal, and S. Guelfat-Reich. 1984. The maturation and ripening of the 'Wonderful' pomegranate. J. Amer. Soc. Hort. Sci. 109:898-902.

Crisosto, C.H., E.J. Mitcham, and A.A. Kader. 1996. Pomegranates. Perishables Handling Quarterly 85:17-18. At http://postharvest.ucdavis.edu/pffruits/pomegranate.

Elyatem, M.S., and A.A. Kader. 1984. Postharvest physiology and storage behavior of pomegranate fruit. Sci. Hort. 24:287-298.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1990. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, rev. Agricultural Handbook 66, U.S. Department of Agriculture, Washington, DC.

Hussein, M.A.H., and M.A.S. Hussein. 1972. Suitability of pomegranate varieties for processing. Assuit J. Ag. Sci. 3:303-307.

Köksal, I. 1989. Research on the storage of pomegranate cv. 'Gökbahçe' under different conditions. Acta Hort. 258:295-302.

Küpper, W. 1995. Wirkungen von Temperatur und CO_2-Konzentration in der Langfristigen CA-Lagerung auf Verschiedene Qualitaetsmerkmale und die Respiration Waehrend der Nachlagerungsphase des Granatapfels (*Punica Granatum* L.) der Sorte 'Hicaznar.' Ph.D. thesis, Institut für Obstbau und Gemüsebau der Rheinschen, Friedrich-Wilhelms-Univertat., Bonn, Germany.

Küpper, W., M. Pekmezci, and J. Henze. 1995. Studies on CA-storage of pomegranate (*Punica granatum* L., cv. 'Hicaz'). Acta Hort. 398:101-108.

LaRue, J.H. 1980. Growing pomegranates in California. Leaflet 2459, University of California, Division of Agricultural Science, Davis, CA.

Llacer, G., R. Martinez Valero, P. Melgarejo, et al. 1994. Present status and future prospects of underutilized fruit tree crops in Spain. pp. 63-75. *In* First Meeting CIHEAM Coop. Res. Network Underutilized Fruit Trees, 1994, Zaragoza, Spain.

Mars, M. 1994. La culture du granadier (*Punica granatum* L.) et du figuier (*Ficus carica* L.) en tunisie. pp. 76-83. *In* First Meeting CIHEAM Coop. Res. Network Underutilized Fruit Trees, 1994, Zaragoza, Spain.

Mercantila. 1989. Guide to Food Transport. Fruit and Vegetables. Mercantilia, Copenhagen, Denmark.

Morton, J. F. 1987. Fruits of Warm Climates. Julia F. Morton, Miami, FL.

Onur, C. 1989. Nar muhafazasında bir yenilik [News on pomegranate storage]. Derim 6:88-93.

Onur, C., and N. Kaska. 1985. Akdeniz bölgesi narlarının (*Punica granatum* L.) seleksiyonu [Selection of pomegranate of Mediterranean region]. Turkish J. Agric. For., D2, 9, 1:25-33.

Onur, C., M. Pekmezci, H. Tibet, et al. 1992. Hicaznarının soğukta muhafazası üzerinde bir araştırma [Research on cold storage of pomegranate cv. Hicaznar]. *In* Proceedings of Turkey 1st National Horticulture Congress, October 13-16, 1992, Ege University Agricultural Faculty, pp: 209-212.

Onur, C., M. Pekmezci, H. Tibet, et al. 1995. Nar (*Punica granatum* L.) muhafazası üzerinde araştırmalar [Investigations on pomegranate storage]. *In* Proceedings of 2nd National Horticulture Congreess, 3-6 October, 1995, Adana, Turkey, vol 1, pp. 696-700. Çukurova University,

Patil, A.V., and A.R. Karale. 1990. Pomegranate. *In* T.K. Kose and S.K. Mitra, eds., Fruits: Tropical and Subtropical, pp. 614-631. Naya Prokash, Calcutta, India.

Pekmezci, M., M. Erkan, H. Gübbük, and S. Gözlekçi. 1998. Effect of modified atmosphere on storage of pomegranate fruits (cv. Hicaznar). 25th International Horticultural Congress, Brussels, Belgium. Acta Hort. PP2/04/A10:368

Ryall, A.L., and W.T. Pentzer. 1974. Handling, Transportation and Storage of Fruit and Vegetables, vol. 2. AVI, Westport, CT.

Salunkhe, D.K., and B.B. Desai. 1984. Postharvest Biotechnology of Fruits, vol. 2. CRC Press, Boca Raton FL.

SeaLand Service. 1991. Shipping guide to perishables. SeaLand Service, Iselim, NJ.

Snowdon, A.L. 1990. A Colour Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 1, General Introduction and Fruits. Wolfe Scientific, London, U.K.

Further Reading

Artes, F., J.G. Marin, and J.A. Martinez. 1996. Controlled atmosphere storage of pomegranate. Z. Lebensm. Unters. Forsch. 203:33-37.

Ben-Arie, R., and E. Or. 1986. The development and control of husk scald on ‘Wonderful’ pomegranate fruit during storage. J. Amer. Soc. Hort. Sci. 111:395-399.

Gil, M., F. Artes, and F. Tomas-Barberan. 1996. Minimal processing and modified atmosphere packaging effects on pigmentation of pomegranate seeds. J. Food Sci. 61:161-164.

Gil, M.I., R. Sanchez, J.G. Marin, and F. Artes. 1996. Quality changes in pomegranates during ripening and cold storage. Z. Lebensm. Unters. Forsch. 202:481-485.

Kader, A.A., A. Chordas,, and S. Elyatem. 1984. Responses of pomegranates to ethylene treatment and storage temperature. Calif. Agri. 38(748):14-15.

Potato

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Scientific Name and Introduction

The white, or Irish, potato, *Solanum tuberosum* L., is an annual of the Solanaceae family. The edible portion is the tuber, an underground stem that forms at the end of stolons. Potato is a cool-season plant. It is native to the Americas, with many close relatives in the Andean region of South America. New varieties commonly have one or more wild *Solanum* species included in their pedigree. Potato is grown throughout the world in temperate zones, with planting in spring and harvest in fall.

There are many skin colors (brown russet, white, red, pink, yellow) and flesh colors (white, cream, yellow, blue/purple/red, and striated). Tuber shapes vary from round to oblate to oblong to long. Stored potatoes are available year-round; fresh potatoes are harvested year-round, albeit in small quantities during winter, spring, and summer. Processed potatoes (frozen french fries, potato chips, flakes, etc.) are manufactured year-round from fresh and stored tubers.

Quality Characteristics and Criteria

A high-quality fresh-market potato tuber is turgid, well shaped, uniform, and brightly colored (especially reds, whites, and yellows), as well as free from adhering soil, mechanical damage, greening, sprouts, diseases, and physiological defects.

Horticultural Maturity Indices

The ability of potato tuber skin to resist abrasion (skinning) during harvest is a common index for maturity. Sugar content is a maturity index for processing potatoes, with both immaturity and overmaturity resulting in higher sugar levels. Vine senescence is used as a preharvest maturity index, but the correlation between vine senescence and tuber skin-set varies among cultivars.

Grades, Sizes, and Packaging

USDA market grades (established in 1991) are Extra No. 1, No. 1, Commercial, and No. 2; grade is distinguished primarily on external condition and appearance. Grades vary among tuber shapes. The minimum diameter for U.S. No. 1 or No. 2 is 4.8 to 5.1 cm (1 7/8 to 2 in) for round potatoes with a weight minimum of 118 g (4 oz) for long potatoes. At times, an additional requirement that ≥60% of the tubers must be a minimum of 148 g (5 oz) is imposed. A “B-size” grade is becoming more common, primarily for round red and white potatoes. B-size grade tubers are <5.1 cm (2 in).

Oblong and long russets are commonly wholesale marketed in “count” boxes of 60, 70, 80, 90 or 100 tubers in a 22.5-kg (50-lb) carton, thus averaging approximately 380, 325, 296, 266, or 237 g each (13, 11, 10, 9, or 8 oz), respectively. These are retailed bulk for consumers to select individual tubers. Common retail packages of 2.27 and 4.55 kg (5 and 10 lbs) plastic and paper bags generally contain 150- to 240-g (5- to 8-oz) tubers. B-size tubers are sold in pint “strawberry” baskets or in bulk. Prepeeled tubers are generally packaged in plastic trays covered with plastic wrap.

Potatoes for processing into such products as french fries or chips are graded using the U.S. grade and size standards in combination with individual quality and size requirements of each processing company. The company requirements vary with the type of product to be manufactured and the purchaser. Tubers are delivered to processing plants in bulk trucks or bins holding about 2,000 lb (910 kg).

Optimum Storage Conditions

Long-term storage of potato tubers—up to 12 mo—requires that they be cured. Curing stimulates suberization and wound healing and reduces respiration. Optimal curing conditions are approximately 20 °C (68 °F) with RH of 80 to 100%. Curing is markedly slower at temperatures <12 °C (54 °F) and >25 °C (77 °F). Similarly, RH <80% delays curing. Curing at 15 °C (59 °F) is commonly recommended to minimize decay. Frequently, potatoes harvested in fall in temperate climates are colder than the optimal curing temperatures. However, respiration in storage will heat the tubers and raise RH. Temperature and RH control during this "sweating" or curing time is managed using fans to bring outside air into the storage room, depending on the need during the night or day. Once cured, a process requiring 1 to 2 weeks, the tuber temperature is lowered by 1 to 2 °C per day until the desired maintenance temperature and RH are reached. In some cases, two additional steps must be employed: drying of wet potatoes upon entry into storage, and heating of tubers before removal from storage. Forced movement of air is used to ensure uniform temperature throughout the storage pile. Maintaining 95 to 99% RH is required at all times to minimize shrink and pressure bruising in storage.

Desired maintenance temperature depends on the desired end use of the tubers. Respiration rate of potato tubers is lowest at 2 to 3 °C (36 to 37 °F). Storage at 0 to 2 °C (32 to 36 °F) increases the risk of freezing or chilling injury. Sprouting accelerates at temperatures >4 °C (40 °F), so seed tubers are commonly stored at 4 to 5 °C (40 °F). Tubers for fresh consumption are stored at 7 to 10 °C (45 to 50 °F), to minimize conversion of non-reducing sugars such as starch to reducing sugars such as glucose, which darken during cooking. Tubers for frying are stored at 10 to 15 °C (50 to 59 °F), depending on the cultivar and its respective sugar conversion characteristics. Many chipping cultivars accumulate excessive sugar if stored <15 °C (59 °F). Thus, chipping cultivars are stored at 15 to 20 °C (59 to 68 °F); new cultivars are being developed that will not accumulate sugar at temperatures as low as 5 to 10 °C (41 to 50 °F).

Quality tubers can be stored for 2 to 12 mo, depending on quality at harvest, quality of storage facilities, variety, and whether or not sprout inhibitors are used. Sprout inhibitor may be applied in the field before senescence begins, on the tubers as they are graded and packaged, or in storage after curing is completed.

Controlled Atmosphere (CA) Conditions

The usefulness of CA storage is minimal, and economic justification doubtful. Periderm development and wound healing are delayed at atmospheres with <5% O_2. Injury from <1.5% O_2 or >10% CO_2 includes induced off odors and flavors, internal discoloration, and increased decay. While higher CO_2 levels tend to inhibit formation of reducing sugars, they also increase sucrose content.

Retail Outlet Display Considerations

Cured and new potatoes, whether displayed in bulk or in cellophane or paper bags are displayed dry. New potatoes that are displayed in bulk are commonly included with other cool-season vegetables that receive periodic water misting or sprinkling.

Chilling Sensitivity

Potatoes freeze at approximately -1 °C (30 °F). Internal mahogany browning can occur at 1 to 2 °C (34 to 36 °F), while temperatures of 3 to 4 °C (37 to 39 °F) typically result in increased reducing sugar levels that are not reversible with reconditioning.

Ethylene Production and Sensitivity

Potatoes produce very low levels of ethylene: <0.1 $\mu L\ kg^{-1}\ h^{-1}$ at 20 °C (68 °F). Cut, bruised, or wounded tubers have greatly increased ethylene production rates. Potato tubers are not very sensitive to external ethylene. Low levels of ethylene elevate respiration, especially in immature potatoes, and result in weight loss and mild shriveling. After 2 to 3 mo at >5 °C (41 °F) without sprout inhibitor, low levels of ethylene may retard sprouting, while high amounts may induce sprouting.

Respiration Rates

Immature potato tubers usually have higher respiration rates than mature or cured tubers. Cooler temperatures and increased air movement are effective at controlling effects of a high rate of respiration. Increased air movement in the absence of high RH, however, will cause desiccation.

Temperature	Immature	Mature (cured)
	--------mg CO_2 kg^{-1} h^{-1}---------	
5 °C	24	6 to 18
10 °C	30 to 40	13 to 19
15 °C	25 to 57	11 to 22
20 °C	32 to 81	14 to 29

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

The most common and serious physiological disorders affecting potatoes include black spot, blackheart, freezing injury, greening, hollow heart, sugar end browning, and internal necrosis.

Black spot results from a physical impact to the tuber; the stem end is most sensitive. Following severe bruising or cutting, the affected tissue turns reddish, then blue, becoming black in 24 to 72 h. Severity increases with time. Cultivars differ significantly in their susceptibility and symptom expression. Soil conditions can predispose tubers to blackspot; poor aeration is the most common cause. Proper fertilization (particularly potassium), water management, careful handling, and high RH to maintain turgidity are important in minimizing black spot. Use of compost and manure helps prevent blackspot.

Blackheart is a storage- or transportation-induced disorder caused by low O_2. Typically, blackheart is induced at >30 °C (86 °F), which increases respiration. If air exchange around tubers is insufficient, low-O_2 conditions develop in the interior of the tuber, and the cells suffocate and turn black. Blackheart is rare in early crop potatoes because of typical marketing practices.

Freezing at -1 °C (30 °F), whether in the field or in storage, typically results in a distinct demarcation between affected and unaffected tissue. Symptoms include a water-soaked appearance, glassiness, and tissue breakdown on thawing. Chilling injury can occur after a few weeks at 0 °C (32 °F) and result in a mahogany discoloration of internal tissue in some varieties. Much longer periods of storage are generally required for chilling injury.

Greening may occur in part of a tuber exposed to light. Affected tubers are easily culled at grading and rarely proceed to marketing channels. Darkness is essential for long-term storage because greening can occur during storage or marketing. Exposure to bright light during postharvest handling, or longer periods (1 to 2 weeks) of low light, can result in development of chlorophyll (greening) and bitter, toxic glycoalkaloids such as solanine. Solanine also forms in response to bruising and wounding (including fresh processing followed by storage) and during sprouting. Glycoalkaloids are heat stable and minimally degraded by cooking. Tubers in market displays should be replaced daily or more frequently to minimize greening.

Enlarged lenticels are a common disorder in early potatoes where excessive irrigation is often applied to maintain cooler soil temperatures in warm or hot climates. These lenticels are subject to pathological infection in the soil or during packing. Infections may remain innocuous; or if transportation conditions are not properly maintained, they can increase rapidly in severity. Tubers that appear sound at the packing shed can become unmarketable during transit.

Skinning is a common disorder in early crop or "new" potatoes (harvested immature). Soil drying and vine death enhance skin set, and thus decrease skinning. Cultivars vary in ability to set-skin, in skin thickness, and thus in skinning susceptibility. "New" potatoes must be kept at a very high RH, near 100%, and must be handled with special care.

Hollow heart, sugar end accumulation, and *internal necrosis* are all production problems related to irregular growth, inadequate water availability, or widely fluctuating temperatures. These conditions do not change during harvest and postharvest handling.

Postharvest Pathology

Diseases are an important source of postharvest loss, particularly in combination with rough handling and poor temperature control. Three major bacterial diseases and a greater number of fungal pathogens are responsible for occasional, serious postharvest losses. The major bacterial and fungal pathogens that cause postharvest losses in transit, in storage, and after-market are bacterial soft rot *(Erwinia carotovora* subsp. *carotovora* and subsp. *atroseptica), Ralstonia* (ex *Pseudomonas,* ex *Burkholderi*) *solanacearum,* late blight *(Phytophthora infestans)*, fusarium dry rot (*Fusarium* spp.), pink rot (*Phytophthora* spp.), water rot (*Pythium* spp.), and silver scurf *(Helminthosporium solani).* Occasionally serious diseases of immature tubers include pink eye *(Pseudomonas fluorescens)* and grey mold *(Botrytis cinerea).*

In addition to careful sorting before placing tubers into storage, management of air, RH, and temperature during storage and transit of potatoes with potential problems can be effective. Lower RH, shortened curing time, and lower temperatures can minimize spread of rot diseases.

Quarantine Issues

Export and import of potato tubers can involve numerous quarantine issues related to grade, diseases, and nematodes. Each country has its own phytosanitary requirements. Inspections and appropriate authorizations are required. Among the most common diseases and nematodes included in quarantine or zero-tolerance requirements are cyst nematode (*Globodera* spp.), viruses and viroids, brown rot *(Pseudomonas solanacearum),* ring rot *(Corynebacterium sepedonicum),* and powdery scab *(Spongospora subterranean).* Similarly, these diseases and nematodes are restricted on potato tubers to be imported. Currently, potato tubers may not be imported into the United States from any country except Canada.

Suitability as Fresh-Cut Product

Potatoes are relatively new as a lightly processed product. Fresh-cut potatoes are not marketed, but par-boiled whole tubers can be prepared and marketed in plastic trays with sealed plastic wrap with low O_2-transmission characteristics. Storage requirements for tubers to be processed in this manner have not been well defined.

Special Considerations

Potatoes may impart an "earthy" odor to apples and pears if held in storage with low air exchange. Potatoes may acquire an off flavor from odor volatiles released by other produce items.

Postharvest handling and storage of late-crop potatoes is very complex and depends on growing conditions, environment at harvest, variety, intended use, and many other factors.

Further Reading

Kader, A.A., ed. 2002. Postharvest Technology of Horticultural Crops, 3rd ed. DANR Pub. no. 3311, University of California, Oakland, CA.

Kleinkopf, G.E. 1979. Translucent end of potatoes. Cur. Info. Ser. 488, University of Idaho, Moscow, ID.

Kleinkopf, G.E. 1995. Dynamics of the stored potato—a management approach. Early season storage. Amer. Potato J. 72:449-462.

Lewis, M.D., M.K. Thornton, and G.E. Kleinkopf. 1997. Commercial application of CIPC sprout inhibitor to storage potatoes. Curr. Info. Ser 059, University of Idaho, Moscow, ID.

Rastovski, A. 1987. Storage of Potatoes: Postharvest Behavior, Store Design, Storage Practice, Handling. Pudoc, Wageningen, Netherlands.

Secor, G.A., N.C. Gudmestad, D.A. Preston, and H.A. Lamey. 1997. Disease Control Guidelines for Seed Potato Selection, Handling, and Planting. North Dakota State University Extension Publication PP-877, North Dakota State University, Fargo, ND.

Shetty, K.K. 1998. Potato storage. *At* http://www.kimberly.uidaho.edu/potatoes.

Shetty, K.K., M.J. Frazier, G.E. Kleinkopf, and P. Nolte. 1997. Silver scurf of potatoes. Curr. Info. Ser. 1060, University of Idaho, Moscow, ID.

Sieczka, J.B., and R.E. Thornton, eds. 1993. Commercial Potato Production in North America, rev. Amer. Potato J. Suppl., vol. 57, and USDA Handbook 267, Potato Assoc. Amer. 1993 Official Pub. Potato Assoc. Amer., Orono, Maine.

Stevenson, W.R., R. Loria, G.D. Franc, and D.P. Weingartner, eds. 2001. Compendium of potato diseases, 2nd ed. American Phytopathological Society Press, St. Paul, MN.

Strand, L., G. Bishop, G. Kleinschmidt, et al., eds. 1992. Integrated pest management for potatoes in the western United States, rev. DANR Pub. no. 3316 *and* Western Regional Res. Pub. no. 011, University of California, Oakland, CA.

Suslow, T., and R. Voss. 2000. Potato (immature early crop). Recommendations in maintaining postharvest quality. Postharvest Technology Research & Information Center, University of California, Davis, CA.

Prickly Pear

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Scientific Name and Introduction

Prickly pear fruit are harvested from various species of the prickly pear cactus, genus *Opuntia* of the cactus family (Cactaceae). Fruit are also called cactus pears or cactus fruit, though these names can result in confusion with fruits from other cactus species. The fruit is a berry, typically weighs 100 to 200 g (0.2 to 0.4 lb), and consists of a thick fleshy skin or rind surrounding a juicy pulp that contains many hard-coated seeds. Fruit vary considerably in color, size, and flavor. Prickly pear fruit are produced in California or are imported from Mexico ("tunas") and Chile.

Quality Characteristics and Criteria

Fruit of high quality need to be harvested near full ripeness to have color and flavor typical of each variety. They should have a high percentage of pulp, low seed content, and peel that is easy to remove. Fruit typically have high sugar content (12 to 17% SSC) and low acidity (0.03 to 0.12% TA). Cactus pears contain considerable amounts of vitamin C (200 to 400 $\mu g\ g^{-1}$). If harvested at maturity from good varieties, fruit have a delicate sweet flavor that differs by variety.

Horticultural Maturity Indices

Stage of maturity or ripeness at harvest is very important for fruit quality since sugar content and sweetness do not increase after harvest. Maturity indices include fruit size and fullness, changes in peel color, abscission of the small spines (glochids), fruit firmness, and flattening of the floral cavity or receptacle. Peel color is the single most important index for commercial harvest.

Grades, Sizes, and Packaging

There are no U.S. grades. Fruit are packed according to color, size, and condition in 4.5 kg (10 lb) cartons or may be packed in single- or double-layer tray cartons. Large fruit may be wrapped in tissue paper to reduce scuffing and other physical injury. Fruit may also be packaged in cartons with perforated plastic liners to reduce water loss under dry storage conditions.

Precooling Conditions

Fruit should be cooled to 5 °C (41 °F) to reduce loss of visual appearance (shiny surface) resulting from water loss. Fruit are usually room-cooled, but may also be forced-air cooled. Cooling may be delayed if fruit undergo curing treatment (see *Special Considerations*).

Optimum Storage Conditions

Depending on variety, ripeness stage, and harvest season, fruit can be kept for 2 to 5 weeks at 5 to 8 °C (41 to 46 °F) with 90 to 95% RH. Factors limiting storage life are decay, dehydration, and chilling injury.

Controlled Atmosphere (CA) Considerations

Limited research indicates that holding cactus pear at 5 °C (41 °F) in 2% O_2 and 2 to 5% CO_2 delays ripening and extends storage life (Kader 2000).

Retail Outlet Display Considerations

Fruit should be kept cold to reduce dehydration. At retail, the surface of cactus fruit may appear dull due to water loss.

Chilling Sensitivity

Cactus pear fruit are especially chilling sensitive when stored at <5 °C (41 °F), but chilling injury may occur in some varieties at <10 °C (50 °F). Symptoms include pitting, surface bronzing and dark spots on the peel, and increased susceptibility to decay. Chilling occurred in a red-fruit variety after only 2 weeks at 6 °C (43 °F), but fruit from other varieties were held for several weeks without signs of chilling. Summer-harvested fruit are more chilling sensitive than autumn-harvested fruit (Schirra et al. 1999). Application of calcium chloride, conditioning, and intermittent warming have had variable success in reducing chilling injury.

Ethylene Production and Sensitivity

Prickly pear fruit produce very low amounts of ethylene, about 0.2 µL kg^{-1} h^{-1} at 20 °C (68 °F). They are not sensitive to ethylene exposure.

Respiration Rates

Fruit are nonclimacteric and respiration rates are low during storage. The respiration rate at 20 ºC (68 ºF) is 27 to 36 mg (15 to 20 µl) CO_2 kg^{-1} h^{-1}. Heat production is about 7,000 BTU ton^{-1} day^{-1} or 1,900 kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

See section above on *Chilling Sensitivity.*

Postharvest Pathology

Harvest damage to the peel and stem-end of cactus fruit will lead to attack by numerous pathogens and result in fruit decay. Common postharvest pathogens on cactus fruit are mostly fungi and include *Fusarium* spp., *Alternaria* spp., and *Penicillium* spp., but yeasts and bacteria also cause decay. Hot water dips at 53 to 55 °C (127 to 131 °F) for 5 min and fungicide-containing waxes may reduce surface decay, but are not effective when there is damage to the stem-ends. For control of decay on stem-ends, see *Special Considerations.* Preharvest calcium sprays result in less postharvest decay (Schirra et al. 1999).

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Even after brushing and washing, the peel of intact cactus fruit may have irritating small spines, and a peeled packaged fruit product could be a useful option. A mixture of cactus fruit of different colors and types could be a potentially attractive product.

Special Considerations

Fruit can be bruised easily by finger compression during harvest, but damage at the stem-end is by far the most serious mechanical injury. Damage at the stem-end can be eliminated by careful harvesting (twisting fruit from the stem or cutting fruit with a small piece of stem attached). Fruit harvested with a bit of stem may be packed that way or cured under moderate temperature of 15 to 20 °C (59 to 68 °F) with airflow so that the bit of stem dries and falls off before fruit are packed. This prevents damage to the stem end and greatly reduces decay incidence. High-gloss fruit waxes are often used to improve appearance and reduce dehydration. This is especially important if fruit are dry-brushed to remove small tufts of spines or glochids.

References

Kader, A. 2000. Cactus (prickly) pear. Recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

Schirra, M., P. Inglese, and T. La Mantia. 1999. Quality of cactus pear [Opuntia ficus-indica (L.) Mill.] fruit in relation to ripening time, CaCl2 preharvest sprays and storage conditions. Sci. Hort. 81:425-436.

Further Reading

Cantwell, M. 1995. Postharvest management of fruits and vegetable stems. *In* G. Barbera, P. Inglese, and E. Pimienta-Barrios, eds., Agroecology, Cultivation and Uses of Cactus Pear, pp. 120-136. Plant Production and Protection Paper 132, Food and Agriculture Organization of the United Nations, Rome, Italy.

Lakshminarayana, S., L. Alvarado y Sosa, and F. Barrientos-Pérez. 1979. The development and postharvest physiology of the fruit of prickly pear (*Opuntia amyclaea* Tenore). *In* G.E. Inglett and G. Charalambous, eds., Tropical Foods, vol. 1, Chemistry and Nutrition, pp. 69-93. Academic Press, New York, NY.

Piga, A., S. D’Aquino, M. Agabbio, and M. Schirra. 1996. Storage-life and quality attributes of cactus pears cv. “Gialla” as affected by packaging. Agr. Med. 126:423-427.

Schirra, M., M. Agabbio, S. D’Aquino, and T.G. McCollum. 1997. Postharvest heat conditioning effects on early ripening ‘Gialla’ cactus pear fruit. HortScience 32:702-704.

Pumpkin and Winter Squash

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Scientific Name and Introduction

Three species of the Cucurbitaceae family produce edible fruit that are harvested when physiologically mature. These are pumpkin or acorn squash (*Cucurbita pepo* L.); winter squash or giant pumpkin (*Cucurbita maxima* Duchesne ex Lam.); and crookneck squash, tropical pumpkin (calabaza), or butternut squash (*Cucurbita moschata* [Duchesne ex Lam.] Duchesne ex Poir.). Mature fruit are harvested in fall, and some can be stored for many months. The distinction between pumpkins and winter squash is culinary rather than taxonomical. Pumpkins have coarser, stronger-flavored flesh and are used for pies. In the United States they are also used for decoration as Halloween jack-o'-lanterns or for their edible seeds. Winter squash have finer-textured and milder-flavored flesh. They are cooked and served as vegetables, but they are also commonly used for "pumpkin" pies. The *C. moschata* tropical pumpkin, or calabaza, is a staple food in the American tropics and is prepared in many ways that overlap the above definitions of pumpkin and squash (Daniel 1995).

Quality Characteristics and Criteria

Pumpkins and winter squash should be fully mature, with hard rinds and, except for some striped varieties, solid external color. Good-quality pumpkins and winter squash have bright-yellow or orange flesh with fine, moist texture and high solids, sugars, and starch (Cantwell and Suslow 1998). Overmature flesh can become dry and stringy.

Horticultural Maturity Indices

Horticultural maturity coincides with physiological maturity and is recognized externally by corking of the stem (initiation of abscission), loss of rind surface sheen or gloss, groundspot yellowing, and die-back of the tendril nearest the fruit. The rind should resist thumbnail pressure. Development of intense yellow or orange flesh color (due to synthesis of carotenoids) and accumulation of sugars and solids are indicators of maturity that are highly correlated with sensory quality (Daniel et al. 1995, Harvey et al. 1997). Delaying harvest is not recommended: It increases occurrence of storage rot (Hawthorne 1990), and sensory quality improves more in storage than on the plant (Edelstein et al. 1989, Harvey et al. 1997).

Grades, Sizes, and Packaging

Grades are U.S. No. 1 and U.S. No. 2 and are based on similar varietal characteristics (shape, texture, and color), maturity, and freedom from damage and decay. There are no standard sizes for pumpkins and winter squashes, though minimum and maximum weights of individual fruit within packages may be specified. Packages are commonly mesh or burlap bags and one- or two-piece fiberboard cartons containing 23 kg (50 lb). Pumpkins and winter squash are also shipped in 19-kg (42-lb, 1 1/9 bushel) crates and 360- to 410-kg (800- to 900-lb) bulk bin cartons.

Precooling Conditions

Pumpkins and winter squash should be room-cooled or loaded directly into refrigerated trucks and containers.

Optimum Storage Conditions

All pumpkins and winter squashes should be well matured, carefully handled, and free from injury or decay. Pumpkins and winter squashes are placed on racks, in bulk bins, or in baskets and are often held in ventilated or common storage in production areas. Recommended conditions for storage of pumpkins and winter squashes are 10 to 13 °C (50 to 55 °F). At higher temperatures of 15 to 20 °C (59 to 68 °F), green varieties will become undesirably yellow and acquire a stringiness of the flesh. Fruit are chilling sensitive (see *Chilling Sensitivity*). The RH should be 50 to 70%. Higher RH promotes decay while lower RH causes excess weight loss and texture deterioration (Ryall and Lipton 1979). The fruit surface should be kept dry, and storage rooms should have good air circulation (Holmes 1951).

Pumpkins generally do not keep as well as hard-shelled winter squashes. Most cultivars of winter squash and pumpkins, as well as the tropical pumpkins, cannot be stored for more than 2 to 3 mo. Acorn-type squashes, such as 'Table Queen,' can be kept 5 to 8 weeks at 10 °C (50 °F). The popular butternut squash can be kept 2 to 3 mo at 10 °C (50 °F). It is often stored longer, but spoilage and shrinkage increase. Weight loss should be kept below 15% to minimize development of hollow neck (Francis and Thomson 1965). Turban and buttercup squashes can be kept 3 mo. Good quality Hubbard squash can be stored 6 mo at 10 to 13 °C (50 to 55 °F) and 70% RH. A 15% loss in weight after 6 mo is about average (Guba 1950).

Controlled Atmosphere (CA) Considerations

CA of 1% O_2 and 7% CO_2 was recommended for buttercup squash (Prange and Harrison 1993). Reduced O_2 and elevated CO_2 maintained green color, while elevated CO_2 reduced "white mealy breakdown"; decay was lower in 7% CO_2 than in other CA treatments. There were no beneficial effects of 5% O_2 or either 5% or 10% CO_2 on decay of spaghetti squash (Lin and Saltveit 1997). Decay was actually greater in CA than air in both cases because RH was higher; decay was reduced when $CaCl_2$ was used to absorb moisture. Control of RH is critical in CA storage.

Retail Outlet Display Considerations

Pumpkins and winter squash can be displayed in ambient conditions.

Chilling Sensitivity

Both pumpkins and winter squashes develop chilling injury at <10 °C (50 °F). Storage at 0 to 4 °C (32 to 39 °F) inhibits yellowing but causes sunken pits on the fruit surface and loss of flavor. Alternaria rot develops on chilled squashes after removal from storage (McColloch 1962). Depending on the cultivar, chilling injury symptoms develop after 1 mo at 5 °C (41 °F) or several months at 10 °C (50 °F) (Cantwell and Suslow 1998).

Ethylene Production and Sensitivity

Pumpkins and winter squash produce only trace amounts of ethylene, but wounding greatly increases ethylene production (Hyodo et al. 1993). Hubbard squash and other dark-green-skinned squashes should not be stored near apples, as the ethylene from apples may cause the skin to turn orange-yellow (Yeager et al. 1945). Ethylene may also cause stem abscission, especially in less mature fruit (Cantwell and Suslow 1998).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
12 °C	88 to 110 (buttercup)
25 °C	61 to 121 (butternut)

Data for buttercup from Irving et al. (1997); data for butternut from L.L. Morris (unpublished).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Damaged areas on fruit turn brown, detracting from their appearance. Pumpkins and winter squash are susceptible to water loss at the recommended 50 to 70% RH, but low RH is necessary to minimize decay. Yellowing can be a problem for green winter squash varieties and is exacerbated by overmaturity, high storage temperatures, and ethylene exposure.

Postharvest Pathology

Decay is the primary cause of storage losses of pumpkins and winter squash. Numerous fungi cause storage rots, including species of *Aspergillus*, *Colletotrichum* (anthracnose), *Didymella*, *Fusarium*, *Mycosphaerella* (black rot), *Rhizopus*, and *Sclerotinia* (Guba 1950, Abdel-Rahim 1988, Hawthorne 1988, Rath et al. 1990, Vigliola 1993, Arvayo-Ortiz et al. 1994). Alternaria rot develops on chill-damaged fruit (McColloch 1962). Delaying harvest of buttercup squash 2 weeks increased fungal storage rots (Hawthorne 1990). Infection starts through wounds and natural openings in the surface. Therefore, careful handling to minimize mechanical damage is recommended to minimize storage rots (Guba 1950). Less rot will develop in Hubbard squash if stems are completely removed before storage (Yeager et al. 1945). Hot water at 60 °C (140 °F) for 2 min reduces storage rots (Francis and Thomson 1965); lower temperatures were not effective (Hawthorne 1989, Arvayo-Ortiz et al. 1994).

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Some large winter squash are cut into sections and seeds removed for retail sale.

Special Considerations

A 10- to 20-day curing period at 24 to 27 °C (75 to 81 °F) before storage can harden the rind of pumpkins and winter squashes (Gorini and Testoni 1978). However, in New York, curing for 3 weeks at 27 °C (81 °F) to heal mechanical injuries and to ripen immature specimens proved unnecessary (Platenius et al. 1934, Schales and Isenberg 1963). Curing butternut, Hubbard, and quality squashes was of no value but not harmful, whereas curing ‘Table Queen’ was detrimental to skin color, texture, and taste (Schales and Isenberg 1963). Cured ‘Table Queen’ also decayed more rapidly than noncured fruit.

References

Abdel-Rahim, A.M. 1988. Postharvest fungal diseases of some vegetables in Kuwait. Arab J. Plant Protect. 6:83-87.

Arvayo-Ortiz, R.M., S. Garza-Ortega, and E.M. Yahia. 1994. Postharvest response of winter squash to hot-water treatment, temperature and length of storage. HortTechnology 4:253-255.

Cantwell, M., and T.V. Suslow. 1998. Pumpkins and winter squashes. Recommendations for maintaining postharvest quality. Perishables Handling Quarterly 94:15-16.

Daniel, A.L. 1995. Tropical Pumpkin Cultigen Postharvest Quality Evaluation and Maturity Studies. M.Sc. thesis, University of Florida, Gainesville, FL.

Daniel, A.L., J.K. Brecht, C.A. Sims, and D.N. Maynard. 1995. Sensory analysis of bush and vining types of tropical pumpkin. Proc. Fla. State Hort. Soc. 108:312-316.

Edelstein, M., H. Nerson, and H.S. Paris. 1989. Quality of spaghetti squash as affected by fruit maturity, storage period, and cooking duration. Acta Hort. 258:543-545.

Francis, F.J., and C.L. Thomson. 1965. Optimum storage conditions for butternut squash. Proc. Amer. Soc. Hort. Sci. 86:451-456.

Gorini, F.L., and A. Testoni. 1978. Long-term storage of pumpkins. Ann. Ist. Sper. Valoriz. Technol. Prod. Agr. 9:131-135.

Guba, E.F. 1950. Spoilage of squash in storage. Massachusetts Agricultural Experiment Station Bull. no. 457, University of Massachusetts, Amherst, MA.

Harvey, W.J., D.G. Grant, and J.P. Lammerink. 1997. Physical and sensory changes during development and storage of buttercup squash. N.Z. J. Crop Hort. Sci. 25:341-351.

Hawthorne, B.T. 1988. Fungi causing storage rots on fruit of *Cucurbita* spp. N.Z. J. Exp. Agr. 16:151-157.

Hawthorne, B.T. 1989. Effects of cultural practices on the incidence of storage rots in *Cucurbita* spp. N.Z. J. Crop Hort. Sci. 17:49-54.

Hawthorne, B.T. 1990. Age of fruit at harvest influences incidence of fungal storage rots on fruit of *Cucurbita maxima* D. hybrid ‘Delica.’ N.Z. J. Crop Hort. Sci. 18:141-145.

Holmes, A.D. 1951. Factors that affect the storage life of butternut squashes. Food Technol. 5(9):372-373.

Hyodo, H., C. Hashimoto, S. Morozumi, et al. 1993. Induction of wound ethylene production and lignin formation in wounded mesocarp tissue of *Cucurbita maxima*. Acta Hort. 343:264-269.

Irving, D.E., P.L. Hurst, and J.S. Ragg. 1997. Changes in carbohydrates and carbohydrate metabolizing enzymes during development, maturation, and ripening of buttercup squash (*Cucurbita maxima* D. ‘Delica’). J. Amer. Soc. Hort. Sci. 122:310-314.

Lin, W.C., and M.E. Saltveit. 1997. Quality of winter squash affected by storage air composition and temperature. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 4, pp. 78-83. University of California, Davis, CA.

McColloch, L.P. 1962. Alternaria rot following chilling of acorn squashes. Marketing Research Report 518, U.S. Department of Agriculture, Washington, DC.

Platenius, H., F.S. Jamison, and H.C. Thompson. 1934. Studies on cold storage of vegetables. New York (Cornell) Agricultural Experiment Station, Bull. no. 602, Cornell University, Ithaca, NY.

Prange, R.K., and P.A. Harrison. 1993. Effect of controlled atmosphere and humidity on postharvest physiology of buttercup winter squash, *Cucurbita maxima* Duch. hybrid ‘Sweet Mama.’ *In* 6th International Controlled Atmosphere Research Conference, June 1993, vol. 2, pp. 759-766. Ithaca, NY.

Rath, G.C., D. Mishra, and N.C. Nayak. 1990. A note on fungi causing rotting of cucurbits in Orissa markets. Orissa J. Agr. Res. 3:161-162.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation, and Storage of Fruits and Vegetables, 2nd ed., vol. 1. AVI, Westport, CT.

Schales, F.D., and F.M. Isenberg. 1963. The effect of curing and storage on chemical composition and taste acceptability of winter squash. Proc. Amer. Soc. Hort. Sci. 83:667-674.

Vigliola, I. 1993. Postharvest diseases and storage conditions in butternut squash (*Cucurbita moschata* Duch.) in Argentina. Acta Hort. 368:33-36.

Yeager, A.F. 1945. The Storage of Hubbard Squash. New Hampshire Agricultural Experiment Station Bulletin, The University of New Hampshire Bull. no. 356, Durham, NH.

Quince

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Scientific Name and Introduction

Quince (*Cydonia oblonga* Mill.) is a many-seeded pome, pyriform type of fruit. Its genus consists of a single species, native to the warmer regions of southeastern Europe and Asia Minor (Childers 1949, Westwood 1978). Few studies have been made of this minor crop (Michelesi et al. 1973, Jankowiak 1976, Muller and Husistein 1979). It is used mostly as a dwarfing rootstock for pear, but is also used for preserves, jams, and jellies. The main cultivars of quince are 'Orange,' 'Champion,' 'Pineapple,' 'Angers,' 'Smyrna,' 'Van Deman,' 'Rea,' and 'Meech' (Childers 1949, Westwood 1978). About 200 acres is grown in the United States, but it is an important crop of 20,000 tons annual production in Argentina (Westwood 1978).

Quality Characteristics and Criteria

Quince are climacteric fruit (Kader 1992) and require a proper ripening process at 20 °C (68 ºF) for high quality fruit for processing. Properly ripened quince of high quality are used chiefly for jellies, marmalades, and preserves and to some extent for baking, canning, and adding flavor to other processed fruit products. Much scientific research has centered on the chemical nature of texture and flavor quality of quince fruit. Literature regarding quality includes Andrade et al. (1972), Gumbaridze (1972a,b), Kozenko et al. (1976) , Rozmyslova and Papunov (1977) , Shimizu and Yoshihara (1977), Strandzhev et al. (1978), Iocheva (1979), Sharova and Illarionova (1980), Tsuneya et al. (1980, 1983), Kornatskaia (1981), Lobachev and Gavrishova (1982), Umano et al. (1986), Guldner and Winterhalter (1991), Lutz and Winterhalter (1992a,b, 1993).

Horticultural Maturity Indices

Quince fruit harvesting criteria and methods are similar to most winter pear cultivars. There is no specific maturity index for quince fruit. Harvest begins when fruit change ground color from deep green to a lighter green (Auchter and Knapp 1929). Green, immature fruit scald readily in storage, and fruit affected with scab do not store well.

Grades, Sizes, and Packaging

There are no official standard grades, sizes, or packaging for quince. According to the California Food and Agricultural Code for quality standards, quince fruit should be marketed at optimum maturity and free from insect damage, mechanical damage, and decay (Kader 1992). Since fruit are rather tender and bruise easily, the shipping container should be lined with soft pads on both ends. The blossom end is turned upwards (Auchter and Knapp 1929). Fruit should be handled carefully to avoid mechanical injury.

Precooling Conditions

No precooling of quince fruit is done commercially.

Optimum Storage Conditions

Optimum storage temperature is -0.5 °C to 0 °C (31 to 32 °F) with about 90% RH. Storage life in air at -0.5 °C (31 °F) is 2 to 3 mo, similar to early apple cultivars, such as 'Jonathan' and 'Grimes Golden' (Williams 1935).

Controlled Atmosphere (CA) Considerations

There is no recommendation for CA storage.

Ethylene Production and Sensitivity

The best ripening temperature for quince fruit after storage is 20 °C (68 ºF). Since quince is a climacteric fruit (Kader 1992), the acceleration of ethylene production during ripening may be expected. However, literature regarding ethylene biosynthesis in quince fruit is lacking.

Postharvest Pathology

Though the skin of quince has a thick coat of fuzz, the fruit is tender and bruises easily (Auchter and Knapp 1929). Quince is subject to decays similar to those found on apples and pears (Halsted, 1892, Tafradzhiiski and Angelov 1977). Treatment with fungicides is necessary to prevent decay during storage and marketing (Pierson et at. 1971).

References

Andrade, P.B., A.R.F. Carvalho, R.M. Seabra, and M.A. Ferreira. 1998. A previous study of phenolic profiles of quince, pear, and apple purees by HPLC diode array detection for the evaluation of quince puree genuineness. J. Agric. Food Chem. 46:968-972.

Auchter, E.C., and H.B. Knapp. 1929. Harvesting, storing and marketing, pp. 1-132, *and* Establishing the orchard, pp. 138-176. *In* A.K. Getman and C.E. Ladd, eds., Orchard and Small Fruit Culture. John Wiley & Sons, New York, NY.

Childers, N.F. 1949. Pear and quince culture. *In* R.W. Gregory, ed., Fruit Science, Orchard and Small Fruit Management, pp. 248-273. J.B. Lippincott, New York, NY.

Durmishidze, S.V., and N.P. Gumbaridze. 1972. Catechins and leucoanthocyanidins of quince fruit. Soobshch. Akad. Nauk. Gruz. Ssr. 67:449-451.

Guldner, A., and P. Winterhalter. 1991. Structures of two new ionone glycosides from quince fruit (*Cydonia oblonga* Mill.). J. Agric. Food Chem. 39:2142-2146.

Gumbaridze, N.P. 1972a. Chlorogenic acid from quince fruit. Soobshch. Akad. Nauk. Gruz. Ssr. 68:729-731.

Gumbaridze, N.P. 1972b. Flavonols of quince fruit. Soobshch. Akad. Nauk. Gruz. Ssr. 65:701-704.

Halsted, B.D. 1892. Some fungous diseases of the quince fruit. Bull. no. 91, New Jersey Agricultural College Experiment Station, New Brunswick, NJ.

Iocheva, E. 1979. Change of catechins in pome fruit during technological processing [quince]. Khranitelna promishlenost 28:33-35.

Jankowiak, J. 1976. Quince is a "new" old-fashioned fruit. Org. Gard. Farming 23(8):114-115.

Kader, A.A., ed. 1992. Postharvest Technology of Horticultural Crops, 2nd ed. DANR Pub. no. 3311, University of California, Oakland, CA.

Kornatskaia, N.M. 1981. Chemical-technological evaluation of some common quince varieties and hybrids fruit processing. Konservnaia I ovoshchesushil'naia promyshlennost' 2:28-29.

Kozenko, S.I., G.A. Kleshchunova, and A.N. Goren'kova. 1976. Amino acid composition of quince fruit and its change caused by canning. Konservn Ovoshchesushil Prom-St' 2:32-34.

Lobachev, A.I.A., and I.F. Gavrishova. 1982. Chemical composition and technological qualities of quince fruit under conditions of the lower Volga River area (varieties and hybrids, RSFSR-in-Europe). Trudy Po Prikladnoi Botanike, Genetike i Selektsii. 74:98-104.

Lutz, A., and P. Winterhalter. 1992a. Bio-oxidative cleavage of carotenoids: important route to physiological active plant constituents. Tetra. Lett. 33:5169-5172.

Lutz, A., and P. Winterhalter. 1992b. Isolation of additional carotenoid metabolites from quince fruit (*Cydonia oblonga* Mill.). J. Agric. Food Chem. 40:1116-1120.

Lutz, A., and P. Winterhalter. 1993. Abscisic alcohol glucoside in quince. Phytochem. 32:57-60.

Michelesi, J.C., J. Brossier, and J.D. Flick. 1973. Premieres observations sur plusieurs varietes de cognassiers a fruits [First observations on several quince fruit varieties]. Arboric. Fruit 233/234:36-38.

Muller, W., and A. Husistein. 1979. Quitte—eine zu beachtende obstart [Quince—a fruit species of interest]. Schweizerische Zeitschrift for Obst- und Weinbau 115(1):4-8.

Pierson, C.F., M.J. Ceponis, and L.P. McColloch. 1971. Market Diseases of Apples, Pears and Quinces. Agriculture Handbook 376, U.S. Department of Agriculture, Washington, DC.

Rozmyslova, A.G., and N.N. Papunov. 1977. Chemical characteristics of quince fruit. Sadovod Vinograd Vinodel Mold 4:55-56.

Sharova, N.I., and Illarionova, N.P. 1980. Value of quince fruit chemical composition, varieties. Sadocodstvo 12:39.

Shimizu, S., and S. Yoshihara. 1977. The constituents of the essential oil from Japanese quince fruit, *Cydonia oblonga* Miller. Agric. Biol. Chem. 41:1525-1527.

Strandzhev, A., M. Krusteva, and D. Kosturkova. 1978. Determination of pectin substances in quince and their transformations during cold storage. Khranitelna Promishlenost 27:26-27.

Tafradzhiiski, I., and T. Angelov. 1977. Study on the control of fruit rot of quince (caused by *Sclerotinia cydoniae*). Gradinar Lozar Nauka 14(6):16-21.

Tsuneya, T., M. Ishihara, H. Shiota, and M. Shiga. 1980. Isolation and identification of novel terpene lactones from quince fruit (*Cydonia oblonga* Mill., Marmelo). Agric. Biol. Chem. 44:957-958.

Tsuneya, T., M. Ishihara, H. Shiota, and M. Shiga. 1983. Volatile components of quince fruit (*Cydonia oblonga* Mill.). Agric. Biol. Chem. 47:2495-2502.

Umano, K., A. Shoji, Y. Hagi, and T. Shibamoto. 1986. Volatile constituents of peel of quince fruit, *Cydonia oblonga* Miller. J. Agric. Food Chem. 34:593-596.

Westwood, M.N. 1978. Fruit and nut species. *In* M.N. Westwood, ed., Temperate-Zone Pomology, pp. 41-76. W.H. Freeman, San Francisco, CA.

Williams, W.J. 1935. Cold storage of figs, raisins, persimmons, quinces, and tobacco. Ice Refrig. 89:367-368.

Radicchio

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Scientific Name and Introduction

Radicchio (*Cichorium intybus* L.) is a member of the Asteraceae (Compositae) family. Plants are characterized by variegate leaves (var. *silvestre* Bishoff) or red leaves (consequence of spontaneous crossings). Plant shape also differs among varieties, including long conical shape with tight red leaves, completely open with red or green-red leaves, or ball-shaped with red leaves. Head and leaves are crisp with a bittersweet flavor similar to Belgian endive and escarole. Some varieties—for example 'di Treviso' and 'Verona'—are held in the dark for 7 to 15 days at 10 to 15 °C (50 to 68 °F) after harvest to promote production of new, very tender leaves; this is called "whitening" (Pimpini 1990). Radicchio is available year-round from California, New Jersey, Mexico, and Italy.

Quality Characteristics and Criteria

Plants and leaves should be very turgid and crisp with bright white midribs. There should be no cracking, splitting, dark spots from mechanical damage, or necrosis on the leaf margins. Compactness is important but depends on the variety; for example, 'Treviso' and 'Chioggia' should have a compact head and very tight leaves, whereas 'Verona' and 'Castelfranco' should have an open, regularly shaped head. The root must be cleanly cut with no secondary roots or evidence of decay and cannot exceed 4 cm (1.5 in).

Horticultural Maturity Indices

Plants are hand-harvested when they reach appropriate size or when the center of the plant has formed a compact "grumolo" (Pimpini 1990). The same variety can be harvested very early (45 days), early (75 to 90 days), or late (120 to 150 days). Varieties that need whitening are harvested with their roots.

Grades, Sizes, and Packaging

There are no USDA grades. Head size is based on weight: 30 g (1 oz) for forced radicchio and 60 g (2 oz) for normal production. Extra fancy radicchio has the quality criteria given above. Fancy radicchio can have some light browning on leaves due to freezing or forcing treatment. Radicchio can be packed in trays with shrinkable plastic film or in corrugated containers with plastic liners to avoid water loss (Suslow and Cantwell 1999).

Precooling Conditions

Radicchio is usually placed directly in a cold room before shipping.

Optimum Storage Conditions

Radicchio can be stored for 20 to 30 days at 3 to 5 °C (37 to 41 °F) with 90% RH. Varieties that are whitened can only be stored 1 to 2 weeks under these conditions. Storage life is reduced to 11 days at 6 °C (43 °F) (Botondi et al. 1996), while storage at -2 to -3 °C (27 to 28 °F) can prolong storage to 3 mo by controlling decay (Bertolini and Pratella 1993).

Controlled Atmosphere (CA) Considerations

Good results were obtained with 3% O_2 and 5% CO_2. Low O_2 promotes internal browning (Suslow and Cantwell 1999), and high CO_2 controls decay (Foschi and Mari 1987).

Retail Outlet Display Considerations

Radicchio can be displayed in the same manner as lettuce. Water sprays are acceptable, but water remaining on the leaves at elevated temperatures promotes bacterial growth.

Chilling Sensitivity

Radicchio is not chilling sensitive. However, there have been reports of metabolic disorders after storage at 0 °C (32 °F) (Botondi et al. 1996).

Ethylene Production and Sensitivity

Radicchio produces very low amounts of ethylene: 0.1 to 0.3 µL kg^{-1} h^{-1} at 0 to 6 °C (32 to 43 °F) and 0.6 to 1.0 µL kg^{-1} h^{-1} at 20 °C (68 °F). Exposure to 10 µL L^{-1} ethylene for 6 days at 7.5 °C (46 °F) with 95% RH increased leaf browning, decay, and pigmentation of midribs (Botondi et al. 1996, Suslow and Cantwell 1999).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	6 to 10
6 °C	10 to 16
7.5 °C	23
25 °C	45

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Desiccation can lead to necrosis of the leaf margins. Wilting can occur after a few days of display if plants are not misted. Leaf abscission is common for some varieties, and reconditioning is often required. Rough handling during harvest or packing causes cracking of leaves or, in the case of abrasion, appearance of browning stains on the white midribs.

Postharvest Pathology

Radicchio is susceptible to bacterial soft rot caused by *Erwinia carotovora* at warmer temperatures and pectolytic *Pseudomonas* at lower temperatures. *Botrytis cinerea* can be frequent, even with good temperature control (Suslow and Cantwell 1999)

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

There is growing interest in fresh-cut lettuce-radicchio mixes.

References

Bertolini, P., and G. Pratella. 1993. Protezione postraccolta del radicchio. I Radicchi Veneti: 20 Anni di Esperienze Produttive e Commerciali, p. 39. ICE, Verona, Italy.

Botondi, R., R. Massantini, G. Anelli, and F. Mencarelli. 1996. Postharvest physiology of red cicory stored at 0° and 6°C. Ital. J. Food Sci. 4:273-282.

Foschi F., and M. Mari. 1987. Controlled atmosphere storage techniques of red chicory. *In* Proc. 17th International Congress on Refrigeration, vol. C, pp. 290-295. Vienna, Austria. International Institute of Refrigeration, Paris, France.

Pimpini, N. 1990. Il radicchio. *In* V.V. Bianco and F. Pimpini, eds., Orticoltura, pp. 320-338. Patron Press, Bologna, Italy.

Suslow, T., and M. Cantwell. 1999. Radicchio. Recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

Radish

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Scientific Name and Introduction

The radish, *Raphanus sativus*, is a member of the Cruciferae family, native to Europe or Asia. It was once grown on a small scale in all areas of the United States and also as a greenhouse vegetable. However, mechanization of harvesting and handling has resulted in more centralized production. The word “raphanus” comes from a Greek word meaning “quick-appearing” or “easily grown.”

The roots are of many shapes, sizes and colors—round, turnip-shaped, oval, olive-shaped, half-long, long. Colors include white, pink-red, purple, yellow, or even black. However, the most common radish is oval with a dark red skin and white flesh (Thompson and Kelly 1957, Maynard and Hochmuth 1997).

Quality Characteristics and Criteria

Radishes should be fresh, well-colored, tender, firm, crisp, smooth with no ridges, free from soil or other foreign material, and free from harvest cuts, abrasions, and insect damage. They should not be stringy or woody, soft, flabby, or wilted. Bunched radishes should have fully intact tops that are dark-green with no yellowing; they may be slightly wilted. Size varies depending on market demand, but larger roots are more likely to be pithy (Thompson and Kelly 1957, Carione and Lucas 1972, USDA 1975).

Horticultural Maturity Indices

Harvest maturity is based on size and market demand. The diameter of oval types should be between 2 and 3 cm (0.75 to 1.25 in). Bunched radishes are harvested in either regular or big bunch size, and roots for cello packages are pulled at regular or jumbo size (Nonnecke 1989).

Grades, Sizes, and Packaging

There are two USDA grades for topped and bunched radishes: U.S. No. 1 and U.S. Commercial. Bunched radishes have full-length tops tied in bunches, while topped radishes have clipped tops no more than 1 cm (0.38 in) long. Root diameter is termed Small, 1.9 cm (0.75 in); Medium, 1.9 to 2.5 cm (0.75 to 1.0 in); Large, 2.5 to 3.2 cm (1 to 1.25 in); and Very Large, 3.2 cm (>1.25 in). U.S. No.1 roots have similar varietal characteristics and are clean, well formed, smooth, firm, and tender. They are also free from decay, cuts, pithiness, disease, and damage caused by freezing, growth cracks, insects, or other means. Bunched radishes have tops that are fresh and free from decay and damage caused by freezing, seed stem, yellowing or other discoloration, diseases, insects, or other means. In order to allow for variation in grading and handling, a 5 to 10% variation by count is acceptable tolerance for a U.S. No. 1 grade product. If the variation is >10% but <20%, they are designated U.S. Commercial (AMS 1968, Maynard and Hochmuth 1997).

Radishes are available in many sizes of container. Topped radishes are packed in perforated plastic bags holding 168 g (6 oz), 224 g (8 oz), 454 g (1 lb), 2.3 kg (5 lb), 11 kg (25 lb), or 18 kg (40 lb). Commonly, 30 168-g (6-oz), 24 224-g (8-oz), or 14 454-g (1-lb) bags are boxed together for retail, while 11-kg (25-lb) bags are used for the foodservice industry (L. Buurma, 1999, personal communication).

Radishes are first graded according to diameter to eliminate spikes that are <1.9 cm (0.75 in) and to accumulate Jumbos that are >3.8 cm (1.25 in). The radishes are then conveyed over grading tables to remove products below acceptable grade standards. After being graded, they are packaged in cellos using vertical form fill machines. These machines form the breathable poly bag, weigh the specific amount of desired radishes, and seal the bag or provide a zipper locking system. These bags are then hand-packed into wax cartons and temporarily stored at 2 °C (36 °F) until shipment.

Precooling Conditions

Hydrocooling at 0 to 4.5 °C (32 to 40 °F) is the preferred method. Cello packs are hydrocooled to restore crispness, bulk stored in bins, and then placed in refrigerated coolers before grading. Bunched radishes are dipped in chlorinated water at 2 °C (26 °F) to restore crispness and freshness to the tops and roots, as well as to remove field debris. They are then packed into cartons, usually 24 bunches per carton, and hydrocooled; and the carton is topped with an ice slurry before shipping (Brooker and Pearson 1970, Ryall and Lipton 1972a).

Optimum Storage Conditions

Topped radishes can be held 3 to 4 weeks at 0 °C (32 °F) with 90 to 95% RH and at least 7 days at 7 °C (45 °F). Bunch radishes are harder to keep fresh due to the perishability of the tops. However, they can be held at 0 °C (32 °F) and 90 to 95% RH for 1 to 2 weeks. Winter or black radishes can be stored under the same conditions for 2 to 4 mo. Addition of top ice aids in keeping the tops fresh (Ryall and Lipton 1972b).

Controlled Atmosphere (CA) Conditions

An atmosphere of 1 to 2% O_2 and 2 to 3% CO_2 at 0 to 5 °C (32 to 41 °F) slightly extends storage life (Ryall and Lipton 1972a, Saltveit 1997).

Retail Outlet Display Considerations

Packaged radishes should be placed in a refrigerated rack. Bunch radishes should be refrigerated and can be iced or misted to help preserve quality.

Chilling Sensitivity

Radishes are not sensitive to chilling. Store them as cold as possible without freezing.

Ethylene Production and Sensitivity

Radishes produce small amounts of ethylene and are not particularly sensitive to ethylene exposure.

Respiration Rates

Temperature	Topped Roots	Bunched Roots with Tops
°C	-----------mg CO_2	kg^{-1} h^{-1}-----------
0	14 to 17	3 to 9
4 to 5	19 to 21	6 to 13
10	31 to 36	15 to 16
15 to 16	70 to 78	22 to 42
20 to 21	124 to 136	44 to 58
25 to 27	158 to 193	60 to 89

Data from Hardenburg et al. (1986).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Freezing injury can cause softening and shriveling, as well as leakage of pigment for red radishes. Growth cracks or air cracks reduce quality when they are >6 mm (0.25 in) deep and associated with discolored tissue. Overmaturity or stress during growth can induce dry, cottony voids, called pithiness, in roots. Yellowing of tops can result from overmaturity, exposure to ethylene, or elevated storage temperature (Murry 1977, Nonnecke 1989).

Postharvest Pathology

The initial lesions of bacterial black spot *(Xanthomonas vesicatoria)* are brown and have a diameter of 1.0 to 2.5 mm (0.04 to 0.1 in). They eventually turn black and coalesce. Protective measures include washing in water with 100 to 200 µL L^{-1} of chlorine. Downy mildew *(Peronospora parasitica)* produces purplish-red to brown surface lesions that become rough and cracked in advanced cases, while the internal tissue can become grayish brown to black. Rhizoctonia root rot *(Rhizoctonia solani)* produces lesions that are initially round and light brown and can become slightly sunken. The tissue can become spongy. This disease favors high RH. Avoid bruising, hydrocool to 4 °C (40 °F), and store at 0 to 2 °C (32 to 35 °F) to control these diseases (Ryall and Lipton 1972a).

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Currently radishes are cut or diced in packaged salad mixes and for food service, particularly for incorporation into salad bars.

References

AMS [USDA Agricultural Marketing Service]. 1968. United States standards for grades of radishes. *At* http://www.ams.usda.gov/AMSv1.0/standards.

Brooker, J., and J. L. Pearson. 1970. Planning data for marketing selected fruits and vegetables in the south, part III, Fresh Vegetable Packing Handbook. Southern Cooperative Ser. Bull. 152, Southern Association of Agricultural Experiment Station Directors, Raleigh, NC.

Carcione, J., and B. Lucas. 1972. The Greengrocer: The Consumer's Guide to Fruits and Vegetables. Chronicle Books, San Francisco, CA.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agricultural Handbook 66, U.S. Department of Agriculture, Washington, DC.

Maynard, D.N., and G.J. Hochmuth 1997. Knott's Handbook for Vegetable Growers, 4th ed. Wiley, New York, NY.

Nonnecke, I.L. 1989. Vegetable Production/Radish, pp. 339-346. Van Nostrand Reinhold, New York, NY.

Murry J. 1977. Fruit and vegetable facts and pointers (radish). United Fresh Fruit and Vegetable Association, Washington, DC.

Ryall, A.L., and W.J. Lipton. 1972a. Handling, Transportation, and Storage of Fruits and Vegetables, vol. 1. AVI, Westport, CT.

Ryall, A.L., and W.J. Lipton. 1972b. Longer storage-life for radishes. Agric. Res., vol. 20, no. 7.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 4, pp. 98-117. University of California, Davis, CA.

Thompson, H.C., and W.C. Kelly. 1957. Vegetable Crops. McGraw-Hill, New York, NY.

USDA [U.S. Department of Agriculture]. 1975. How To Buy Food for Economy and Quality: Recommendations of the United States Department of Agriculture. Dover, New York, NY.

Rambutan

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Scientific Name and Introduction

Rambutan fruit (*Nephelium lappacium* L.) are large ovoid or globose fruit about 4.5 cm (1.8 in) long and 2.5 to 3.7 cm (1 to 1.5 in) wide that grow on woody stalks in clusters of 10 to 18. The outer skin is 2 to 4 mm (0.1 to 0.2 in) thick and covered with soft, long spines (spinterns) that turn red or yellow when ripe. The edible aril flesh is attached to a single, large seed. The fruit is related to litchi and longan (Nakasone and Paull 1998).

Quality Characteristics and Criteria

Quality criteria include fruit size, shape, and weight; bright skin and spine color; uniformity; absence of defects; and freedom from disease and insects. High SSC and low TA are desirable (Ketsa and Klaewkasetkorn 1992). Mechanical injury and dehydration are major causes of appearance loss.

Horticultural Maturity Indices

Skin and spine coloration is the main horticultural maturity index. Fruit having green skin and greenish-red spines are sour. Ripe fruit have both skin and spines red or yellow, depending on the variety. Between these two stages, sugar content increases about 20% and acid level decreases by half (Mendoza et al. 1982). The acceptable stage is 16 to 28 days after color break, at which time skin and spines are brightly colored (O'Hare 1992). Over-ripe fruit have a watery texture (Somboon 1984) which may be a senescence-induced tissue breakdown.

Grades, Sizes, and Packaging

There are no U.S. or International grade standards. Fruit are sold in 2.25-kg (5-lb) and 4.5-kg (10-lb) one-piece fiberboard cartons. Sometimes fruit are prepacked in punnets. In Southeast Asia, clusters of fruit are sold in bunches still attached to the stem.

Precooling Conditions

Only room-cooling is recommended.

Optimum Storage Conditions

Store at 8 to 15 °C (46 to 59 °F) with 90 to 95% RH to achieve a storage life of 14 to 16 days. There may be changes in the skin and spine coloration after storage, but the flesh is unaffected. Temperature recommendations vary for different cultivars (O'Hare 1992). Fruit held at 20 °C (68 °F) with 60% RH last about 3 to 5 days.

Controlled Atmosphere (CA) Considerations

CA of 7 to 12% CO_2 and 3 to 5% O_2 at 10 °C (50 °F) is recommended (Kader 1993). At 9 to 12% CO_2, color loss is reduced and shelf-life extended by 4 to 5 days, while low O_2 (3%) has little effect (O'Hare et al. 1994, O'Hare 1995). Raising CO_2 levels above 12% has no additional effect, and decay can begin after a few weeks' storage. The MA/CA effect appears to derive more from CO_2 elevation and minimizing water loss than through any effect of low O_2. Storage in sealed polyethylene film bags or plastic containers is effective in reducing water loss (Mendoza et al. 1972, Mohamed and Othman 1988, Ketsa and Klaewkasetkorn 1995), while wax coatings are less effective (Mendoza et al. 1972, Lam and Ng 1982, Brown and Wilson 1988). A shelf-life of 14 to 21 days can be expected.

Retail Outlet Display Considerations

Rambutan should be displayed in trays with a clear film overwrap or in clam shell containers with no perforations at 10 to 12 °C (50 to 55 °F). Fruit should not be misted or iced.

Chilling Sensitivity

If maintained at 5 °C (41 °F), fruit can be stored for up to 3 weeks, but the skin and spines change from red to brownish-red; the edible aril is white and remains in good condition (Lam and Ng 1982). Somboon (1984) reported that after 3 days at 5 °C (41 °F), the aril turned from white (translucent) to being more transparent and juicier.

Ethylene Production and Sensitivity

This nonclimacteric fruit has a very low rate of ethylene production: <0.04 $\mu L\ kg^{-1}\ h^{-1}$ (O'Hare et al. 1994). Higher rates of up to 3 $\mu L\ kg^{-1}\ h^{-1}$ can occur if there is a fungal infection. The presence of 5 $\mu L\ L^{-1}$ ethylene in CA (9 to 12% CO_2) or the presence of an ethylene absorber does not influence rate of skin color loss (O'Hare 1995).

Respiration Rates

Respiration is 40 to 100 mg (about 23 to 57 µL) $CO_2\ kg^{-1}\ h^{-1}$ at 25 ºC (77 ºF). This is a nonclimacteric fruit and the rates are for mature fruit; immature fruit respiration rates are higher (Mendoza et al. 1972). To calculate heat production, multiply mg $kg^{-1}\ h^{-1}$ by 220 to get BTU $ton^{-1}\ day^{-1}$ or by 61 to get kcal $tonne^{-1}\ day^{-1}$.

Physiological Disorders

Chilling injury and darkening of spines and skin are major postharvest disorders. Darkening is caused by dehydration and mechanical injury (Landrigan et al. 1996). Preharvest disorders include skin splitting and poor filling of fruit (O'Hare 1992). Skin splitting occurs in thin-skinned cultivars often following heavy rains during the last phase of fruit growth. Poor filling has been associated with poor nutrition and dry conditions just after flowering.

Postharvest Pathology

Postharvest losses to disease are low (Ketsa and Klaewkasetkorn 1992), though stem end rot and fruit rots are found. Sangchote et al. (1992) found that the spectrum of fungi associated with rambutan decay varied with storage temperatures. *Collectotrichum gloeosporioides* and *Botryodiplodia theobromae* are considered the most serious pathogens. Other pathogens recorded include *Pestalotiopsis* spp. and *Phomopsis* spp. (Farungasang et al. 1991).

Quarantine Issues

Rambutan is a fruit fly host, and the available treatments are irradiation and heat treatment. Heat treatment leads to rapid loss of skin color. Mealy bugs are often found on the fruit, but they do not damage the flesh (Ketsa and Klaewkasetkorn 1992).

Suitability as Fresh-Cut Product

Suitability is limited, since it is difficult to separate aril and seed.

References

Brown, B.I., and P.R. Wilson. 1988. Exploratory study of postharvest treatments on rambutan (*Nephelium lappaceum*) 1986/1987 season. Rare Fruit Counc. Austral. Newsletter 48:16-18.

Farungsang, U., N. Farungsang, and S. Sangchote. 1991. Postharvest diseases of rambutan during storage at 13 or 25 °C. *In* 8th Australasian Plant Pathology Society Conference, 7-11 October, 1991, Sydney, Australia. Sydney University, Sydney, Australia.

Kader, A.A. 1993. Modified and controlled atmosphere storage of tropical fruits. *In* B.R. Champ, E. Highley and G.I. Johnson, eds., Proceedings of the International Conference on Postharvest Handling of Tropical Fruits, Chiang Mai, Thailand, July 1993, pp. 239-249. ACIAR Pub. no. 50. Australian Centre for International Agricultural Research, Canberra, Australia.

Ketsa, S., and O. Klaewkasetkorn. 1992. Postharvest quality and losses of 'Rongrein' rambutan fruits in wholesale markets. Acta Hort. 321:771-777.

Ketsa, S., and O. Klaewkasetkoan. 1995. Effect of modified atmosphere on chilling injury and storage-life of rambutan. Acta Hort. 398:223-231.

Lam, P.F., and K.H. Ng. 1982. Storage of waxed and unwaxed rambutan in perforated and sealed polyethylene bags. Report no. 251, Malaysian Agricultural Research and Development Institute, Food Technology Division, Selangor, Malaysia.

Landrigan, M., S.C. Morris, D. Eamus, and W.B. McGlasson. 1996. Postharvest water relationships and tissue browning of rambutan fruits. Sci. Hort. 66:201-208.

Mendoza, D.B., E.B. Pantastico, and F.B. Javier. 1972. Storage and handling of rambutan (*Nephelium lappaceum* L.). The Philippines Agriculturist 55:322-332.

Mendoza, D.B., P.T. Ramos, G.R. del Mundo, et al. 1982. Maturity and ripening guide for rambutan cultivars. Tech. Bull. 5. ASEAN-PHTRC, University of the Philippines, Los Banos, Philippines.

Mohamed, S., and E. Othman. 1988. Effect of packaging and modified atmosphere on the shelf life of rambutan *(Nephelium lappaceum).* Pertanika 11:217-228.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K.

O'Hare, T.J. 1992. Rambutan: postharvest physiology and storage. Trop. Fruit News 26:4-6.

O'Hare, T.J. 1995. Postharvest physiology and storage of rambutan. Postharv. Biol. Technol. 6:189-199.

O'Hare, T.J., A. Prasad, and A.W. Cooke. 1994. Low temperature and controlled atmosphere storage of rambutan. Postharv. Biol. Technol. 4:147-157.

Sangchote, S.,U. Farungsang, and N. Farungsang. 1992. Rambutan diseases. *In* G.I. Johnson and E. Highley, eds., Proceedings of the Workshop on Development of Postharvest Handling Technology for Tropical Tree Fruits, July 1992, Bangkok, Thailand, p. 51-59. Australian Center for International Agricultural Research, Canberra, Australia.

Somboon, Y. 1984. Effect of Temperature and Maturity Stages on Biochemical Changes During Storage of Rambutan (*Nephelium lappaceum* Linn.) cv. Seechompoo and cv. Rongrien. M.S. thesis. Kasetsart University, Bangkok, Thailand.

Raspberry

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Scientific Name and Introduction

Raspberries (*Rubus ideaus* L.) are a member of the Rosaceae family, grown as a perennial crop. Raspberries are available commercially in red, yellow, purple, and black forms. The red or yellow raspberry is classified into two subspecies: *R. idaeus* subsp. *vulgatus* Arrhen. (European red raspberry) and *R. idaeus* subsp. *strigosus* Michx. (American red raspberry). Black raspberries found in eastern North America are *R. occidentalis* L.; *R. glaucus* L. is a South American tetraploid black raspberry. Purple raspberries (*R. neglectus* Peck.) result from crosses of black and red raspberries.

All commercially important raspberry species are prized for their unique and delicate fruit flavor and are often used in fresh desserts. The berries are compound fruits, made up of many drupelets and a hollow center where the fruit detaches from the receptacle. Berries are soft, juicy, and have a distinct aroma. Important cultivars include 'Meeker,' 'Heritage,' 'Tulameen,' 'Willamette,' 'Chilliwack,' and 'Munger.'

Quality Characteristics and Criteria

High-quality raspberries are free of injury, decay, and sunscald; are uniformly colored; and appear turgid.

Horticultural Maturity Indices

For fresh market, raspberries are best harvested when bright red (red raspberries) or fully colored (black, purple, or yellow raspberries). Berries should pull or shake easily from the receptacle yet be firm, not mushy. Color development after harvest is highly cultivar-dependent; 'Heritage' berries turn purple-red quickly while 'Nova' retain a full red color. Cultivars known to change color rapidly are sometimes picked when pink, though acid levels are higher and flavor low or lacking at this color stage.

Grades, Sizes, and Packaging

Raspberries are graded as U.S. No. 1 or No. 2 based on freedom from mold, decay, sunscald, over-ripeness, and injury. A limit of 1% of berries for mold and 10% total for defects separates No. 1 grade from No. 2. No. 2 fruit can have no more than 2% berries with decay. Trays holding 12 half pints (125 g), usually vented plastic clamshell containers, are the standard package. No minimum berry size is required.

Precooling Conditions

Raspberries should be forced-air cooled to 1 °C (34 ºF) within 12 h of harvest (Moore and Robbins 1992).

Optimum Storage Conditions

Raspberries should be held no more than 2 to 5 days, depending on cultivar, at -0.5 to 0 ºC (31 to 32 ºF) with >90% RH.

Controlled Atmosphere (CA) Considerations

Raspberries benefit from 10 to 20% CO_2 and 5 to 10% O_2 (Kader 1997). CA storage slows respiration, ethylene production, softening, color change, and growth of molds. Levels of CO_2 >20% can cause discoloration, softening, and off flavor (Agar and Streif 1996).

Retail Outlet Display Conditions

Raspberries should be stored and displayed at the coldest refrigeration temperature possible without freezing. As little as 1 day at 20 °C (68 °F) can result in growth of gray mold (*Botrytis cinerea* Pers.).

Chilling Sensitivity

Raspberries are not known to be chilling sensitive.

Ethylene Production and Sensitivity

The presence of ethylene can stimulate growth of *Botrytis cinerea* (gray mold) on raspberries; also, color can be adversely affected, darkening to a purple-red in red raspberries. Ethylene production is cultivar-dependent, from 1 to 12 µL kg^{-1} h^{-1} at 20 °C (68 °F) (Burdon and Sexton 1990, Perkins-Veazie and Nonnecke 1992).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
2 °C	16 to 18
4 to 5 °C	18 to 27
10 °C	31 to 39
15 to 16 °C	28 to 55
20 to 21 °C	74 to 175

Data from Haller et al. (1941), Perkins-Veazie and Nonnecke (1992), and Perkins-Veazie (unpublished).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Shriveling (water loss), leakers (berries with leakage of juice), and UV damage (white drupelets) are the primary disorders found in raspberries.

Postharvest Pathology

The most common postharvest diseases are gray mold (*Botrytis cinerea* Pers.) and rhizopus rot (*Rhizopus stolonifer* Ehrenb.:Fr.) (Ellis et al. 1991).

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Raspberries are incorporated into mixed fruit cups.

Special Considerations

Raspberries damage easily; they are one of the most fragile and perishable of all fruits.

Acknowledgments

Some information in this chapter is from the University of California, Davis, website on “Produce Facts” at http://postharvest.ucdavis.edu/produce_information.

References

Agar, I.T., and J. Streif. 1996. Effect of high CO_2 and controlled atmosphere (CA) storage on the fruit quality of raspberry. Gartenbauwissenschaft 61:261-267.

Burdon, J.N., and R. Sexton. 1990. Fruit abscission and ethylene production in red raspberry cultivars. Sci. Hort. 43:95-102.

Ellis, M.A., R.H. Converse, R.N. Williams, and B. Williamson, eds. 1991. Compendium of Raspberry and Blackberry Diseases and Insects. APS, St. Paul, MN.

Haller, M.H., D.H. Rose, and P.L. Harding. 1941. Studies on the respiration of strawberry and raspberry fruits. Circular 613, U.S. Department of Agriculture, Washington, DC.

Kader, A.A. 1997. A summary of CA requirements and recommendations for fruits other than apples and pears. *In* A.A. Kader, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 3, pp. 1-34. University of California, Davis CA.

Moore, P. P., and J. Robbins. 1992. Fruit quality of stored, fresh red raspberries after a delay in Precooling. HortTechnology 2:468-470.

Perkins-Veazie, P., and G. Nonnecke. 1992. Physiological changes during ripening of raspberry fruit. HortScience 27:331-333.

Rhubarb

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Scientific Name and Introduction

Rhubarb, or "pie plant," (*Rheum rhabarbarum* L.) is a perennial of the Polygonaceae family. Fleshy petioles are the edible portion. Petioles may be green, pink, or white depending on the variety. Field production in North America is mainly in Washington, Oregon, Michigan, and Ontario. Rhubarb is forced in heated structures in Washington, Michigan, and Ontario. Fresh rhubarb is mostly available in late winter through spring (Foust and Marshall 1991), but limited supplies are available at other times.

Quality Characteristics and Criteria

Petiole color is associated with quality. The order of preference is red, pink, and green. Petioles should appear fresh with no signs of desiccation or decay whether presented for sale intact or cut into sections.

Grades, Sizes, and Packaging

U.S. grades for field-grown rhubarb include U.S. Fancy, U.S. No. 1, U.S. No. 2, and Unclassified (USDA 1966). Grade is based primarily on petiole color, frequency of defects, and appearance. State and provincial grades have been developed for forced rhubarb. For example, Washington rhubarb is marketed as Fancy and Extra Fancy (McGregor 1987), while Michigan rhubarb is classed as Choice, Small Fancy, or Fancy (Pennell 1976). Rhubarb is packed in 4.5-, 6.8-, or 9.0-kg (10-, 15-, or 20-lb) cartons (Anon 1995).

Precooling Conditions

Rhubarb petioles should be precooled to 0 °C (32 °F) by hydrocooling or forced-air cooling (McGregor 1987).

Optimum Storage Conditions

Rhubarb petioles can be stored for 2 to 4 weeks at 0 °C (32 °F) with 95 to 100% RH (McGregor 1987).

Controlled Atmosphere Considerations

CA storage has not yet been used for rhubarb.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	9 to 13
5 °C	11 to 18
10 °C	25
15 °C	31 to 48
20 °C	40 to 57

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal tonne^{-1} day^{-1}.

Physiological Disorders

Petioles lacking small leaf lamina are subject to splitting when exposed to moisture. Overmature petioles become pithy. Abrasion of petioles by sand or rough handling adversely affects appearance.

Postharvest Pathology

Several diseases may cause postharvest losses of rhubarb (Snowdon 1992). Anthracnose *(Colletotrichum erumpens)* causes oval, soft, watery lesions on petioles. Bacterial soft rot *(Pseudomonas marginalis*, *Erwinia caratovra)* causes a soft, slimy decay. Gray mold *(Botrytis cinerea)* causes soft, brown lesions on petioles. Postharvest decay is usually traced to poor sanitation of hydrocooling water, so proper sanitation with recommended storage temperature is essential to avoid infection.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Suitability has not been evaluated.

References

Anonymous. 1995. Packer Sourcebook. Vance, Lenexa, KS

Faust, C.M., and D.E. Marshall. 1991. Culinary rhubarb production in North America: history and recent statistics. HortScience 26:1360-1363.

McGregor, B.M. 1987. Tropical Products Transport Handbook. Agriculture Handbook 668, U.S. Department of Agriculture, Washington, DC.

Pennell, J.T. 1976. Rhubarb production. Leaflet 555, U.S. Department of Agriculture, Washington, DC.

Snowdon, A.L. 1992. Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables. CRC Press, Boca Raton, FL.

AMS [USDA Agricultural Marketing Service]. 1966. United States standards for grades of rhubarb (field grown). U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC.

Rutabaga

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Scientific Name and Introduction

Rutabaga (*Brassica napus* L.; Napobrassica group), also referred to as swedes, Swedish turnips, and turnip-rooted cabbage, is a member of the Cruciferae. The edible portion is the large, usually yellow-fleshed storage root. The three main commercial varieties of rutabagas include 'American Purple Top,' 'Laurentian,' and the 'Thomson strain' of 'Laurentian.' Rutabaga is a cool-season vegetable that withstands frost and mild freezing. In North America, rutabaga is primarily grown in Canada, California, Colorado, Wisconsin, and Minnesota.

Quality Characteristics and Criteria

A high-quality rutabaga is a well-shaped, purple-topped root having a smooth, small neck and a well-defined taproot with a minimum of side roots. It is free of blemishes and bruises. The root should be firm, fresh looking, sweet and not bitter, and heavy for its size. Lightweight rutabagas may be "woody" (Gardner and Nonnecke 1987).

Horticultural Maturity Indices

Rutabagas should be harvested when fully mature, since immature rutabagas can have a bitter taste. Good quality rutabagas are harvested at maximum sugar accumulation. Winter crops should be harvested before weather becomes hot or roots will become pithy and woody. Harvesting fall crops after the first frost can sweeten flavor (Suzuchi and Cutcliffe 1981).

Grades, Sizes, and Packaging

Grades include U.S. No. 1 and U.S. No. 2, based on subjective external appearance. Sizes are defined as Small, diameter of 5.1 to10.2 cm (2 to 4 in); Small-Medium, 8.9 to 14 cm (3.5 to 5.5 in); Medium, 10.2 to 15.2 cm (4 to 6 in); and Large, 13 to 17.8 cm (5 to 7 in). Common packaging is 23-kg (50-lb) bushel cartons or bags (about 20 roots) and 11-kg (25-lb) 0.5-bushel cartons (about 10 roots).

Precooling Conditions

Roots should be cooled as quickly as possible in order to avoid excessive moisture loss. Brown surface discoloration called "storage burn" can be largely controlled by rapid cooling at 0 °C (32 °F) together with adequate air circulation (Franklin and Lougheed 1975). If harvested when the soil or air is above 25 °C (77 °F), rutabagas should be cooled within 3 to 4 h to avoid loss of quality during storage. Room-cooling is most commonly used; however, forced-air cooling, hydrocooling, and package-icing can also be used to retard development of skin discoloration, weight loss, and decay.

Optimum Storage Conditions

Rutabagas can be kept for 4 to 6 mo at 0 °C (32 °F) with 98 to 100% RH (van den Berg and Lentz 1973). They should be stored unwrapped, in a cool, moist, dark area with good ventilation. If held 6 mo at 2 °C (36 °F) with 95% RH or 5 °C (41 °F) with 90% RH, weight loss can be as high as 6 and 11%, respectively (Cutcliffe and Anderson 1989). Rutabagas for immediate marketing are often waxed to enhance appearance and protect against excessive moisture loss. Waxed roots will keep well under refrigerated conditions for 1 to 2 mo. Roots for long-term storage should not be waxed, since wax coatings become unsightly during storage and may impede gas exchange.

Controlled Atmosphere (CA) Considerations

There are no indications that rutabagas stored in CA have superior quality or longer shelf-life than roots stored at normal atmosphere at 0 °C (32 °F) with high RH (Tomkins 1959, Franklin and Lougheed 1975). Furthermore, CO_2 >8% is injurious to rutabagas.

Retail Outlet Display Considerations

Rutabagas should be held in a refrigerated display. Use of top ice is accepted; misting is not recommended.

Chilling Sensitivity

Rutabagas are not sensitive to chilling and should be stored as cold as possible. They can stand slight freezing without injury.

Ethylene Production and Sensitivity

Rutabagas produce very low amounts of ethylene: <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F). Exposure to ethylene is not an important factor.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	4 to 6
5 °C	8 to 12
10 °C	9.5 to 19
15 °C	20 to 31
20 °C	34 to 40

Data from International Institute of Refrigeration (1967).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Rutabagas freeze at about -1 °C (30 °F), and freezing may be initiated at -0.5 °C (31 °F). Symptoms include small, water-soaked spots on the surface and light browning of the flesh. Injured tissue appears tan or gray and gives off a fermented odor.

Brown heart or water-core of rutabagas is caused by boron deficiency. Stored roots with brown heart may suffer tissue breakdown and moisture loss, becoming spongy. They may also develop brown spots and cracks (Ryall and Lipton 1983).

Postharvest Pathology

Rot diseases are promoted by storage at higher-than-recommended temperatures. Brown soft rot caused by *Botrytis cinerea* is a major pathogen. Mold growth typically begins at sites of tissue damage and then spreads to adjacent roots, creating a dense surface growth of mycelium and conidia. Black rot caused by *Phoma lingam* causes restricted dry, corky, dark brown or blackish lesions with a sparse superficial growth of white mycelia. *Phoma* lesions can occur both at cut surfaces, where discoloration frequently spread into the vascular tissue, and as small craters on undamaged skin (Geeson et al. 1989). Bacterial soft rot caused by *Erwinia carotovora* has also been associated with postharvest deterioration of roots during storage (Shattuck and Proudfoot 1990).

Quarantine Issues

Rutabagas must be completely free of soil because many plant pests are soil-borne. A permit to import rutabagas into Canada is required for areas of New York State (because of the possible presence of golden nematode, *Heterodera rostochiensis*), off-continent United States, and all other countries.

Suitability as Fresh-Cut Product

Rutabagas are good candidates for sale in consumer-size packages. Prepeeled rutabagas packaged in consumer film bags keep in good condition for 3 weeks at 0 °C (32 °F). Fresh-cut rutabagas stored in 15% O_2 will keep for 10 days at 10 °C (50 °F) and 20 days at 1 °C (34 °F). Fermentation may occur at lower O_2 levels (Alexander and Francis 1964). Storage of cubed, shredded, or peeled rutabaga in 5% O_2 and 5% CO_2 at 0 to 5 °C (32 to 41 °F) reduces respiration rate and has a moderate potential (Gorny 1997).

Special Considerations

Strong odors may be transferred to fruits and leafy vegetables if they are held in the same storage area with rutabagas.

Acknowledgments

Some of the information in this chapter is from the Agriculture Canada, Canadian Food Inspection Agency website at http://www.cfia-acia.agr.ca; the USDA-Animal and Plant Health Inspection Service, Plant Protection and Quarantine website at http://www.aphis.usda.gov/plant_health/index; and the USDA-Agricultural Marketing Service website at http://www.ams.usda.gov/AMSv1.0/standards.

References

Alexander, B., and F.J. Francis. 1964. Packaging and storage of pre-peeled rutabagas. Proc. Amer. Soc. Hort. Sci. 85:457-464.

Cutcliffe, J.A., and J.B. Anderson. 1989. Effects of added nitrogen and potassium on yield and storability of rutabagas. Can. J. Plant Sci. 69:1359-1363.

Franklin, E.W., and E.C. Lougheed. 1975. Storing rutabagas. Factsheet 75-068, AGDEX 258/64, Ministry of Agriculture and Food Ontario, Guelph, Ontario, Canada.

Gardner, J., and I.L. Nonnecke. 1987. Rutabagas (table turnips). Factsheet 87-032, AGDEX 258/20, Ministry of Agriculture and Food Ontario, Guelph, Ontario, Canada.

Geeson, J.D., K.M. Browne, and H.P. Everson. 1989. Long-term refrigerated storage of swedes. J. Hort. Sci. 64(4):479-483.

Gorny, J.R. 1997. A summary of CA and MA requirements and recommendations for fresh-cut (minimally processed) fruits and vegetables. *In* J.F. Gorny, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 5, pp. 30-66. University of California, Davis, CA.

International Institute of Refrigeration. 1967. Recommended conditions for cold storage of perishable produce, 2nd ed. International Institute of Refrigeration, Paris, France.

Ryall, A.L., and W.J. Lipton. 1983. Handling, Transportation, and Storage of Fruits and Vegetables, 2nd ed., vol. 1. AVI, Westport, CT.

Shattuck, V.I., and K.G. Proudfoot. 1990. Rutabaga breeding. Plant Breeding Rev. 8:217-248.

Suzuki, M., and J.A. Cutcliffe. 1981. Sugars and eating quality of rutabagas. Can. J. Plant Sci. 61:167-169.

Tomkins, R.G. 1959. The biological effects of sealed plastic containers by prepacked fresh fruit and vegetables. International Institute of Refrigeration Bull. 40, annex 3. International Institute of Refrigeration, Paris, France.

van den Berg, L., and C.P. Lentz. 1973. High humidity storage of carrots, parsnips, rutabagas, and cabbage. J. Amer. Soc. Hort. Sci. 98:129-132.

Salad Greens

Kimberly P. Wright

Wright is with Dole Fresh Vegetables, Salinas, CA.

Scientific Names and Introduction

Various greens other than lettuce are used in raw salads. These include corn salad; lamb's lettuce; field salad; mâche *(Valerianella locusta* [L.] Latterrade em. Betcke *[V. olitoria]);* dandelion (*Taraxacum officinale* Wiggers); French or round sorrel *(Rumex scutatus)*; garden sorrel (*R. acetosa* L.); miner's lettuce; winter purslane; claytonia *(Montia perfoliata [Claytonia perfoliata]);* mizuna (*Brassica rapa* L. subsp. *japonica* group Japonica); purslane (*Portulaca oleracea* L.); and rocket salad, roquette, arugula, rucola, or rugula (*Eruca vesicaria* [L.] Cav. subsp. *sativa* [Mill.] Thell). Young leaves are generally used.

Quality Characteristics and Criteria

Greens used in raw salads must be fresh, tender, and turgid with no yellowing, decay, or insect or mechanical damage. Whole plants of rocket and lamb's lettuce are sometimes sold with roots attached, which lengthens postharvest life.

Horticultural Maturity Indices

Greens are harvested as individual leaves, leaf clusters, or whole plants and should be young, tender, and mild flavored. Plants that have flowered are usually too strong in flavor and tough in texture for use in raw salads.

Grades, Sizes, and Packaging

These crops are not graded or sized in the United States. Salad greens may be packed in fiberboard cartons lined with perforated polyethylene bags or in small sealed plastic bags, trays, or clamshell containers. These greens may also be packed as bunches of leaves or plants (Rubatzky and Yamaguchi 1997, Péron and Rees 1998).

Precooling Conditions

Greens for salads should be cooled to 0 °C (32 °F) as soon as possible after harvest. Vacuum-cooling is effective for removing field heat.

Optimum Storage Conditions

Salad greens should be stored at 0 to 2 °C (32 to 36 °F) with 95 to 100% RH. Rocket salad typically lasts 7 to 10 days and other leafy greens 10 to 14 days (Cantwell 1997). Top icing can be used.

Controlled Atmosphere (CA) Considerations

CA is generally not beneficial. MAP is mostly beneficial for controlling RH. However, lamb's lettuce retains acceptable quality after 28 days in sealed plastic bags with reduced O_2 and elevated CO_2 at <4 °C (39 °F) (de Leiris 1987). MAP reduces yellowing and decay of sorrel (Aharoni et al. 1993).

Retail Outlet Display Considerations

Use of water sprinklers is acceptable. Leafy greens are highly susceptible to water loss and wilting.

Chilling Sensitivity

Salad greens are not sensitive to chilling and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Salad greens have very low ethylene production but are highly sensitive to ethylene exposure (Cantwell 1997), which typically results in loss of chlorophyll leading to yellowing of leaves.

Respiration Rates

Temperature	Rocket salad	Lamb's lettuce
	----------mg CO_2 kg^{-1} h^{-1}----------	
0 °C	42	12
5 °C	113	-
7 °C	-	67
10 °C	-	81
20 °C	-	139

Data from Cantwell and Reid (1993), Cantwell (1997), Peiris et al. (1997), Rubatzky and Yamaguchi (1997), and Piergiovanni et al. (1999).

Respiration rates for other greens are not reported, but would be expected to be similar.

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day 1 or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Because of the delicate texture of the leaves, greens are highly susceptible to mechanical damage, which may result in discoloration and decay.

Postharvest Pathology

Low temperatures must be maintained throughout the cold chain to minimize pathological disorders and prolong shelf-life. Salad greens are typically susceptible to the same bacterial soft rot and fungal decay as lettuce.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Intact leaves are sometimes included in packaged salad mixes.

Special Considerations

Greens must be handled carefully to avoid mechanical damage and water loss.

References

Aharoni, N., O. Dvir, D. Chalupowicz, and Z. Aharon. 1993. Coping with postharvest physiology of fresh culinary herbs. Acta Hort. 344:69-78.

Cantwell, M. 1997. Properties and recommended conditions for storage of fresh fruits and vegetables. *At* http://postharvest.ucdavis.edu/produce_information/storagefreshproduce.

Cantwell, M.I., and M.S. Reid. 1993. Postharvest physiology and handling of fresh culinary herbs. J. Herbs, Spices and Medicinal Plants 1:93-127.

de Leiris, J. 1987. The packaging of fresh vegetables in barrier films and modified atmospheres. *In* Proceedings of the 1st International Conference on Packaging Advances, pp. 135-162. Nova-Pack, Dusseldorf, Germany.

Peiris, K.H.S., J.L. Mallon, and S. J. Kays. 1997. Respiratory rate and vital heat of some specialty vegetables at various storage temperatures. HortTechnology 7:46-49.

Péron, J.Y., and D.C. Rees. 1998. High-tech production of corn salad (*Valerianella locusta* (L.) Laterr.), a local, French vegetable crop. Acta Hort. 467:259-268.

Piergiovanni, L., P. Fava, and S. Ceriani. 1999. A simplified procedure to determine the respiration rate of minimally processed vegetables in flexible permeable packaging. Ital. J. Food Sci. 11:99-110.

Rubatzky, V.E., and M. Yamaguchi. 1997. World Vegetables: Principles, Production and Nutritive Values, 2nd ed. Chapman & Hall, London, U.K.

Salsify

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Scientific Name and Introduction

Salsify (*Tragopogon porrifolius* var. *sativus* [Gaterau] Br.-Bl.) belongs to the Compositae family. It is also called vegetable oyster and oyster plant. It is a biennial that produces an edible taproot. The root is light yellow outside and white inside and 15 to 30 cm (6 to 12 in) long with a diameter of 2 to 2.5 cm (0.75 to 1 in). Black salsify (*Scorzonera hispanica* L.) belongs to the same family. Its taproot is larger, more cylindrical in shape, brown-black on the outside, and white inside. Both are rich in iron, vitamins (B1, B2, and E) and inulin, asparagin, and the glycoside laricin. Inulin is poorly digested by humans and can be used as a bulking ingredient in foods formulated with artificial sweeteners (see "Jerusalem Artichoke" chapter) and as a source of fructose (Kierstan 1978).

Quality Characteristics and Criteria

There are no U.S. or international standards. Taproots must be sound, clean, fresh, and without any foreign smell or taste. They must be full-bodied, straight, and unbranched. They should not be woody. Color must be uniform light-yellow or brown-black.

Horticultural Maturity Indices

Harvest is based on root size and time from seeding—usually after 150 to 210 days.

Grades, Sizes, and Packaging

No official grades exist; sizing is based on length and diameter. Salsify is packaged in plastic liners or trays wrapped with plastic film to minimize water loss.

Precooling Conditions

Precooling is not necessary.

Optimum Storage Conditions

Under refrigerated conditions, salsify roots can be stored for 3 to 4 mo at 0 ºC (32 ºF) with 95 to 98% RH (Hardenburg et al. 1986). In the absence of refrigeration, roots are also commonly stored in clamps (Hak 1993).

Controlled Atmosphere (CA) Considerations

Black salsify can be stored in 3% CO_2 and 3% O_2 for 6 mo at 0 ºC (32 ºF) with excellent results (Stoll 1974).

Retail Outlet Display Considerations

The skin is very delicate, and salsify easily loses water if not in plastic-lined trays. Misting with water is beneficial.

Chilling Sensitivity

Salsify is not chilling sensitive. It should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Salsify produces very little ethylene and has low sensitivity to ethylene.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 ºC	22 to 28
5 ºC	33 to 53
10 ºC	40 to 57
20 ºC	193

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 ºC (32 ºF), 1.9 at 10 ºC (50 ºF), and 1.8 at 20 ºC (68 ºF). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Freezing is a risk during storage.

Postharvest Pathology

The most frequent diseases in the field are *Albugo tragopogonis*, causing russet spotting on leaves, and powdery mildew (*Erysiphe cichoriacearum* DC.), which compromises quality.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Salsify is not currently marketed as fresh-cut product.

References

Hak, P.S. 1993. Kuilbewaring van fabrieksaardappelen, suikerbieten, rode bieten, schorseneren en winterpeen. Bedrijfsontwikkeling 14:799-801.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. Salsify. *In* R.E. Hardenburg, A.E. Watada, and C.Y. Wang, The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, p. 69. Agricultural Handbook 66, U.S. Department of Agriculture, Washington, DC.

Kierstan, M.P.J. 1978. Production of fructose syrups from inulin-containing plants [Jerusalem artichokes, chicory, salsify extracts]. Biotech. Bioeng. 20:447-450.

Stoll, K. 1974. Storage of vegetables in modified atmospheres. Acta Hort. 38:13.

Sapodilla and Related Fruits

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This chapter discusses black sapote, lucuma, mamey apple, sapodilla, sapote, star apple, and white sapote.

Note regarding respiration data for Sapodilla and related fruit:
To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Black Sapote

Scientific Name and Introduction

Black sapote *(Diospyros dignya)* resembles a large, round, green tomato. It weighs 200 to 250 g, is 5 to 12 cm in diameter, and has a thin skin. The green color changes to brown or black when ripe. During ripening, pulp becomes soft and black.

Optimum Storage Conditions and Chilling Sensitivity

Black sapote is chilling sensitive. Fruit held at 15, 20, or 25 °C (59, 68, or 77 °F) for up to 7, 10, or 15 days and then transferred to 25 °C (77 °F) ripened normally (Miller et al. 1997). Fruit held at 10 °C (50 °F) for 7 days and then transferred to 25 °C (77 °F) also ripened normally. However, some fruit held at 10 °C (50 °F) for 10 or 15 days showed abnormal ripening, and most fruit stored at 1 to 5 °C (34 to 41 °F) did not ripen normally or failed to ripen regardless of storage duration.

Black sapote will tolerate irradiation at 0.15 kGy, but abnormal ripening of some fruit is likely when treated at 0.3 kGy (Miller et al. 1997).

Lucuma

Scientific Name and Introduction

The lucuma (lucumo, lucmo, lucma, rucma, or mamon) (*Lucuma obovata*, HBK) is round or ovate with a green surface and yellow, mealy flesh. Fruit are about 7 cm long. The lucuma is a climacteric fruit. It has a low water content (64 to 72%) and higher amounts of riboflavin, niacin, and ascorbate than apples or bananas (Wenkam and Miller 1965, Lopez 1984).

Horticultural Maturity Indices

The maturity index commonly used is a change of peel color from green to yellow. However, variability exists in peel and pulp color, ranging from green to yellowish-green peel and light-yellow to orange-yellow pulp (Lizana 1980). SSC can be used as a harvest index, but fruit have a dense and dry pulp. To measure SSC, it is necessary to disrupt pulp by mechanical means and dilute with water. Otherwise apparent SSC content will appear lower than the true value (Lizana et al. 1986).

A classification of five stages of maturity was developed according to peel and pulp color, texture, SSC, and respiration (Lizana 1980). The classes in relation to peel and pulp color are—

Class	Peel color	Pulp color
1	light-yellow	light-yellow
2	light-green	creamy-yellow
3	yellow-green	yellow
4	green-yellow	dark-yellow
5	green-yellow	orange-yellow

Fruit ripened on the tree usually become soft and very fragile (Lizana 1980). The pulp is very dry when ripe (Lizana 1980). Intense respiratory activity and sugar accumulation occur during ripening (Lizana et al. 1986).

Mamey Apple

Scientific Name and Introduction

Mamey apple, also know as mamey and zapote, *(Mammea americana)* is a fruit of about 300 to 500 g having a peachlike flavor. The fruit is a drupe about the shape and size of an orange, with a russet surface covered with small spots. It is round with a thick, brown, leathery skin containing one large single seed surrounded by a thin layer of flesh. The tough rind is about 4 mm thick. The flesh, or endocarp, is yellow, about 2 to 5 mm thick, and fused with the testa.

Chilling Sensitivity

Chilling injury symptoms include failure to ripen, accelerated softening, development of brown spots in pulp, and development of off flavors and aromas.

Ethylene Production

Ethylene production at 27 °C (81 °F) is as much as 400 µL kg^{-1} h^{-1}, among the highest of all fruits (Akamine and Goo 1978).

Respiration Rates

Mamey apple is a climacteric fruit. The respiration rate at 27 °C (81 °F) is 28 to 40 mg (14 to 20 µL) CO_2 kg^{-1} h^{-1} (Akamine and Goo 1978).

Sapodilla

Scientific Name and Introduction

Sapodilla (*Manilkara achras* [Mill] Fosb., syn *Achras sapota*, L.) is the fruit of the chicle tree and is also known as sapota, chiku, ciku, dilly, nasberry, sapodilla plum, chico zapote, zapote, chico, néspero, and sapota plum. The fruit is a fleshy berry—ellipsoidal, conical, or oval—and contains one or several shiny black seeds. It weighs about 70 to 300 g and has a dull brown color, thin skin, and yellowish, light brown, or red pulp. Sapodilla fruit are prized for a pleasant aroma and sweet taste. Fruit growth follows a sigmoid pattern (Lakshminarayana and Subramanyam 1966). Fruit are very susceptible to mechanical injury.

Horticultural Maturity Indices

The erratic flowering habit of sapodilla and the presence of fruit at all stages of development on the tree make it difficult to determine optimum harvest time (Lakshminarayana 1980). Fruit harvested later than optimum time usually soften very rapidly and become very difficult to handle. Fruit harvested earlier than physiological maturity may not soften, are usually low in sweetness and high in astringency when ripe with a rather unappealing alcoholic aftertaste, and form pockets of coagulated latex that lower quality. Unripe fruit are highly astringent and contain large amounts of leucoanthocyanidins. The sucrose content and pulp-to-peel ratio increase during maturation (Pathak and Bhat 1953).

Fruits shed brown scaly external material and become smooth when reaching physiological maturity (Lakshminaryana 1980). Fruit ready for harvest do not show green tissue or latex when scratched with a fingernail. Fully mature fruit have brown skin and separate easily from the stem without leaking latex. Extent of scurfiness is also a good indicator of maturity (Kute and Shete 1995). A fruit with a smooth surface, shining potato color, and rounded stylar end is considered mature (Kute and Shete 1995).

Grades, Sizes, and Packaging

Fruit are commonly cell-packed in fiberboard or wood flats with 25 to 49 fruit (4.5 kg; 10 lb) per flat (McGregor 1987).

Optimum Storage Conditions

Postharvest life is 2 to 3 weeks at 12 to 16 °C (54 to 61 °F) with 85 to 90% RH. Storage life is about 13 days at 25 °C (77 °F), 15 days at 20 °C (68 °F), and 22 days at 15 °C (59 °F) (Broughton and Wong 1979). Short-term holding of fruit—less than 10 h at 4 °C (39 °F)—before storage at 20 °C (68 °F) extends storage life up to 24 days with satisfactory quality (Broughton and Wong 1979). Exposure of fruit to gamma irradiation at 0.1 kGy extended storage life by 3 to 5 days at 27 °C (80 °F) and 15 days at 10 °C (50 °F) without any effect on ascorbate content (Salunkhe and Desai 1984).

Modified Atmosphere (MA) and Controlled Atmosphere (CA) Considerations

Storage life of sapodilla is extended by use of MA and removal of ethylene (Broughton and Wong 1979, Yahia 1998). Storage life at room temperature increased from 13 days to 18 days in 5% CO_2, 21 days in 10% CO_2, and to 29 days in 20% CO_2. However, fruit held in 20% CO_2 failed to ripen, and this level of CO_2 is deleterious.

'Kalpatti' fruit treated with 6% Waxol, with 250 or 500 µL L^{-1} Bavistin, or with hot water at 50 °C (122 °F) for 10 min and wrapped in 150 gauge polyethylene film with 1% ventilation ripened later than the controls, but fungal rot was high (Bojappa and Reddy 1990). Fruit treated with 6% wax emulsion and packed in 200-guage polyethylene covers containing ethylene and CO_2 absorbents had a shelf-life of 45 days at 12 °C (54 °F), 10 days more than controls (Chundawat 1991).

'Jantuang' fruit were successfully stored using MAP for 4 weeks at 10 °C (50 °F) and 3 weeks at 15 °C (59 °F), a week longer than fruit without MAP (Mohamed et al. 1996).

Chilling Sensitivity

Sapodilla fruit are highly susceptible to chilling injury. Storage of fruit at 6 to 10 °C (43 to 50 °F) causes irreversible damage and results in poor flavor (Broughton and Wong 1979, Salunkhe and Desai 1984). Chilling injury also occurred in fruit stored for 21 days at 10 °C (50 °F). However, fruit waxed with a fatty acid sucrose ester kept for 40 days at 10 °C (50 °F).

Ethylene Production and Sensitivity

Ethylene production is 2.8, 3.7 and 6.1 µL kg^{-1} h^{-1} at 15, 20 and 25 °C (59, 68 and 77 °F), respectively (Broughton and Wong 1979). Treatment of sapodilla fruit with etherel at 1 to 3 mL L^{-1} accelerated ripening and reduced pectin content, phenolic content, SSC, sugar content, and vitamin C content (Shanmugavelu et al. 1971, Das and Mahapatra 1977, Ingle et al. 1982). Removing ethylene delays ripening (Chundawat 1991).

Respiration Rates

Sapodilla is a climacteric fruit (Lakshminaryana and Subramanyam 1966, Broughton and Wong 1979) but does not reach the climacteric while on the tree (Lakshminaryana and Subramanyam 1966). The respiration rate at 24 to 28 °C (75 to 82 °F) was 16 mg (9 µl) CO_2 kg^{-1} h^{-1} (Lakshminaryana and Subramanyam 1966). Preharvest sprays of isopropyl *n*-phenylcarbamate (IPC) at 100 µL L^{-1} retard respiration, while maleic hydrazide at 0.5 to 1.0 mL L^{-1} accelerates it (Lakshminarayana and Subramanyam 1966).

Postharvest Pathology

Diseases and pests are rare. *Phytophthora palmivora* and species of *Pestalotiopsis* and *Phomopsis* can cause fruit rot (Snowdon 1990). Some species of bacteria are associated with fruit latex (Pathak and Bhat 1952).

Insects that infest sapodilla fruit include *Nephopteryx engraphella* Rag., fruit flies, and an unidentified borer (Kute and Shete 1995). The most troublesome fruit flies are the Mediterranean (C*eratitis capitata*, Wied.) and Mexican (*Anastrepha ludens*, Loew.) species.

Sapote

Scientific Name and Introduction

The sapote (zapote, mamey, mamey colorado, mamey sapote, chico-mamey, marmalade-fruit, marmalade-plum, or grosse sapote) (*Pouteria sapota* Jacq., H.E. Moore & Stearn; syn. *Colocarpum sapota* Jacq. Merr., *Calocarpum mammosum* Pierre., *Achras mammosa* L., *Lucuma mammosa* Gaertn., *Vitellaria mammosa* Radlk., and *Achradelpha mammosa* Cook) is ovoid to ellipsoid in shape, 7 to 15 cm long, and 10 to 15 cm in diameter. The skin is thick and woody with a russet-brown and somewhat scurfy surface. The pulp of mature fruit is soft and smooth to finely granular in texture and salmon pink, orange, and red or reddish-brown in color. The pulp has a rich, sweet, almondlike flavor; low fiber content; and creamy texture. Fruit weigh 0.3 to 3 kg and contain a large elliptical seed that has a shiny, hard, dark-brown surface with a light-brown hilum on the ventral side.

Quality Characteristics and Criteria

Inferior or improperly ripened mamey sapotes will develop a pronounced squashlike flavor.

Horticultural Maturity Indices and Harvesting

Fruit are harvested when the flesh begins to turn red and are mature when the newly exposed layer has turned from green to pinkish-brown, orange, or red. Immature fruit fail to soften, and their pulp will turn dark-brown and inedible. Harvesting must be done carefully to avoid mechanical damage. The fruit should be twisted until it breaks from the stem. Poles with knifes at the end are also used to harvest fruit. Fruit should not be allowed to fall on the ground.

Grades, Sizes, and Packaging

Fruit are packed in 3-kg-capacity flat fiberboard boxes using sleeves or excelsior (McGregor 1987).

Optimum Storage Conditions

Storage life is 2 to 6 weeks at 13 to 18 °C (55 to 64 °F) with 85 to 90% RH.

Ethylene Production and Sensitivity

The fruit is climacteric and is one of the most prolific producers of ethylene: >100 µL kg^{-1} h^{-1} at 20 °C (68 °F) (Kader 1992).

Physiological Disorders

Fruit are chilling sensitive. Symptoms include brown spots on the skin, poor color development, and off flavor.

Star Apple

Scientific Name and Introduction

The star apple (caimito, sweetsop, or anon) (*Chrysophyllum cainito* L.) is an apple-sized fruit, commonly round but sometimes ovate, heart-shaped, or conical. It has a smooth, waxy skin. The fruit appears as a star when cross-sectioned. Fruit have a soft flesh and are yellowish green in color with a mild, sweet flavor. The pulp is white or creamy white with numerous embedded small, shiny, dark-brown seeds.

Harvesting

Fruit should be matured on the tree but picked before fully ripe. Fruit picked immature will be astringent and contain a sticky white latex. Fruit left to ripen on the tree often split open, especially during the rainy season.

Packaging

Fruit are tray-packed in fiberboard boxes of 4.5 kg (10 lb) capacity (McGregor 1987).

Precooling

Precooling should be done by hydrocooling or forced-air cooling.

Optimum Storage Conditions

Star apple intended for cold storage are picked at the half-ripe stage, cured in a well-ventilated room for 2 days, and held at 3 to 6 °C (37 to 43 °F) with 90% RH for about 3 weeks.

Chilling Sensitivity

This fruit is slightly sensitive to chilling injury.

Ethylene Production and Sensitivity

Ethylene production at 20 °C (68 °F) is 10 to 100 mL kg^{-1} h^{-1}. The fruit does not respond significantly to treatment with ethylene (Pratt and Mendoza 1980).

Respiration Rates

The star apple is a nonclimacteric fruit. The respiration rate at 20 °C (68 °F) is 25 to 50 mg (13 to 25 µL) CO_2 kg^{-1} h^{-1}. Heat evolution is 1,600 to 4,400 BTU ton^{-1} day^{-1}, equivalent to a respiration rate of 7 to 20 mg CO_2 kg^{-1} day^{-1} at 3 to 6 °C (37 to 43 °F) (Pratt and Mendoza 1980).

Postharvest Pathology

The most important pests include the annona seed borer and the ambrosia beetle. The annona seed borer lays eggs in the seeds of very young fruits. Insects develop in the seeds and emerge as adults when the fruit matures.

White Sapote

Scientific Name and Introduction

White sapote, or zapote blanco, (*Casimiroa edulis* llave & Lex) is also known as matasano in Spanish, meaning “killing healthy person” because of the presence of the glucoside casimirosine, mainly in seeds but also in bark and leaves. This compound has sedative effects, induces sleep, and can also calm rheumatic pains. The fruit is dull-green to greenish-yellow, subglobose to oblate, and 5 to 10 cm in diameter. The fruit is round, oval, or ovoid. The skin is very thin and the flesh is cream-colored to yellowish, soft, and very sweet, with 1 to 5 large, hard, ovoid seeds. Green-skinned varieties have white flesh, and yellow-skinned varieties have yellow flesh. The skin is thin and smooth and the flesh has a custardlike texture and sweet flavor.

Quality Characteristics and Criteria

Quality fruit are yellow to yellowish-green and 60 to 120 mm in diameter (McGregor 1987).

Horticultural Maturity Indices

White sapote fruit ripen 6 to 9 mo after bloom. Fruit color at maturity ranges from apple-green to orange-yellow, depending on the cultivar. Overripe fruit are commonly pungent with an unpleasant flavor. Fruit taste best when tree-ripened, but should be picked before ripening. Fruit should be handled very carefully during harvesting because they are easily bruised, turning the skin black and the flesh bitter.

Optimum Storage Conditions

Storage life is 2 to 3 weeks at 19 to 21°C (66 to 70 °F) and 85 to 90% RH.

Postharvest Pathology

White sapote is resistant to phytophthora and to armillaria, but some cultivars can be attacked by fruit flies.

Acknowledgments

Some of the information in this chapter is from the University of Florida website at http://ifas.ufl.edu.

References

Akamine, E.K., and T. Goo. 1978. Respiration and ethylene production in Mammee apple (*Mammea americana* L.). J. Amer. Soc. Hort. Sci. 103:308-310.

Bojappa, K.K.M., and T.V. Reddy. 1990. Postharvest treatments to extend the shelf life of sapota fruit. Acta Hort. 269:391.

Broughton, W.J., and H.C. Wong. 1979. Storage conditions and ripening of chiku fruits *Achras* sapota L. Sci. Hort. 10:377-385.

Chundawat, B.S. 1991. Postharvest handling and marketing of sapota fruits. National Seminar on Optimizing Production and Utilization of Sapota, October 1991, Navsari, Gujarat, India.

Das, R.C., and S.K. Mahapatra. 1977. Effect of growth substances and fungicidal wax emulsion on ripening of sapota. Prog. Hort. 8:75.

Ingle, G.S., D.M. Khedkar, and R.S. Dabhade. 1982. Ripening studies in sapota fruit. Indian Food Packer 36:72-77.

Kader, A.A., ed. 1992. Postharvest Technology of Horticultural Crops, 2nd ed. DANR Pub. no. 3311, University of California, Oakland, CA.

Kute, L.S., and M.B. Shete. 1995. Sapota (Sapodilla). *In* D.K. Salunkhe and S.S. Kadam, eds., Handbook of Fruit Science and Technology, pp. 475-484. Marcel Dekker, New York, NY.

Lakshminarayana S. 1980. Sapodilla and prickly pear. *In* S. Nagy and P.E. Shaw, eds., Tropical and Subtropical Fruits: Composition, Properties and Uses, pp. 415-441. AVI, Westport, CT.

Lakshminarayana S., and H. Subramanyam. 1966. Physical, chemical and physiological changes in sapota fruit (*Achras sapota* L.) during development and ripening. J. Sci. Food Sci. Technol. (Mysore) 3:15-154.

Lizana, L.A. 1980. Lucuma. *In* S. Nagy, P.E. Shaw, and W.F. Wardowski, eds., Fruits of Tropical and Subtropical Origin, pp. 373-380. Florida Science Source, Lake Alfred, FL.

Lizana, L.A., G. Reginato, and J.C. Lavanderos. 1986. Characterization of the maturation of the lucuma (*Lucuma bifera* Mol., L. Obovata H.B.K.). Proc. Interam. Soc. Trop. Hortic. 30:105-10.

Lopez, C. 1984. Cultivation of the lucumo and its industrialization. Rev. Campesino 115:38-53.

McGregor, B.M. 1987. Tropical Products Transport Handbook. Agriculture Handbook 668, U.S. Department of Agriculture, Washington, DC.

Miller, W.R., J.L. Shari, and E. Baldwin. 1997. Quality of irradiated and non-irradiated black sapote (*Diospyros digyna* Jacq.) after storage and ripening. Proc. Fla. State Hort. Soc. 110:215-218.

Mohamed, S., B. Taufik, and M.N.A. Karim. 1996. Effects of modified atmosphere packaging on the physiological characteristics of ciku (*Arcas sapota* L.) at various storage temperatures. J. Sci. Food Agric. 70:231-240.

Pathak, S., and J.V. Bhat. 1952. Studies on the microorganisms associated with *Achras sapota*. J. Univ. Bombay 20(5):14-18.

Pathak, S., and J.V. Bhat. 1953. The carbohydrate metabolism of *Acras sapota* fruit. J. Univ. Bombay 21(5):11-16, Section A.

Pratt, H.K., and D.B. Mendoza Jr. 1980. Fruit development and ripening of the star apple (*Chrysophyllum cainito* L.). HortScience 15:721-722.

Salunkhe, D.K., and B.B. Desai. 1984. Postharvest Biotechnology of Fruits, vol. 2, pp. 387-396. CRC Press, Boca Raton, FL.

Shanmugavelu, K., G. Srinivasan, and V.N.M. Rao. 1971. Influence of etherel (2-chloroethyle phosphonic acid) on ripening of sapota (*Achras zapota* L.). Hortic Adv. 8:33-36.

Snowdon, A.L. 1990. Postharvest disease and disorders of fruits and vegetables, vol. I. General introduction and fruits. CRC Press, Boca Raton FL.

Wenkam, N.S., and C.D. Miller. 1965. Composition of Hawaii fruits. Bull. 135, Hawaii Agricultural Experimental Station, Honolulu, HI.

Yahia, E.M. 1998. Modified/controlled atmospheres for tropical fruits. Hort. Rev. 22:123-183.

Southern Pea

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Scientific Name and Introduction

Southern pea, or cowpea, (*Vigna unguiculata* [L.] Walp.) is a native of Africa and is adapted to hot, dry climates. The southern pea is not actually a pea, and thus differs considerably from the green or English pea *(Pisum sativum)* (Peirce 1987). Prized in the southern United States, southern peas are rich in folic acid, fiber, and calcium. Peas are distinguished by pod color, pea color and pattern, and hilum color. Five groups of cultivars are recognized on the basis of seed and pod coloration and seed packing in pod. They include black-eyed (‘California Blackeye No. 5’), cream (‘Elite’), purplehull (‘Pinkeye Purple Hull’), crowder (‘Mississippi Silver’), and miscellaneous other colored, noncrowder peas (‘Dixielee’). ‘Bettersnap’ was developed specifically for edible pods (Fery and Dukes 1995).

Quality Characteristics and Criteria

Some cultivars have edible pods (similar to green beans) and should be harvested when the pods are 10 to 16 cm (4 to 6 in) long, flexible, and dark green. Shelled peas should be a mature size, have smooth skin, and exhibit characteristic color.

Horticultural Maturity Indices

Fresh-market southern peas are harvested when the pods are at the mature-green stage (peas are fully developed and the majority of the pods have undergone a color change). It is acceptable to have some pods that have not undergone a complete color change (green with some purpling in the case of purplehulls) provided the peas are mature size. Shelled peas should be light green in color.

Pea color is affected both by maturity and cultivar. Tan or white peas are perceived to be too mature (except for cream types). Blackeye cultivars exhibit the most difficulty in determining when to harvest for fresh use because the color of the black hilum does not fully develop until peak maturity. The color will be purple to chocolate-brown if harvested early. If southern peas are to be harvested for edible pod use, they must be selected when quite young and tender—no more than half of the expected diameter of mature green pods—unless it is a cultivar specifically developed for edible pod use.

Grades, Sizes, and Packaging

USDA grades of southern peas are U.S. No. 1 (95% of pods must be at least 12.5 cm [5 in] long), and U.S. Commercial (no minimum length). Shelled peas are marketed in 4.5- to 5.4-kg (10- to 12-lb) plastic bags (considered the equivalent of a shelled bushel) or in 0.45-kg (1-lb) bags. Some large operations package peas in vacuum-packed 0.45- and 4.5-kg (1- and 10-lb) bags. No grades exist for southern peas used as snap beans. Fresh southern peas may also be sold in the hull by the bushel. A USDA bushel is 11.4 kg (25 lbs); however, at the local market level the bushel weight varies widely from region to region or from 7.3 to 13.6 kg (16 to 30 lbs). Pods for shelling are packed primarily in mesh bags (cabbage sacks) or wooden bushel baskets (becoming less common).

Precooling Conditions

In both shelled and unshelled states, peas are very prone to decay if held at room temperature. Unshelled peas are best cooled using a forced-air system. Contact with water greatly accelerates their deterioration. Shelled peas should be blown free of foreign material and then hydrocooled in a solution of 100 µL L^{-1} chlorine to remove heat quickly, preserve green color, and slow microbial growth. Peas to be trucked for processing are shelled into field bins where temperatures may reach 38 °C (100 °F) (Hardenburg et al. 1986). Peas start to yellow and decay after a few hours at 25 °C (77 °F). Flavor deterioration and off flavor in shelled peas may be a problem if they are held for as much as 7 h at 30 °C (86 °F) before processing.

Optimum Storage Conditions

Southern peas in the pod can be held for 6 to 8 days at 4 to 5 °C (39 to 41 °F) with 95% RH. Without refrigeration, they remain edible only about 2 days and show extensive decay in 4 to 6 days. Shelled peas should be held for no more than 24 to 48 h at 4 to 5 °C (39 to 41 °F) (Jenkins 1954).

Controlled Atmosphere (CA) Considerations

Effects of CA are unknown.

Retail Outlet Display Conditions

Peas should be kept under high RH and refrigerated to slow decay and color loss.

Chilling Sensitivity

Unknown. Southern peas are probably sensitive when held at 5 °C (41 °F) or below.

Ethylene Production and Sensitivity

Ethylene production rate is unknown. Southern peas are probably sensitive to ethylene with effects characterized by yellowing of pods.

Respiration Rates

Temperature	Whole pods	Shelled peas
	------mg CO_2 kg^{-1} h^{-1}--------	
2 °C	13 to 36	26 to 33
5 °C	16 to 33	-
20 °C	145 to 151	90 to 161

Data from P. Perkins-Veazie (unpublished) from pods 15 to 23 cm long of cultivars ‘Excel,’ ‘BetterSnap,’ ‘Early Scarlet,’ and ‘Pinkeye Purple Hull BVR.’

Higher respiration values are for less mature (more green) peas and pods.

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Brown spots, cracking, and seed-coat splitting are problems with pods and peas.

Postharvest Pathology

Very little research has been done on postharvest pathogens of southern pea. *Botrytis cinerea* (gray mold) can quickly develop on pods and shelled peas (Roland E. Roberts, Texas A&M, 2002, personal communication).

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Snap pea or yard-long cowpea cultivars, such as 'Bettersnap,' can be used as a fresh-cut product. These types must be harvested at the immature pod stage.

Special Considerations

Failure to precool shelled peas prior to packaging results in condensation in the bags and rapid souring and spoiling of the peas. Insect damage can create major postharvest grading problems due to feeding damage and misshaped peas caused by stinkbugs and due to the presence of punctures and larvae inside peas as a result of cowpea cucurlio.

References

Fery, R.L., and P.D. Dukes. 1995. 'Bettersnap' southernpea. HortScience 30:1318-1319.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agricultural Handbook 66, U.S. Department of Agriculture, Washington, DC.

Jenkins, W.F. 1954. Postharvest changes in refrigerated and non-refrigerated southern peas. Proc. Amer. Soc. Hort. Sci. 64:327-330.

Peirce, L.C. 1987. Legumes-southern pea. *In* L.C. Peirce, Vegetables: Characteristics, Production, and Marketing, pp. 345-347. J. Wiley and Sons, New York, NY.

Sprouts

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Scientific Name and Introduction

Sprouts are young seedlings just after seed germination. The most common marketed sprout is mung bean (*Vigna radiata* L. Wilczek; syn., *Phaseolus aureus* Roxb.). Other sprouts include alfalfa (*Medicago sativa* L.); buckwheat (*Fagopyrum esculentum* Moench); green pea (*Pisum sativum* L.); kidney, pinto, and navy bean (*Phaseolus vulgaris* L.); lentil (*Lens culinaris* Medik.), mustard (*Brassica nigra* L. Koch; *Sinapis alba* L.); onion (*Allium cepa* L.); radish (*Raphanus sativus* L.); red clover (*Trifolium partense* L.); soybean (*Glycine max* L. Merr.); watercress (*Nasturtium officinale* R.Br.); and wintercress (*Barbarea vulgaris* R.Br.).

Quality Characteristics and Criteria

Fresh mung bean sprouts have crisp white hypocotyls and yellow or green cotyledons. Symptoms of deterioration include darkening of the root and cotyledons, development of dark streaks on the hypocotyl, and eventual development of sliminess, decay, and a musty odor. Sprouts vary in texture and taste: Some are spicy (such as radish and onion sprouts); others are hardy and often used in Asian foods (such as mung bean sprouts); while others are more delicate and used in salads and sandwiches to add texture and moistness (such as alfalfa sprouts).

Horticultural Maturity Indices

Sprouts are harvested after 1 to 8 days of growth, depending on the type and desired plant height and width. For example, mung bean sprouts are normally harvested after 3 to 8 days when length is 1.3 to 7.6 cm (0.5 to 3 in), alfalfa sprouts are harvested after 1 to 2 days when length is 2.5 to 3.8 cm (1 to 1.5 in), and radish sprouts after 2 to 4 days when length is 1.3 to 2.5 cm (0.5 to 1 in).

Grades, Sizes, and Packaging

There are no established USDA quality standards for sprouts. Perforated film packaging helps maintain the quality of fresh sprouts by reducing water loss. Alfalfa sprouts are marketed in 112- or 168-g (4- or 6-oz) containers with 12 containers per case. Mung bean sprouts are marked in the same size containers and in 2.3-kg (5-lb) open flats.

Precooling Conditions

Sprouts should be cooled immediately and held at 0 °C (32 °F). Vacuum-cooling, hydrocooling, and forced-air cooling are common methods.

Optimum Storage Conditions

Sprouts are highly perishable and most last 5 to 10 days at 0 °C (32 °F) with 95 to 100% RH. Mung bean sprouts stored at 0, 2.5, 5 or 10 °C (32, 37, 41 or 50 °F) reach the lower limit of marketability after 8.5, 5.5, 4.5 and 2.5 days, respectively (Lipton et al. 1981). The shelf-life of bean sprouts held at 0 °C (32 °F), but exposed daily to 20 °C (68 °F) for 30 min can be reduced by 50%. Alfalfa and radish sprouts stored at 0 °C (32 °F) with >95% RH had a shelf-life of 7, and 5 to 7 days, respectively (Cantwell 1997).

Controlled Atmosphere Considerations

The shelf-life of mung bean sprouts can be increased by storage under MA in which O_2 is reduced and CO_2 is increased (Varoquaux et al. 1996). For instance, they can be held for 4 to 5 days at 8 °C (46 °F) in packages containing 5% O_2 and 15% CO_2. Darkening of sprouts is reduced and development of sliminess is delayed.

Retail Outlet Display Considerations

Sprouts should be held close to 0 °C (32 °F). They should not be misted.

Chilling Sensitivity

Sprouts are highly perishable and should be stored as cold as possible without freezing. In some cases, the cotyledons of mung bean sprouts darken more at lower temperatures. However, due to faster deterioration at higher temperatures, storage at 0 °C (32 °F) is recommended.

Ethylene Production and Sensitivity

Sprouts produce little ethylene. Mung bean sprouts produce 0.15, 0.05, 0.24, and 0.90 µL kg^{-1} h^{-1} at 0, 2.5, 5, and 10 °C (32, 37, 41 and 50 °F), respectively (Lipton et al. 1981).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	23
2.5 °C	29
5 °C	42
10 °C	96

Data from Lipton et al. (1981).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Mung bean sprout hypocotyls darken with age, becoming beige to light tan. However, some develop light-tan to rusty-brown streaks, mainly along the lower portion of the axis (Lipton et al. 1981). Such streaks may be present at harvest and are thought to arise from a group of cells that were injured before or during germination.

Darkening of the radicles and browning of the cotyledons are other changes associated with the deterioration of mung bean sprouts. Cotyledon color in mung bean sprouts may blacken at low temperatures, and this may be a symptom of chilling injury (DeEll et al. 2000).

Postharvest Pathology

Development of decay, sliminess, and musty odors are symptoms of deterioration.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

No current potential exists.

Special Considerations

Sprouts have been associated with human pathogenic bacteria, such as *Aeromonas hydrophila*, *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Salmonella* spp., and *Bacillus cereus* (Brackett 1999). Therefore, the importance of proper storage and handling, along with good worker hygiene and sanitation, cannot be stressed enough.

Acknowledgments

Some information in this chapter is from the International Sprout Growers Association website at http://www.isga-sprouts.org.

References

Brackett, R.E. 1999. Incidence, contributing factors, and control of bacterial pathogens in produce. Postharv. Biol. Technol. 15:305-311.

Cantwell, M. 1997. Properties and recommended conditions for storage of fresh fruits and vegetables. *At* http://postharvest.ucdavis.edu/produce_information/storagefreshproduce.

DeEll, J.R., C. Vigneault, F. Favre, et al. 2000. Vacuum cooling and storage temperature influence the quality of stored mung bean sprouts. HortScience 35(5):891-893.

Lipton, W.J., W.K. Asai, and D.C. Fouse. 1981. Deterioration and CO_2 and ethylene production of stored mung bean sprouts. J. Amer. Soc. Hort. Sci. 106:817-820.

Varoquaux, P., G. Albagnac, C. Nguyen-The, and F. Varoquaux. 1996. Modified atmosphere packaging of fresh bean sprouts. J. Sci. Food. Agr. 70:224-230.

Squash

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Scientific Name and Introduction

Summer squash are the young fruit of *Cucurbita pepo*. They are members of the Cucurbitaceae family. There are six horticultural groups of summer squash: cocozelle, crookneck, scallop, straightneck, vegetable marrow, and zucchini (Paris 1986). Summer squash are cultivated throughout the world and is available year-round. Zucchini is the most widely grown and economically important summer squash.

Quality Characteristics and Criteria

Tenderness and firmness are the major quality characteristics. The surface of summer squash should be shiny; dullness is a sign of senescence. Fruit should be firm and free of physical injury. Dark green types should be entirely green; yellowish areas are a sign of senescence. Water loss results in a dull surface and loss of firmness.

Horticultural Maturity Indices

Summer squash are harvested up to 1 week after anthesis, when they are still shiny. Small fruit are more desirable than large fruit because small fruit's flesh and seeds are more tender and slightly sweet.

Grades, Sizes, and Packaging

Summer squash are graded U.S. No. 1 and U.S. No. 2 (AMS 1984). Summer squash can be harvested over a wide range of sizes, from <50 g to >400 g (<2 oz to >0.9 lb). Acceptable size is a function of the type of squash and market demand. Squash may be field-packed directly into shipping containers or transported to the packinghouse in field boxes or bulk bins for washing and sizing before packing. Squash are packed in a variety of containers including bushel baskets, wire-bound wooden crates, and fiberboard boxes (McGregor 1987). A plastic liner should be used in all wooden containers to prevent abrasion and retard water loss.

Precooling Conditions

Room-cooling, forced-air cooling, and hydrocooling are acceptable methods for removing field heat from summer squash (Lill and Read 1982). Prompt precooling after harvest reduces the rate of water loss and is essential for maximum postharvest life.

Optimum Storage Conditions

Summer squash are highly perishable and not suited for storage longer than 2 weeks (Hardenburg et al. 1986). For maximum shelf-life, summer squash should be held at 5 to 10 °C (41 to 50 °F) with 95% RH.

Controlled Atmosphere (CA) Considerations

Storage in low-O_2 atmospheres appears to be of little or no value for zucchini squash (Mencarelli et al. 1983, Leshuk and Saltveit 1990).

Retail Outlet Display Considerations

Summer squash should not be stacked more than four layers deep and should be arranged carefully so they do not fall off the rack. The display should be refrigerated, but direct contact with ice should be avoided as it can cause physical damage as well as lead to chilling injury.

Chilling Sensitivity

Summer squash are chilling sensitive and should not be exposed to temperatures below 5 °C (41 °F) (Ryall and Lipton 1979). However, variation in chilling tolerance among summer squash types is great (Sherman et al. 1987, Suslow and Cantwell 1998). Chilled summer squash show surface pitting and decay rapidly at nonchilling temperatures, though damage may be absent during refrigeration. Chilled fruit have increased rates of water loss upon transfer to nonchilling temperatures (McCollum 1989).

Ethylene Production and Sensitivity

Summer squash produce low to moderate amounts of ethylene: 0.1 to 1.0 µL kg^{-1} h^{-1} at 20 °C (68 °F). The rate of ethylene evolution is greatly increased in fruit that have been held at chilling temperatures (McCollum 1989). Increased yellowing may result if green-skinned summer squash are exposed to ethylene (Ryall and Lipton 1979).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	24 to 26
5 °C	27 to 37
10 °C	65 to 68
15 °C	139 to 167
20 °C	153 to 175

Data from Hardenburg et al. (1986).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Summer squash are very susceptible to water loss. Shriveling may become evident with as little as 3% weight loss. Precooling and storage at high RH minimize weight loss. Squash can be waxed, but only a thin coating should be applied. Waxing provides some surface lubrication that reduces chafing in transit. Summer squash skin is very tender; skin breaks and bruises can be a serious source of water loss and microbial infection.

Postharvest Pathology

Decay caused by fungal and bacterial pathogens can cause significant postharvest losses in summer squash. The incidence of decay increases in fruit that have physical injury or chilling stress. Common postharvest diseases include alternaria rot, bacterial soft rot, cottony leak, fusarium rot, phythopthora rot, and rhizopus rot. Alternaria rot can be especially pronounced following chilling injury.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Summer squash is frequently sliced and marketed in foam trays overwrapped with polyethylene.

Special Considerations

All types of summer squash are extremely tender and are injured by the slightest scratch, bruise, or scuff. Yellow and scalloped squash show scuffing clearly because the ensuing darkening is obvious on a light background. Summer squash should be handled gently throughout marketing; sorters and packers should wear cotton gloves to prevent fingernail cuts.

References

AMS [USDA Agricultural Marketing Service]. 1984. United States Standards for Grades of Summer Squash. U.S. Department of Agriculture, Agricultural Marketing Service, Washington, DC. *At* http://www.ams.usda.gov/AMSv1.0/standards.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agricultural Handbook 66, U.S. Department of Agriculture, Washington, DC.

Leshuk, J.A., and M.E. Saltveit. 1990. Controlled atmospheres and modified atmospheres for the preservation of vegetables. *In* M. Calderon, ed., Food Preservation by Modified Atmospheres, pp. 315-352. CRC Press, Boca Raton, FL.

Lill, R.E., and A.J. Read. 1982. Storage conditions for zucchini. N.Z. Comm. Grow. 37:26.

McCollum, T.G. 1989. Physiological changes in yellow summer squash at chilling and nonchilling temperatures. HortScience 24:633-635.

McGregor, B.M. 1987. Tropical Products Transport Handbook. Agriculture Handbook 668, U.S. Department of Agriculture, Washington, DC.

Mencarelli, F., W.J. Lipton, and S.J. Peterson. 1983. Response of 'zucchini' squash to storage in low-O_2 atmospheres at chilling and non-chilling temperatures. J. Amer. Soc. Hort. Sci. 108:884-890.

Paris, H.S. 1996. Summer squash: history, diversity, and distribution. HortTechnology 6:6-13.

Ryall, A.L. and W.J. Lipton. 1979. Handling, Transportation, and Storage of Fruits and Vegetables, vol. 1. AVI, Westport CT.

Sherman, M., H.S. Paris, and J.J. Allen. 1987. Storability of summer squash as affected by gene B and genetic background. HortScience 22:920-922.

Suslow, T.V., and M. Cantwell. 1998. Squash (soft rind). Recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

Strawberry

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Scientific Name and Introduction

Strawberry, *Fragaria* × *ananassa*, is a perennial of the Rosaceae family. The edible portion, not a true berry, is a multiple fruit comprised of many achenes (seeds) and receptacle tissue. Fruit are produced on short-day and day-neutral plants in many growing areas. However, the major production in the United States is in California, Oregon, and Florida.

Quality Characteristics and Criteria

A high-quality strawberry is uniformly red, firm, flavorful, and free of defects and disease. Sugar content does not increase after harvest; therefore, harvest when fully ripe for best flavor. For acceptable flavor, a minimum SSC of 7% and a maximum TA of 0.8% are recommended (Kader 1999).

Horticultural Maturity Indices

Maturity is based on surface color. The U.S. minimum is half or three-fourths of the berry's surface showing red or pink color, depending on grade. The California minimum is two-thirds of the berry's surface showing red or pink.

Grades, Sizes, and Packaging

U.S. No. 1 grade consists of strawberries with calyx (cap) attached which are firm, not overripe or undeveloped, of uniform size, and free of decay and damage. Each fruit must have at least three-fourths of its surface showing pink or red color. U.S. No. 2 grade consists of strawberries free from decay or serious damage and with at least half of each fruit showing pink or red color. U.S. Combination grade is a mixture of U.S. No. 1 and 2, with at least 80% meeting U.S. No. 1 grade. Strawberries are often packaged by pickers in the field either into open-mesh baskets or into clear clamshell containers of 1 dry pint or 1 dry quart capacity. The mesh baskets or clamshells are held in a corrugated fiberboard tray holding about 4 to 5 kg (9 to 11 lb).

Precooling Conditions

Strawberries are extremely perishable, and it is important to begin cooling within 1 h of harvest to avoid loss of quality and reduction in amount of marketable fruit (Maxie et al. 1959). Temperature management is the single most important factor in minimizing strawberry deterioration and maximizing postharvest life. Forced-air cooling is highly recommended, though room-cooling is used in some cases (Mitchell et al. 1996).

Optimum Storage Conditions

Store at 0 °C (32 °F) with 90 to 95% RH. Strawberry fruit can be stored for up to 7 days at 0 °C (32 °F), depending on disease pressure.

Controlled Atmosphere (CA) Considerations

MAP for shipment with 10 to 15% CO_2 reduces growth of *Botrytis cinerea* (Wells and Uota 1970) and reduces respiration rate (Li and Kader 1989), thereby extending postharvest life. Use of whole pallet covers for MA is the most common method (Mitchell et al. 1996). Off flavors can develop if higher levels of CO_2 are used.

Retail Outlet Display Considerations

Refrigerated display greatly extends shelf-life and maintains quality. Covered baskets maintain higher RH around berries, reducing water loss and shrivel.

Chilling Sensitivity

Strawberry fruit are not sensitive to chilling and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Strawberries produce very low amounts of ethylene: <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F). They do not respond to ethylene (Mason and Jarvis 1970). Removal of ethylene from storage air may reduce disease development (El-Kazzaz et al. 1983).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	12 to 20
10 °C	50 to 100
20 °C	100 to 200

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Perhaps because of rapid marketing and very short storage, few physiological disorders occur after harvest. CO_2 injury, particularly when >15% CO_2 is used, is manifested as a bluing of the skin (Ke et al. 1991), whitening of inner fruit tissues (Gil et al. 1997), and fermentative off flavors.

Postharvest Pathology

Disease is the greatest cause of postharvest loss. The most common decay is botrytis rot, also called gray mold, caused by *Botrytis cinerea* (Ceponis et al. 1987). This disease can begin preharvest, remaining as a latent infection; or it can begin postharvest. The fungus continues to grow at 0 °C (32 °F), but growth is slow at this temperature. Rhizopus rot, caused by *Rhizopus stolonifer,* is another important disease of strawberry. This fungus cannot grow at temperatures <5 °C (41 °F). Postharvest fungicides are not used on strawberries; therefore, prompt cooling, storing at 0 °C (32 °F), preventing injury, and shipping at 0 °C (32 °F) under high CO_2 are the best methods for disease control. Damaged fruit should be eliminated from baskets to prevent spread of the disease to healthy berries (nesting) (Sommer et al. 1973).

Quarantine Issues

Methyl bromide fumigation is routinely used for strawberries shipped from the United States to Japan and Australia to eliminate live insects. For California, two-spotted spider mites and western flower thrips are the main pests of quarantine concern in exported fruit.

Suitability as Fresh-Cut Product

Strawberries are suitable, and slices have a shelf-life of about 7 days at 2.5 °C (37 °F) and 5 days at 5 °C (41 °F) (Rosen and Kader 1989, Wright and Kader 1997).

Special Considerations

Strawberry fruit are very delicate and easily damaged. Since the harvest crew is responsible for grading, packing, and gentle handling, their training is critical to packing a quality product.

References

Ceponis, M.J., R.A. Cappellini, and G.W. Lightner. 1987. Disorders in sweet cherry and strawberry shipments to the New York market, 1972-1984. Plant Dis. 71:472-475.

El-Kazzaz, M.K., N.F. Sommer, and R.J. Fortlage. 1983. Effect of different atmospheres on postharvest decay and quality of fresh strawberries. Phytopathology 73:282-285.

Gil, M.I., D.M. Holcroft, and A.A. Kader. 1997. Changes in strawberry anthocyanins and other polyphenols in response to carbon dioxide treatments. J. Agric. Food Chem. 45:1662-1667.

Kader, A.A. 1999. Fruit maturity, ripening, and quality relationships. Acta Hort. 485:203-208.

Ke, D., L. Goldstein, M. O'Mahony, and A.A. Kader. 1991. Effects of short-term exposure to low O_2 and high CO_2 atmospheres on quality attributes of strawberries. J. Food Sci. 56:50-54.

Li, C., and A.A. Kader. 1989. Residual effects of controlled atmospheres on postharvest physiology and quality of strawberries. J. Amer. Soc. Hort. Sci. 114:629-634.

Mason, D.T., and W.R. Jarvis. 1970. Postharvest ripening of strawberries. Hort. Res. 10:125-132.

Maxie, E.C., F.G. Mitchell, and A. Greathead. 1959. Quality study on strawberries. Calif. Agric. 13:6,15.

Mitcham, E.J., C.H. Crisosto, and A.A. Kader. 1996. Strawberry. Recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

Mitchell, F.G., E.J. Mitcham, J.F. Thompson, and N. Welch. 1996. Handling strawberries for fresh market. Pub. no. 2442, University of California, Division of Agriculture and Natural Resources, Davis, CA.

Rosen, J.C., and A.A. Kader. 1989. Postharvest physiology and quality maintenance of sliced pear and strawberry fruits. J. Food Sci. 54 (3):656-659.

Sommer, N.F., R.F. Fortlage, F.G. Mitchell, and E.C. Maxie. 1973. Reduction of postharvest losses of strawberry fruits from gray mold. J. Amer. Soc. Hort. Sci. 98 (3):285-288.

Wells, J.M., and M. Uota. 1970. Germination and growth of five fungi in low-oxygen and high-carbon dioxide atmospheres. Phytopathology 60:50-53.

Wright, K.P., and A.A. Kader. 1997. Effect of slicing and controlled-atmosphere storage on the ascorbate content and quality of strawberries and persimmons. Postharv. Biol. Technol. 10:39-48.

Sweet Corn

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Scientific Name and Introduction

Sweet corn (*Zea mays* L. var. *rugosa* Bonaf.) is an annual grass of the Poaceae (grass) family. Traditional varieties are *su1* (*sugary1*) mutants that contain about twice the sugar (primarily sucrose) content of field corn, as well as 8 to 10 times more water-soluble polysaccharide. The latter imparts a creamy consistency to *su1* sweet corn. Other mutants with increased sugar content have more recently been used, primarily *sh2 (shrunken 2),* which has at least double the sugar content of *su1* but almost no water-soluble polysaccharide. Less commonly used is *su1/se (sugary-enhancer); se* modifies *su1* to also double the sugar content, but with no loss of water-soluble polysaccharide content (Wann et al. 1997). The *sh2* mutation inhibits starch biosynthesis while *se* does not. These newer varieties are referred to as "supersweet" and have become the dominant type in all major U.S. sweet corn production regions. The high initial sugar content, coupled with inhibited starch synthesis in *sh2* varieties, doubles the potential postharvest life of sweet corn. However, all supersweet varieties remain extremely perishable.

Quality Characteristics and Criteria

High-quality sweet corn has uniform size and color (yellow, white, or bicolor); sweet, plump, tender, well-developed kernels; and fresh, tight, green husks. It is free from insect injury, mechanical damage, and decay. Sweetness is the most important factor in consumer satisfaction (Evensen and Boyer 1986). All sweet corn varieties lose sweetness and aroma during storage, but the taste of *su1* and *su1/se* varieties becomes starchy while *sh2* varieties eventually taste watery and bland.

Horticultural Maturity Indices

Sweet corn harvest maturity is determined by a combination of ear fill, silk drying, kernel development, kernel sweetness, and kernel tenderness. The appearance of the juice, or endosperm, is a good indicator of maturity for *su1* and *se* varieties, in which a milky (not watery or doughy) consistency represents proper maturity, but not for *sh2* varieties, which always have a watery endosperm.

Grades, Sizes, and Packaging

Grades include U.S. Fancy; U.S. Fancy, Husked; U.S. No. 1; U.S. No. 1, Husked; and U.S. No. 2. Grade is based primarily on maturity, freshness, and cob length, as well as freedom from various injuries and decay. Sweet corn is commonly handled in wire-bound wooden crates and less commonly in waxed fiberboard cartons or in returnable plastic containers. All contain 54 to 60 ears with a weight of about 19 kg (42 lb). Some is prepackaged in polyvinylchloride (PVC) film-wrapped trays (Risse and McDonald 1990, Aharoni et al. 1996) with the ends of ears trimmed and husks partially removed to expose some kernels. PVC film is highly permeable to O_2 and CO_2 while acting as a moisture barrier.

Precooling Conditions

Sweet corn is often >30 °C (86 °F) when harvested, and rapid removal of field heat is critical to retard deterioration. Maximum quality is retained by precooling corn to 0 °C (32 °F) within 1 h of harvest and holding it at 0 °C (32 °F) during marketing. In practice, cooling to this extent is rarely achieved. However, cooling is the first step in a good temperature-management program. Sweet corn has a high respiration rate, which results in a high rate of heat generation. Supersweet varieties have respiration rates equal to that of traditional sweet corn varieties and lose sugar as rapidly (Evensen and Boyer 1986, Olsen et al. 1991), so cooling is still critical with these newer varieties. Sweet corn should not be handled in bulk unless copiously iced because it tends to heat throughout the pile.

Vacuum-cooling can adequately precool sweet corn, but the corn must be first wetted (and top-iced after cooling) to minimize water loss from husks and kernels (Showalter 1957, Stewart and Barger 1960). Crated sweet corn can be vacuum-cooled from about 30 °C (86 °F) to 5 °C (41 °F) in 30 min. Hydrocooling by spraying, showering, or immersion in water at 0 to 3 °C (32 to 38 °F) is effective, though it takes longer than vacuum-cooling if the sweet corn is packed. Bulk sweet corn takes about 60 min to cool from 30 to 5 °C (86 to 41 °F) in a well-managed hydrocooler, while crated sweet corn takes about 80 min (Talbot et al. 1991)—and few if any operators leave it in that long. Periodic monitoring of sweet corn temperature is needed to ensure proper cooling to at least 10 °C (50 °F). Hydrocooling nomographs for bulk and crated sweet corn are available (Stewart and Couey 1963).

After hydrocooling, top-icing is desirable during transport or holding to continue cooling, remove the heat of respiration, and keep the husks fresh. When precooling facilities are not available, sweet corn can be cooled with package ice and top ice. Injection of an ice-water slurry (slush ice) into cartons was as effective as hydrocooling and better than vacuum-cooling in maintaining quality (Talbot et al. 1991), probably due to residual ice in the cartons, since the cooling rate was slower than for the other methods.

Optimum Storage Conditions

Traditional sweet corn varieties are seldom stored for more than a few days because of the resulting serious deterioration and loss of tenderness and sweetness. The loss of sugar is about 4 times as rapid at 10 °C (50 °F) than at 0 °C (32 °F). At 30 °C (86 °F), 60% of the sugar in *su1* sweet corn can be converted to starch in a single day, while only 6% is converted at 0 °C (32 °F). While *sh2* varieties lose sugar at the same rate as *su1* varieties, their higher initial sugar levels keep it sweet-tasting longer. For *sh2* varieties, water loss and pericarp toughening supplant loss of sweetness in limiting postharvest life (Brecht et al. 1990). The former is minimized by prompt cooling, trimming flag leaves and long shanks, and maintaining high RH, usually by icing. Denting of kernels is promoted by water loss from husk leaves (Showalter 1967). A loss of 2% moisture may result in objectionable kernel denting. Pericarp toughening can also be minimized by prompt cooling and by maintaining sweet corn at 0 °C (32 °F). Under optimum storage conditions, the potential postharvest life of *sh2* sweet corn is >2 weeks.

Controlled Atmosphere (CA) Considerations

Increased attention for CA and MAP was spurred by an interest in marine transport to export sweet corn from the United States to Europe and the Far East, which can involve transit times of >2 weeks. Injurious atmospheres at 2 °C (35 °F) contain <2% O_2 or >15% CO_2 (Spalding et al. 1978), resulting in fermentation, off flavors, and odors. Reduced O_2 and elevated CO_2 reduce respiration and slow sucrose loss; elevated CO_2 also reduces decay and maintains green husk color (Spalding et al. 1978, Schouten 1993, Aharoni et al. 1996).

Retail Outlet Display Considerations

Sweet corn should be displayed in refrigerated cases or with ice.

Chilling Sensitivity

Sweet corn is not chilling sensitive. It should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Sweet corn produces only trace ethylene, and exogenous ethylene is not a problem, though high ethylene amounts can lead to husk yellowing given sufficient exposure time.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	30 to 51
5 °C	43 to 83
10 °C	90 to 120
15 °C	142 to 175
20 °C	210 to 311
25 °C	282 to 435

Data from Tewfik and Scott (1954), Scholz et al. (1963), and Robinson et al. (1975).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

There are no significant disorders.

Postharvest Pathology

Decay is not usually a serious problem, but when present it typically occurs on the husk and silks. Trimming ears can promote decay development on the cut kernels and other damaged tissues mainly caused by *Alternaria alternata* (Fr.) Keissler, *Fusarium moniliforme* Sheldon, and *Mucor hiemalis* Wehmer (Aharoni et al. 1996). Thus, proper sanitation and temperature management are important to minimize decay in trimmed sweet corn.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Fresh-cut sweet corn kernels are extremely perishable. Their respiration rate is very high, several times that of intact ears. Thus, temperature control is extremely critical if the kernels are to have acceptable shelf-life. Problems during handling can include off flavors, microbial survival and growth, and discoloration if the temperature is not maintained near 0 °C (32 °F). Especially troublesome is browning when the kernels are cooked. This browning is greater in kernels from more mature ears and is correlated with temperature, storage duration, and extent of physical damage.

References

Aharoni, Y., A. Copel, M. Gil, and E. Fallik. 1996. Polyolefin stretch films maintain the quality of sweet corn during storage and shelf life. Postharv. Biol. Technol. 7:171-176.

Brecht, J.K., S.A. Sargent, R.C. Hochmuth, and R.S. Tervola. 1990. Postharvest quality of supersweet *(sh2)* sweet corn cultivars. Proc. Fla. State Hort. Soc. 103:283-288.

Evensen, K.B., and C.D. Boyer. 1986. Carbohydrate composition and sensory quality of fresh and stored sweet corn. J. Amer. Soc. Hort. Sci. 111:734-738.

Olsen, J.K., R.E. Giles, and R.A. Jordan. 1991. Postharvest carbohydrate changes and sensory quality of three sweet corn cultivars. Sci. Hort. 44:179-189.

Risse, L.A., and R.E. McDonald. 1990. Quality of supersweet corn film-overwrapped in trays. HortScience 25:322-324.

Robinson, J.E., K.M. Browne, and W.G. Burton. 1975. Storage characteristics of some vegetables and soft fruits. Ann. Appl. Biol. 81:339-408.

Scholz, E.W., H.B. Johnson, and W.R. Buford. 1963. Heat evolution rates of some Texas-grown fruits and vegetables. J. Rio Grande Valley Hort. Soc. 17:170-175.

Schouten, S.P. 1993. Effect of temperature and CA storage on visual quality aspects, sugars, and ethanol content of sweet corn. *In* 6th International Controlled Atmosphere Research Conference, Ithaca, NY, June 1993, vol. 2, pp. 797-799. Northeast Regional Agricultural Engineering Service, Cornell University, Ithaca, NY.

Showalter, R.K. 1957. Effect of wetting and top icing upon the quality of vacuum cooled and hydro-cooled sweet corn. Proc. Fla. State Hort. Soc. 70:214-219.

Showalter, R.K. 1967. Sweet corn shelf life as affected by trimming and packaging. Proc. Amer. Soc. Hort. Sci. 91:881-884.

Spalding, D.H., P.L. Davis, and W.F. Reeder. 1978. Quality of sweet corn stored in controlled atmospheres or under low pressure. J. Amer. Soc. Hort. Sci. 103:592-595.

Stewart, J.K., and W.R. Barger. 1960. Effects of cooling method and top-icing on the quality of peas and sweet corn. Proc. Amer. Soc. Hort. Sci. 75:470-475.

Stewart, J.K., and H.M. Couey. 1963. Hydro-cooling vegetables—a practical guide to predicting final temperatures and cooling times. Market Research Report 637, U.S. Department of Agriculture, Washington, DC.

Talbot, M.T., S.A. Sargent, and J.K. Brecht. 1991. Cooling Florida sweet corn. Circular 941, Florida Extension Service, Gainesville, FL.

Tewfik, S., and L.E. Scott. 1954. Respiration of vegetables as affected by postharvest treatment. J. Agr. Food Chem. 2:415-417.

Wann, E.V., C.Y. Lee, M.C. Bourne, and D.L. Downing. 1997. Sweet corn. *In* D. Smith, J. Cash, W. Nip, and Y. Hui, eds., Processing Vegetables: Science and Technology, pp. 325-354. Technomic, Lancaster, PA.

Sweetpotato

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Scientific Name and Introduction

The sweetpotato, *Ipomoea batatas* (L.) Lam., is a member of the Convolvulaceae family that is grown for its fleshy storage roots. Though a perennial, the crop is grown as an annual. Sweetpotato is the seventh most important food crop in the world. However, in the United States it is used primarily as an occasional vegetable. Sweetpotato confers a wide range of health benefits (Kays and Kays 1998) that have enhanced its popularity. The traditional North American type of sweetpotato, typified by the cultivars 'Beauregard' and 'Jewel,' are deep orange in color, moist (soft) in texture, and very sweet when cooked. The orange/moist types, however, are not preferred in most other areas of the world, nor by certain ethnic groups within the United States.

Quality Characteristics and Criteria

Sweetpotato cultivars vary in color (white to cream to orange to purple), flavor (sweet to nonsweet; mild to intensely flavored), and textural properties (firm to very soft). In the United States, postharvest conditions that favor a very sweet, moist-textured cooked product are desirable.

Horticultural Maturity Indices

The storage roots of sweetpotato do not have a developmental stage at which they are mature. Rather the roots continue to grow and under favorable conditions will enlarge until the interior of the root becomes anaerobic or rots. As a consequence, the crop is harvested when the majority of roots have reached the desired size.

Grades, Sizes, and Packaging

Sweetpotatoes are graded into U.S. Extra No. 1, U.S. No. 1, U.S. Commercial, U.S. No. 2, and Unclassified. Grading is based largely on size, condition, and absence of defects. Desired sizes are 8.3 to 8.9 cm (3.25 to 3.5 in) in diameter and 0.53 to 0.59 kg (18 to 20 oz). During storage, roots are handled in 360-kg (800-lb) bulk bins but are generally marketed in 18-kg (40-lb) boxes. At the retail level, roots are typically displayed loose.

Curing

Roots should be cured immediately after harvest at 29±1 °C (84±2 °F) and 90 to 97% RH for 4 to 7 days (Kushman 1975). During curing, ventilation is required to remove CO_2 and replenish O_2 because roots consume about 63 L tonne^{-1} day^{-1} (2 ft^3 ton^{-1} day^{-1}) of O_2 and release equivalent amounts of CO_2. Curing heals wounds from harvest and handling, helping reduce moisture loss during storage and decreasing the potential for microbial decay. In addition, curing facilitates the synthesis of enzymes that are operative in flavor development during cooking (Wang et al. 1998). The effect of temperature and RH on the rate of wound healing has been extensively investigated (Morris and Mann 1955).

During curing, initially the outermost parenchyma cells at the wound site desiccate. The subtending parenchyma cells subsequently become suberized (Walter and Schadel 1983), which is followed by formation of a ligninlike wound periderm beneath the suberized layer. Roots are adequately healed when the wound periderm is 3 to 7 cells thick, the status of which can be assessed using a relatively simple color test (Walter and Schadel 1982). The structure and chemical composition of suberin and lignin in both the epidermis and healed wounds have been characterized (Walter and Schadel 1983).

Radiation Treatments

Extension of sweetpotato shelf-life via treatment with gamma irradiation in general offers no advantage over proper storage temperature management.

Optimum Storage Conditions

Following curing, sweetpotatoes should be carefully moved, usually in palletized containers, to a separate storage room and held at 14±1 °C (57±2 °F) with 90% RH (Kushman 1975). Long-term storage experiments have shown that roots can be stored successfully under these conditions for up to 1 year without sprouting (Picha 1986), though sensory quality declines with extended storage. Storage room air flow should be 1,125 L min^{-1} $tonne^{-1}$ (36 ft^3 min^{-1} ton^{-1}) of roots at optimal temperature and RH. Storage at 19 °C (66 °F) or above results in considerable sprouting after several months of storage and an associated loss in root quality and marketability. Storage of roots at <12 °C (55 °F) results in chilling injury.

Controlled Atmosphere (CA) Considerations

Sweetpotatoes can be stored under CA conditions that reduce the rate of respiratory losses and increase total sugars (Chang and Kays 1981). However, additional research on O_2 and CO_2 concentrations, timing, and cultivar requirements are needed. Uncured roots have been shown to decay rapidly when stored in low O_2; though after curing, 2 and 4% O_2 did not appear to be harmful (Delate and Brecht 1989). To date, the beneficial effects of CA storage have not been shown to outweigh the additional expense.

Retail Outlet Display Considerations

Sweetpotatoes are typically displayed loose (unpackaged) in unrefrigerated display cases at approximately 21°C (70 °F).

Chilling Sensitivity

Sweetpotato roots freeze at -1.9 °C (28.6 °F) (Whiteman 1957) and are susceptible to chilling injury when stored at <12 °C (55 °F) (Lewis and Morris 1956, Picha 1987). Symptoms of chilling injury include root shriveling, surface pitting, abnormal wound periderm formation, fungal decay, internal tissue browning, and hardcore formation (Buescher et al. 1975a, Daines et al. 1976). Synthesis of chlorogenic acid and other phenolic compounds has been associated with tissue browning symptoms (Walter and Purcell 1980).

Hardcore is a physiological disorder in which various areas within the root become hard, apparently due to cold-induced alterations in cellular membranes (Yamaki and Uritani 1972). The disorder is not apparent in fresh roots but appears after cooking or processing. All cultivars appear to be susceptible to hardcore; however, there is substantial variation in susceptibility among cultivars, and noncured roots appear to be more susceptible than cured roots.

The severity of chilling injury depends on the temperature and length of exposure below 12 °C (54 ºF). The respiratory rate of roots at 16 °C (61 °F), after holding at chilling temperatures, increased in relation to the duration of the holding period. Lower storage temperature also increased respiratory rate after removal from the cold storage (Lewis and Morris 1956, Picha 1987). Total sugar content of roots stored at 7 °C (45 °F) was significantly greater than in those stored at 16 °C (61 °F), though the effect was highly cultivar-dependent.

Ethylene Production and Sensitivity

Exposure of sweetpotatoes to ethylene should be avoided. Roots exposed to 10 µL L^{-1} ethylene had reduced β-amylase activity (Buescher et al. 1975b). In addition, ethylene enhances synthesis of phenolic compounds and phenolic oxidizing enzymes, resulting in increased discoloration. The effect, however, requires exposure of roots to ambient ethylene that would normally not be encountered during storage with proper ventilation. Therefore, ethylene exposure under normal storage conditions is a relatively minor concern.

Physiological Disorders

In addition to chilling-induced hardcore, the sweetpotato is susceptible to other physiological disorders. Roots may be lost during curing or storage because of exposure to anaerobic conditions before harvest caused by excessive moisture (Ahn et al. 1980, Chang et al. 1982). Roots may appear sound, only to decompose rapidly once in storage, emitting a distinctive sour, fermented odor. Pithiness is another disorder found in apparently sound roots; it is characterized by reduced density and a spongy feel when squeezed. Curing and storage conditions that promote a high metabolic rate facilitate development, as do sprouting in storage and exposure to low soil temperatures of 5 to 10 °C (41 to 50 °C) before harvest.

Postharvest Pathology

Storage rots are caused by a number of microorganisms. Among the more commonly encountered are *Lasiodiplodia theobromae* (Java black rot) (synomyous with *Botryodiplodia theobromae* and *Diplodia gossypina*), *Ceratocystis fimbriata* (black rot), *Erwinia chrysanthemi* (bacterial soft rot), *Fusarium oxysporum* (surface rot), *Fusarium solani* (root rot), *Macrophomina phaseolina* (charcoal rot), *Monilochaetes infuscans* (scurf), and *Rhizopus stolonifer* (soft rot) (for details on etiology, see Clark and Moyer 1988). Timing of infection varies with the organism and field, harvest, and storage conditions (Moyer 1982). Black rot, fusarium root rot, scurf, and bacterial soft rot can occur preharvest, during harvest, and postharvest. In contrast, soft rot infections tend to occur at harvest or postharvest, while charcoal rot, dry rot, surface rot, and root rot occur during harvest. Harvest and postharvest pathogens are typically opportunistic pathogens that require wounds to gain entry into the root.

Internal cork is a virus-mediated disorder in which root tissue develops necrotic lesions during storage (Kushman and Pope 1972). The number and size of lesions varies widely and increases with storage duration and elevated storage temperature. Lesions are found primarily in the interior, but may also be present on the surface.

Control of postharvest diseases centers on prevention, since little can be done once the root is infected. During harvest, care must be taken to minimize damage to roots and exercise proper sanitation. After harvest, roots should be cured immediately and then stored at the proper temperature. Creating entry wounds via mechanical damage during movement from the curing room to storage areas should be judiciously avoided, as well as after storage during washing, sorting, and grading prior to marketing. Wash-water should be frequently changed to prevent accumulation of inoculum, and the use of calcium hypochlorite in the water is recommended. Postharvest pesticides, if used, must be applied in accordance to State and Federal laws.

Postharvest Entomology

The sweetpotato weevil (*Cylas formicarius* [F.]) (Coleoptera:Brentidae) is a serious storage insect pest. Infested roots should not be stored, because adequate control measures are unavailable. Fruit flies (*Drosophila* spp.) and soldier flies *(Hermetia illucens)* (Diptera:Stratiomyidae) can be problems when there are diseased, soured, or damaged roots in storage. Both can be controlled with sanitation or appropriate insecticide treatment.

Quarantine Issues

Viruses and the sweetpotato weevil are serious quarantine issues. Viral diseases are of concern if roots are used for propagation material because the disease is transferred in roots and transplants (slips) produced from them. Roots from most production areas can be shipped throughout the continental United States, but they may not be imported because of the risk of viral diseases.

The sweetpotato weevil is the single most devastating insect pest of the crop worldwide and is a pest in both field and storage. To date, there are no adequate field or storage control measures, though CA storage treatments may have promise (Delate and Brecht 1989). Roots should not be shipped from weevil-infested production sites to other areas of the country.

Suitability as Fresh-Cut Product

No current potential.

References

Ahn, J.W., W.W. Collins, and D.M. Pharr. 1980. Gas atmosphere in submerged sweet potato roots. HortScience 15:795-796.

Buescher, R.W., W.A. Sistrunk, J.L. Bowers, and C.F. Boettinger. 1975a. Susceptibility of sweet potato lines to development of hardcore, a chilling disorder. Ark. Farm Res. 24(6):2.

Buescher, R.W., W.A. Sistrunk, and P.L. Brady. 1975b. Effects of ethylene on metabolic and quality attributes in sweet potato roots. J. Food Sci. 40:1018-1020.

Chang, L.A., and S.J. Kays. 1981. Effect of low oxygen on sweet potato roots. J. Amer. Soc. Hort. Sci. 106:481-483.

Chang, L.A., L.K. Hammett, and D.M. Pharr. 1982. Ethanol, alcohol dehydrogenase and pyruvate decarboxylase in storage roots of four sweet potato cultivars during simulated flood damage and storage. J. Amer. Soc. Hort. Sci. 107:674-677.

Clark, C.A., and J.W. Moyer. 1988. Compendium of Sweet Potato Diseases. American Phytopathological Society, St. Paul, MN.

Daines, R.H., D.F. Hammond, N.F. Haard, and M.J. Ceponis. 1976. Hardcore development in sweet potatoes. A response to chilling and its remission as influenced by cultivar, curing temperatures and time and duration of chilling. Phytopathology 66:582-587.

Delate, K.M., and J.K. Brecht. 1989. Quality of tropical sweetpotatoes exposed to controlled-atmosphere treatment for postharvest insect control. J. Amer. Soc. Hort. Sci. 114:963-968.

Kays, S.J., and S.E. Kays. 1998. Sweetpotato chemistry in relation to health. *In* Sweetpotato Production Systems toward the 21st Century, pp. 231-272. Kyushu National Agricultural Experiment Station, Miyakonojo, Japan.

Kushman, L.J. 1975. Effect of injury and relative humidity during curing on weight and volume loss of sweet potatoes during curing and storage. HortScience 10:275-277.

Kushman, L.J., and D.T. Pope. 1972. Causes of pithiness in sweet potatoes. Tech. Bull. 207, North Carolina Agricultural Experiment Station, Raleigh, NC.

Lewis, D.A., and L.L. Morris. 1956. Effects of chilling storage on respiration and deterioration of several sweet potato varieties. Proc. Amer. Soc. Hort. Sci. 68:421-428.

Morris, L.L., and L.K. Mann. 1955. Wound healing, keeping quality and compositional changes during curing and storage of sweet potatoes. Hilgardia 24:143-183.

Moyer, J.W. 1982. Postharvest disease management for sweet potatoes. *In* Proceedings of the First International Symposium of the Asian Vegetable Research and Development Center, pp. 177-184. AVRDC, Shanhua, Tainan, Taiwan.

Picha, D.H. 1986. Weight loss in sweet potatoes during curing and storage: contribution of transpiration and respiration. J. Amer. Soc. Hort. Sci. 111:889-892.

Picha, D.H. 1987. Chilling injury, respiration and sugar changes in sweet potatoes stored at low temperature. J. Amer. Soc. Hort. Sci. 112:497-502.

Walter, W.M. Jr., and A.E. Purcell. 1980. Effect of substrate levels and polyphenol oxidase activity on darkening in sweet potato cultivars. J. Agric. Food Chem. 28:941-944.

Walter, W.M. Jr., and W.E. Schadel. 1982. A rapid method for evaluating curing progress in sweet potatoes. J. Amer. Soc. Hort. Sci. 107:1129-1133.

Walter, W.M. Jr., and W.E. Schadel. 1983. Structure and composition of normal skin (periderm) and wound tissue from cured sweet potatoes. J. Amer. Soc. Hort. Sci. 108:909-914.

Wang, Y., R.J. Horvat, R.A. White, and S.J. Kays. 1998. Influence of postharvest curing treatment on the synthesis of the volatile flavor components in sweetpotato. Acta Hort. 464:207-212.

Whiteman, T.M. 1957. Freezing points of fruits, vegetables and florist stocks. Marketing Research Report 196, U.S. Department of Agriculture, Washington, DC.

Yamaki, S., and I. Uritani. 1974. The mechanism of chilling injury in sweet potato. XI. Irreversibility of physiological deterioration. Plant Cell Physiol. 15:385-388.

Swiss Chard

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Scientific Name and Introduction

Swiss chard *(Beta vulgaris* L. var. *cycla)* is a biennial plant belonging to Chenopodiacae family. The edible parts are the elongated, oval, smooth or wrinkled leaves, which can reach 50 cm (20 in) in length including the petiole. The prominent petiole is white or dark-red. It is a good source of folacin (Gami and Chen 1985), vitamin C, and flavonoids (Gil et al. 1998).

Quality Characteristics and Criteria

Leaves must be turgid and dark green, with the midrib and petiole completely white or red depending on the variety. Leaves must not show any symptoms of yellowing or browning or have soil residue. Harvested leaves with petioles can be 20 to 50 cm (7.5 to 20 in) long.

Horticultural Maturity Indices

Leaves are periodically hand-harvested beginning about 60 days after seeding. The harvest season can last 2 to 3 mo in spring and 4 to 6 mo in fall and winter. Sometimes the whole plant is harvested.

Grades, Sizes, and Packaging

There are no U.S. grade standards for Swiss chard. Leaves of similar size and quality are banded together and packed loose in waxed cardboard, wooden, or plastic boxes. Using plastic film to cover packaging reduces water loss.

Precooling Conditions

Room-cooling is often used, but hydrocooling and vacuum-cooling result in faster cooling.

Optimum Storage Conditions

Can be stored for 1 to 2 weeks at 0 °C (32 °F) with 95 to 98% RH.

Controlled Atmosphere (CA) Considerations

Storage can be increased to 1 mo using 2 to 3% CO_2 and 10% O_2 at -0.5 °C (31 °F) (Tesi 1990).

Retail Outlet Display Considerations

Leaves are very delicate and lose water easily if not in plastic liners. Misting with water and refrigerated storage are recommended.

Chilling Sensitivity

Swiss chard is not chilling sensitive and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Ethylene production is very low: 0.13 to 0.14 µL kg^{-1} h^{-1} at 20 °C (68 ºF). Sensitivity, however, is very high. Exposure results in yellowing and senescence.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
2 °C	18 to 20
20 °C	29

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production,

multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal per tonne per day.

Physiological Disorders

Freezing is a risk during refrigerated storage, as are yellowing and browning of leaf margins caused by ethylene exposure.

Postharvest Pathology

The most frequent field pathogens are *Peronospora schachtii* Fuckel and *Cercospora beticola* Sacc.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

No current potential exists.

References

Gami, D.B., and T.S. Chen. 1985. Kinetics of folacin destruction in Swiss chard during storage. J. Food Sci. 50:447-449.

Gil, M.I., F. Ferreres, and F.A. Tomas-Barberan. 1998. Effect of modified atmosphere packaging on the flavonoids and vitamin C content of minimally processed Swiss chard. J. Agric. Food Chem. 46:2007-2012.

Tesi, R. 1990. Bietola da costa. *In* V. Bianco and F. Pimpini, eds., Orticoltura, pp. 323-328. Patron Press, Bologna, Italy.

Tamarillo

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Scientific Name and Introduction

The tamarillo or "tree tomato" (*Cyphomandra betacea* [Cav.], or as renamed by Sendtner, *Solanum betaceum* [Cav.]) is a fruit-bearing subtropical tree of the Solanaceae family. Fruit are smooth-skinned, oval berries capped with a calyx and stem. The three main fresh market types are based on peel and pulp color: red, dark-red, and yellow. The mucilaginous, juicy, seedy pulp has a sweet-acid taste reminiscent of the tomato, and the fruit are sometimes eaten raw; usually, however, they are cooked. Tamarillos can be produced in California, but most dark-red tamarillos in U.S. markets are imported from New Zealand.

Quality Characteristics and Criteria

Fruit should be firm and heavy with no decay or discoloration. Color should be characteristic of the variety. Good quality tamarillos are juicy when ripe with moderate sugar content (8 to 10%) and TA no higher than 1 to 2%.

Horticultural Maturity Indices

The best maturity index for tamarillo is peel and pulp color. Other indices correlated with skin color are changes in firmness, juice content, and SSC. For dark-red-skinned types, which progress from green to dark purple (color due to chlorophyll and anthocyanins) to red, harvesting at the dark purple stage is considered best. If fruit are harvested green, flavor score, juice content, SSC, and color of ripened fruit are inferior to those of fruit harvested at the dark-purple stage (Heatherbell et al. 1982, El-Zeftawi et al. 1988).

Grades, Sizes, and Packaging

There are no U.S. grade standards. Fruit are typically packed into tray packs in single cartons based on four or five fruit size categories.

Precooling Conditions

Room-cooling to storage temperature appears to be the only way tamarillo fruit are precooled. No guidelines are available regarding maximum allowable cooling delays.

Optimum Storage Conditions

Tamarillo fruit can be stored for 4 to 8 weeks (plus an additional week for marketing) at 3 to 5 °C (37 to 40 °F) with 90 to 95% RH (Harman and Patterson 1982). Chilling injury occurs if fruit are stored below 3 °C (37 °F), and fungal decay occurs on the stem and calyx if stored above 5 °C (40 °F). Storage at 7 °C (45 °F) was superior to storage at 0 °C (32 °F) for 35 days, with more discoloration of the calyx and stem at 0 °C (32 °F) but more decay and firmness loss at 7 °C (45 °F) (Espina and Lizana 1991).

Controlled Atmosphere (CA) Considerations

No considerations can be reported at this time.

Retail Outlet Display Considerations

Fruit should be kept cool and dry throughout marketing.

Chilling Sensitivity

Tamarillos are sensitive to chilling injury if stored below 3 °C (37 °F). Symptoms include pitting and a scaldlike browning of the skin, calyx, and stem. Discoloration on the peel is observed within 15 days of storage at 0 °C (32 °F) (Espina and Lizana 1991).

Ethylene Production and Sensitivity

Ethylene production is very low (<0.1 µL kg^{-1} h^{-1}) until fruit begin to senesce (Pratt and Reid 1976). Green and partially ripe fruit respond to ethylene with increased respiration (Pratt and Reid 1976) and accelerated red color development (Prohens et al. 1996). Green fruits, however, have less color development and lower SSC:TA ratio when ripe than fruit harvested partially ripe (Prohens et al. 1996).

Respiration Rates

The respiration rate is 18 to 36 mg (10 to 20 µL) CO_2 kg^{-1} h^{-1} at 18 to 20 ºC (64.4 to 68.0 ºF). Heat production is 3,960 to 7,920 BTU ton^{-1} day^{-1} or 1,098 to 2,196 kcal $tonne^{-1}$ day^{-1}. Data from Pratt and Reid (1976) and Espina and Lizana (1991).

Physiological Disorders

Viral diseases attacking tamarillo plants may cause mottling on the fruit surface.

Postharvest Pathology

Decay is the single most important cause of postharvest losses in tamarillo. The most common decay is bitter rot caused by *Colletotrichum acutatum* and *C. gloeosporioides*. This fungus attacks fruit on the tree, but decay does not develop until fruits start to ripen or are stored for several weeks. A good orchard control program with postharvest applications of fungicides can control development of the disease (Blank et al. 1987). Hot water dip of 50 °C (122 °F) for 10 min, followed by waxing, is also effective (Yearsley et al. 1988). With good decay-control measures, storage life may be extended to 10 to 12 weeks at 3.5 °C (38 °F) (Harman and Patterson 1982).

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

No current potential exists.

References

Blank, R.H., H.M. Dance, R.E. Hampton, et al. 1987. Tamarillo (*Cyphomandra betacea*): effect of field-applied fungicides and postharvest fungicide dips on storage rots of fruit. N.Z. J. Exp. Agric. 15:191-198.

El-Zeftawi, B.M., L. Brohier, L. Dooley, et al. 1988. Some maturity indices for tamarillo and pepino fruits. J. Hort. Sci. 63:163-169.

Espina, S., and L.A. Lizana. 1991. Comportamiento de tamarillo (*Cyphomandra betacea* (Cav.) Sendtner) en almacenaje refrigerado. Proc. Interamer. Soc. Trop. Hort. 35:285-290.

Harman, J.E., and K.J. Patterson. 1982. Kiwifruit, tamarillos and feijoas. Maturity and storage. AgLink HPP 103, Ministry of Agriculture and Fisheries, Wellington, N.Z.

Heatherbell, D.A., M.S. Reid, and R.E. Wrolstad. 1982. The tamarillo: chemical composition during growth and maturation. N.Z. J. Sci. 25:239-243.

Pratt, H.K., and M.S. Reid. 1976. The tamarillo: fruit growth and maturation, ripening, respiration, and the role of ethylene. J. Sci. Fd. Agric. 27:399-404.

Prohens, J., J.J. Ruiz, and F. Nuez. 1996. Advancing the tamarillo harvest by induced postharvest ripening. HortScience 31:109-111.

Yearsley, C.W., B.Y. Huang, H.J.W. McGrath, et al. 1988. Red tamarillos (*Cyphomandra betacea*): comparison of two postharvest dipping strategies for the control of fungal storage disorders. N.Z. J. Exp. Agric.16:359-356.

Tamarind

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Scientific Name and Introduction

Tamarind fruit (*Tamarindus indica* L.; synonyms *T. occidentalis* Gaertn., *T. officinalis* Hook.) are indehiscent, beanlike, curved pods 3 to 20 cm (1.2 to 7.9 in) long weighing 15 to 20 g (0.5 to 0.7 oz). Fruit have a scurfy brown, woody, fragile shell with brown pulp and 8 to 10 blackish-brown, hard, shiny seeds (Hernandez-Unzon and Lakshminarayana 1982a). Fruit are about 30% shell, 30% pulp, and 40% seeds. The color of the pulp comes from the presence of several anthocyanins, of which vitexene is the most important (Lewis and Neelakantan 1964). There are also fruit with red pulp; these are not commonly cultivated. However, the reddish-flesh types are distinguished in some regions and are regarded as superior in quality. Fruit are eaten at the green-mature stage or when the shell pod has become brittle and the pulp brown. Tamarind is a good source of calcium, phosphorous, and iron and an excellent source of riboflavin, thiamin, and niacin; but it contains only small amounts of vitamins A and C (Bueso 1980).

Tamarind is of minor importance in the United States. The two major types are "sweet-fruited" and "acid-flavored." Tamarind is considered to be both the sweetest and the most sour of all fruits—on a fresh weight basis, mature tamarind pulp has 30 to 35% sugar and 12 to 24% TA. Some cultivars have sweeter pulp, such as 'Makham Waan' in Thailand and 'Manila Sweet' in Florida (Morton 1958).

Quality Characteristics and Criteria

Both green immature pods and brown ripe pods are normally marketed when 5 to 20 cm (2.0 to 7.9 in) long.

Horticultural Maturity Indices

Tamarind fruit take about 8 mo from fruit set to harvest, and growth is a typical sigmoid type (Hernandez-Unzon and Lakshminarayana 1982a). As pods mature, skin develops into a brown, brittle shell, the pulp turns brown or reddish-brown, and seeds become covered with dry and sticky pulp. When fully ripe, the shells are brittle and easily broken. Mature fruit can be left on the tree for more than 6 mo after ripening without significant spoilage; however, birds and insects become pests. Fruit should be harvested when the moisture content is <20% to facilitate separation of the shell from the pulp.

Harvesting

Ripe fruit should be harvested so as to prevent improper ripening and difficulties in separation of the peel after harvest. Fruit can be pulled off the peduncle or cut using scissors (Hernandez-Tuzon and Lakshminarayana 1982b). Fruit for immediate processing are harvested by pulling pods away from the stalk. Some can be harvested by shaking the branches, leaving the remaining fruit to fall naturally when ripe. In humid climates, fruit are readily attacked by beetles and fungi and should therefore be harvested before they are fully ripe. Dry, ripe fruits are easily cracked, and the pulp and fibers separated from the broken shell.

Optimum Storage Conditions

The high SSC:TA and the low water content contribute to a long storage life. Tamarind can be stored with the skin or as a separated dry pulp. Tightly packaged pods can be stored at about 20 °C (68 °F) for several weeks. The pulp of mature tamarind is commonly compressed and packed in palm leaf mats or plastic bags and stored at 20 °C (68 °F). It can be stored for a significant length of time when processed into a paste. It can be frozen and stored for 1 year, or refrigerated for up to 6 mo. During storage, the dry, dark-brown pulp becomes soft, sticky, and almost black. The pulp can be stored for a longer period after drying or steaming.

Respiration Rates

Tamarind fruit are nonclimacteric. Maximum CO_2 production occurs 4 weeks after fruit set and then gradually declines (Hernandez-Unzon and Lakshminarayana 1982b).

Postharvest Pathology

Tamarind fruit are very tolerant to pathogens and insects, except for occasional incidence of scab. This resistance may be due to the low water content and high acid and sugar content, as well as high polyphenol content in the peel. Ripe fruit are susceptible to mold, insects, and birds.

Quarantine Issues

Various weevils and borers can infest the ripening pods or stored fruits. Pulp separated from the peel is highly susceptible to molds. Tamarind beetle *(Pacymerus [Coryoborus] gonogra)* and tamarind seed borer *(Calandra [Sitophilus] lineris)* can infest ripening pods and persist in the stored fruits. The rice weevil *(Sitophilus oryzae)*, rice moth *(Corcyra cepholonica)*, and fig moth *(Ephestia cautella)* can infest fruit in storage.

Suitability as Fresh-Cut Product

Tamarind is not suitable as a fresh-cut product at this time.

Special Considerations

Fruit are commonly processed into juices, nectars, fruit punch, concentrates, and glaceéd and crystallized fruit. The pulp can withstand thermal processing without affecting the original flavor profile (Bueso 1980).

References

Bueso, C.E. 1980. Soursop, tamarind and chironja. *In* S. Nagy and P.E. Shaw, eds., Tropical and Subtropical Fruits: Composition, Properties and Uses, pp. 375-406. AVI, Westport, CT.

Hernadez-Unzon, H.Y., and S. Lakshminarayana. 1982a. Biochemical changes during development and ripening of tamarind fruit (*Tamarindus indica* L.). HortScience 17:940-942.

Hernadez-Unzon, H.Y., and S. Lakshminarayana. 1982b. Developmental physiology of tamarind fruit (*Tamarindus indica* L.). HortScience 17:938-940.

Lewis, Y.S., and S. Neelakantan. 1964. The real nature of tamarind anthoxanthin. Curr. Sci. 15:460.

Morton, J.F. 1958. The tamarind, its food, medicinal and industrial uses. Proc. Fla. State Hort. Soc. 79:355-366.

Taro

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Scientific Name and Introduction

Taro (*Colocasia esculenta* [L.] Schott) is one of the oldest of food crops, widely distributed throughout Asia and the Pacific. The plant is also known as tannier, malanga, dasheen, eddoe, and cocoyam. There is also substantial production in Egypt and the Caribbean (O'Hare and Asokan 1986). There are up to 600 varieties. The root (also called a corm or tuber) is consumed, as are the petioles and leaves. Corm flesh varies from white to yellow and red to purple. The corm is high in starch and low in protein and fat. All parts of the plant must be cooked prior to eating because of the presence of acridity substance(s) associated with raphides, needle-shaped crystals of calcium oxalate (Paull et al. 1999).

Quality Characteristics and Criteria

There are two main types of taro: the smaller segmented root up to 14 cm (5.5 in) long and the larger cylindrical root upwards of 35 cm (14 in) long and 10 to 15 cm (4 to 6 in) in diameter. Both are brown. The corm should have no sprouts and be free from cuts, insects, and disease damage. The smaller eddoe possesses some degree of dormancy, while there is no dormancy in the larger taro corms.

Horticultural Maturity Indices

Roots are harvested when they are the size desired by the market. Most often this is after they have stopped growing and leaves have begun to die back 8 to 12 mo after planting. The main corm is harvested and smaller coromels removed; diseased areas on main corms are excised. In eddoe, the coromels are also harvested. Young taro leaves are also harvested, bunched, and marketed as a leafy vegetable.

Grades, Sizes, and Packaging

There are no U.S. or international standards. Corms are graded by size, skin color, shape, and flesh texture. They are packed in 22.5-kg (50-lb) cartons, crates, or sacks. The small root (dasheen) may also be sold in 4.5-kg (10-lb) cartons.

Precooling Conditions

Taro should be room-cooled to 10 to 14 °C (50 to 57 °F).

Optimum Storage Conditions

Good ventilation is essential for storage. The storage recommendation is 7 to 10 °C (45 to 50 °F) with 80 to 95% RH for up to 18 weeks. However, roots must be eaten within 2 days of removal to ambient temperature (Snowdon 1992). At 11 to 13 °C (52 to 55 °F), storage life is up to 8 weeks. At 20 °C (68 °F), storage life is from 2 to 4 weeks.

Controlled Atmosphere (CA) Considerations

There are no published reports on CA and taro. However, MAP in polyethylene film bags of the related xanthosoma and taro at 27 to 32 °C (81 to 90 °F) reduces weight loss (Passam 1982).

Retail Outlet Display Considerations

Taro should be displayed dry and should not be misted.

Chilling Sensitivity

Chilling injury leads to pitting and increased postharvest disease.

Ethylene Production and Sensitivity

Taro roots have a very low ethylene production. There is no known response of taro roots to ethylene application.

Respiration Rates

Respiration rates of taro have not been documented.

Physiological Disorders

Chilling injury is a common problem with large taro roots. Variation in cooked texture sometimes occurs; the cause is unknown.

Postharvest Pathology

Pythium root rot can be a major problem in wetland taro. Corm rots can also be associated with a complex of microorganisms, including *Fusarium*, *Sclerotinia*, *Erwinia*, *Botryodiplodia*, and *Ceratocystis*. These decay organisms are associated with field infection through wounds. After washing roots to remove soil and then cutting out diseased tissue, corms should be dried (cured) so that wounds can heal. Curing is best done at 20 to 30 °C (68 to 86 °F), followed by cooling to control further disease development (Snowdon 1992).

Quarantine Issues

Aphids can be a major problem on taro leaves.

Suitability as Fresh-Cut Product

Taro must be cooked before eating.

Special Considerations

Corms are roasted, baked, boiled, or deep-fried. Grated, cooked corm is sometimes mixed with coconut milk. Corms are boiled, mashed, and sieved for poi.

References

O'Hare, S.K., and M.P. Asokan. 1986. Edible aroids: botany and horticulture. Hort. Rev. 8:43-99.

Passam, H.C. 1982. Experiments on the storage of eddoes and tannias (*Colocasia* and *Xanthosoma* spp) under ambient conditions. Trop. Sci. 24:39-46.

Paull, R.E., C.S. Tang, K.C. Gross, and G. Uruu. 1999. The nature of the taro acridity factor. Postharv. Biol. Technol. 16:71-78.

Snowdon, A.L. 1992. Tropical roots and tubers—cocoyams (tannias and taros). *In* A.L. Snowdon, Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables, pp. 350-357. CRC Press, Boca Raton FL.

Tomatillo

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Scientific Name and Introduction

The tomatillo, or husk tomato, (*Physalis ixocarpa* Brot. ex Hornem) is a warm-season vegetable of the Solanaceae family. The small, spherical, green or green-purple fruit is surrounded by an enlarged calyx, or "husk." As the fruit matures, it fills the husk and can split it open by harvest time. Tomatillo is the key ingredient in fresh and cooked green salsas and other Latin American dishes. Tomatillos are available year-round. In the United States tomatillo are produced mainly on small acreages in California, but large volumes are imported from Mexico (Smith et al. 1999).

Quality Characteristics and Criteria

The freshness and greenness of the calyx (husk) are quality criteria. Fruit should be firm and bright green, since the color and acidic flavor are the main culinary contributions of tomatillos (Moriconi et al. 1990, Bock et al. 1995).

Horticultural Maturity Indices

Tomatillos can be harvested at various stages of development. For commercial marketing, they should be harvested when fruit are well formed and have substantially filled the husk but are still bright green. Overmature fruit that are light green or yellowing should be avoided, since they are sweeter and undesirable for most uses.

Grades, Sizes, and Packaging

There are no U.S. Grades. Fruit are not usually sized before packing. They are packed in 18-kg (40-lb) crates (Mexican fruit) or in 4.5-kg (10-lb) cartons (U.S. fruit).

Precooling Conditions

Forced-air cool or room-cool to retain fresh appearance of the husk.

Optimum Storage Conditions

Tomatillos can be stored under a wide range of conditions. At ambient temperatures, the husks will dry, but the fruit will remain in good condition for about 1 week. The freshness of fruit and husk can be extended by storage at 5 to 10 °C (41 to 50 °F) with 80 to 90% RH. Chilling injury can occur after 3 weeks at 5 °C (41 °F).

Controlled Atmosphere (CA) Considerations

No information is available.

Retail Outlet Display Considerations

Tomatillos should be kept cool to reduce water loss and minimize superficial decay. They should not be misted.

Chilling Sensitivity

Tomatillos can be stored for 1 mo at 10 °C (50 °F) without developing chilling injury symptoms. Fruit begin to show symptoms (surface pitting and decay) after 3 weeks at 5 °C (41 °F); symptoms become more pronounced at 2.5 °C (37 °F).

Ethylene Production and Sensitivity

Immature tomatillos produce low amounts of ethylene: 0.5 to 2.0 µL kg^{-1} h^{-1} at 10 to 20 °C (50 to 68 °F). More mature fruit produce greater amounts: 1 to 10 µL kg^{-1} h^{-1}. Ethylene production can be high, 20 to 40 µL kg^{-1} h^{-1} at 20 °C (68 °F), in overmature fruit (that is, fruit showing color changes due to ripening). Exposure of mature fruit to ethylene causes undesirable color changes (Cantwell et al. 1992).

Respiration Rates

Respiration rates remain relatively constant during storage at 5 and 10 °C (41 to 50 °F); rates decrease during storage at 20 °C (68 °F). Respiration rates of developing fruit are about 25% higher than those of mature fruit.

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	12 to 14
10 °C	13 to 19
20 °C	27 to 36

Data for mature-green fruit from Cantwell et al. (1992).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

See *Chilling Sensitivity.*

Postharvest Pathology

Chilling injury can encourage the development of black mold caused by *Alternaria alternata*, the same organism often found on chill-injured red tomatoes. Superficial molds occur on the husk during storage under high RH, but they have not been identified. Washing in chlorinated water reduces superficial mold growth, but this may be difficult to implement commercially since it is difficult to remove all moisture inside the husk.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Not suitable for fresh-cut product at this time.

References

Bock, M.A., J. Sanchez-Pilcher, L.J. McKee, and M. Ortiz. 1995. Selected nutritional and quality analyses of tomatillos (*Physalis ixocarpa*). Plant Foods Human Nutr. 48:127-133.

Cantwell, M., J. Flores-Minutti, and A. Trejo-González. 1992. Developmental changes and postharvest physiology of tomatillo fruits (*Physalis ixocarpa* Brot.). Sci. Hort. 50:59-70.

Moriconi, D.N., M.C. Rush, and H. Flores. 1990. Tomatillo: a potential vegetable crop for Louisiana. *In* J. Janick and J.E. Simon, eds., Advances in New Crops: Research, Development, Economics, pp. 407-413. Timber Press, Portland, OR.

Smith, R., M. Jimenez, and M. Cantwell. 1999. Tomatillo production in California. Pub. no. 7246, University of California, Division of Agriculture and Natural Resources, Davis, CA.

Tomato

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Scientific Name and Introduction

Tomato (*Solanum lycopersicum* L.) is a warm-season crop with origins in elevated regions of Peru and Ecuador. A member of the Solanaceae family, tomato is the second most produced vegetable in the United States, behind the potato. The round, red-fleshed tomato predominates in the fresh market, but red- and yellow-fleshed round, plum (roma), cluster, cherry, grape, and minipear types are also available. Domestic production is year round, though winter and spring imports from Mexico are increasing. Most tomatoes are grown in the field, but the use of protected culture is on the rise around the world. Dominant suppliers of greenhouse-grown tomatoes to U.S. markets are Holland, Spain, Israel, and Canada.

Quality Characteristics and Criteria

High-quality fruit have a firm, turgid appearance; uniform and shiny color; and no signs of mechanical injury, shriveling, or decay. Principal causes for postharvest losses are decay, external damage incurred during harvest and handling, and harvest at an improper maturity stage.

Horticultural Maturity Indices

Depending on the market and production area, tomatoes are harvested at stages of maturity ranging from physiological maturity (mature-green stage) through full-ripe. Immature tomatoes are available for certain regional dishes. It is difficult to accurately determine the completion of physiological maturity. Depending on the growing area and time of harvest, the percentage of immature tomatoes (M-1) in lots of green-harvested tomatoes can range from 20 to 80% (Sargent and VanSickle 1996). Tomatoes harvested at the mature-green stage (M-3 or M-4) will ripen to high quality if handled properly (Maul et al. 1998). Tomatoes harvested at the M-2 stage will ripen to moderate quality, while those harvested at M-1 stage will not ripen to acceptable levels of quality.

Maturity stage	Internal appearance (equatorial section)
M-1	Seeds immature (white) and can be cut when the tomato is sliced; no gel in the locule.
M-2	Seeds mature (tan); gel formation in at least two locules.
M-3	Seeds pushed aside when tomato sliced; all locules have gel; internal color is still green.
M-4	Appearance of red color in gel and pericarp tissue.

Adapted from Kader and Morris (1976).

Ripeness stages are defined according to the following standards for red-fleshed tomatoes (AMS 1991):

Ripeness stage	External color
(1) Green	Fruit surface is completely green; the shade of green may vary from light to dark.
(2) Breaker	There is a definite break in color from green to tannish-yellow, pink, or red on not more than 10% of the surface.
(3) Turning	10 to 30% of the surface is not green; in the aggregate, shows a definite change from green to tannish-yellow, pink, red, or a combination thereof.
(4) Pink	30 to 60% of the surface is not green; in the aggregate, shows pink or red color.

(5) Light red	60 to 90% of the surface is not green; in the aggregate, shows pinkish-red or red.
(6) Red	More than 90% of the surface is not green; in the aggregate, shows red color.

Tomato Color Standards are based on the USDA Visual Aid TM-L-1, which consists of a chart containing twelve color photographs illustrating the color classification requirements.

Grades, Sizes, and Packaging

Grades for field-grown tomatoes include U.S. No. 1, U.S. , No. 2, U.S. Combination, and No. 3, with tolerances established for defects at shipping point and en route or at destination (AMS 1991). Fruit within a grade should have similar varietal characteristics and be uniformly mature, not overripe or soft, clean, well developed, fairly well formed, fairly smooth, and uniform in color. Fruit should be free from decay, freezing injury, sunscald, and damage caused by bruising, discoloration, sunken scars, cuts and broken skins, puffiness, catfaces, other scars, radial or concentric growth cracks, and hail or insect injury.

Tomatoes are rigorously sized with a 0.8 mm (1/32-in) overlap permitted between sizes, according to the following dimensions (AMS 1991):

Size	Minimum diameter[1]	Maximum diameter[2]
Small	5.40 cm (2 4/32 in)	5.79 cm (2 9/32 in)
Medium	5.72 cm (2 8/32 in)	6.43 cm (2 17/32 in)
Large	6.35 cm (2 16/32 in)	7.06 cm (2 25/32 in)
Extra large	7.00 cm (2 24/32 in)	

[1] Will not pass through a round opening of the designated diameter when tomato is placed with the greatest transverse diameter across the opening.

[2] Will pass through a round opening of the designated diameter in any position.

Field-grown tomatoes are typically packed in lidded, 11.4-kg (25-lb) cartons, 30×40×24 cm (12×16×9.5 in) (W×L×H), that stack 10 cartons per layer on a 100×120 cm (40×48 in) pallet.

Grades for greenhouse tomatoes include U.S. No. 1 and No. 2 (AMS 2007). Ripeness stages and defects are similar to field-grown tomatoes. These fruit are sized as follows:

Size	Weight
Small	<99.4 g (<3.5 oz)
Medium	99.4 to 256 g (3.5 to 9 oz)
Large	>256 g (>9 oz)

Greenhouse-grown tomatoes are generally harvested at turning stage or later and packed according to ripeness and size (count) in single- or double-layer cartons, with or without bottom trays. Cluster tomatoes are usually picked when the least mature tomato begins to show red color. Uniformity of fruit color, stem freshness, and fruit attachment to the stem are important quality characteristics for this tomato type. Cluster tomatoes are usually packed in single-layer cartons but sometimes in netted bags. Foam bottom pads may be inserted to reduce abrasion and bruising.

There are currently no U.S. grade standards for other types of tomatoes. They are all typically harvested once ripening has started and are sorted by defect and color. Roma-type tomatoes are normally packed in 11.4-kg (25-lb) cartons by color, while cherry, grape, and minipear tomatoes are packed in 227- to 454-g (8- to 16-oz) baskets or clamshell containers and placed in larger master cartons to facilitate palletizing.

Precooling Conditions

Following commercial packing, tomatoes are routinely palletized and cooled to 20 °C (68 °F) for ripening or to 12 °C (54 °F) for storage. While room-cooling is common, forced-air cooling is more uniform and produces better quality fruit. Packed, palletized tomatoes with pulp temperature of 28 °C (83 °F) actually increased 2 °C (4 °F) immediately after being stored at 20 °C (68 °F), and only cooled to 23 °C (73 °F) after 24 h using room-cooling (Brecht 1996). However, with forced-air cooling, tomatoes cooled to 20 °C (68 °F) in 2.5 h and ripened more uniformly throughout the pallet than those room-cooled.

Optimum Storage Conditions

Optimal storage temperatures depend on the maturity stage of the tomatoes. Ideal conditions for ripening are 19 to 21 °C (66 to 70 °F) with 90 to 95% RH. Storage at temperatures >27 °C (81 °F) reduces intensity of red color, while storage at <13 °C (55 °F) retards ripening and can lead to development of chilling injury, particularly in tomatoes at the mature-green stage. Red tomatoes can be stored at 7 °C (45 °F) for a couple of days, though tomatoes stored at 10 °C (50 °F) were rated lower in flavor and aroma than those held at 13 °C (55 °F) (Maul et al. 2000).

Controlled Atmosphere (CA) Considerations

Tomatoes can be stored under CA to extend product quality (see below). The exact combination of CO_2 and O_2 varies among maturity stages and cultivars; but a satisfactory CA is 3% O_2 and 2% CO_2 (Wills et al. 1998). Storage under CA delays quality loss as measured by several factors, such as lycopene synthesis and sugar and chlorophyll degradation (Goodenough and Thomas 1980, Nakhasi et al. 1991). Storage in 3% O_2 and 97% N_2 extended postharvest life of mature-green tomatoes for 6 weeks at 13 °C (55 °F) without the development of off flavors (Parsons et al. 1970). Storage under CA may reduce development of undesirable symptoms caused by mechanical injury (Kader 1986). However, Moretti et al. (1999) observed that CA storage did not alleviate development of internal bruising (disruption of locular gel ripening) following impacts.

Ripeness stage	Temperature	O_2(%)	CO_2(%)	Benefit
Mature green	12 to 20 °C	3 to 5	2 to 3	slight
Red	10 to 15 °C	3 to 5	3 to 5	moderate

Data from Saltveit (1997).

Retail Outlet Display Considerations

Tomatoes are normally displayed at the retail level in single-layer, corrugated cartons or in plastic clamshell containers at about 20 °C (68 °F). Grading, sizing, and packing fruit adds value and convenience to the final product. An important issue in the marketing of high-quality tomatoes is uniformity of size, grade, firmness, and color. Consumers tend to avoid packages of fruit with different colors, decay, or external blemishes. Some distributors also offer tomatoes in bulk containers, giving the consumer the option to choose among different maturities, sizes, and types of tomato. However, since tomato fruit are sensitive to compression stress, care must be taken to avoid overloading the display.

Chilling Sensitivity

Tomato fruit are chilling sensitive, and the recommended storage temperature varies with the maturity stage. Mature-green fruit will ripen normally at 13 to 21 °C (55 to 70 °F). On the other hand, ripe tomato fruit can be stored at 10 °C (50 °F) without visible symptoms of chilling injury, though flavor and aroma are negatively affected (Maul et al. 2000). Visual symptoms of chilling injury include pitting, nonuniform ripening, and storage decays (see *Postharvest Pathology*) (Wills et al. 1998).

Ethylene Production and Sensitivity

Tomato fruit produce moderate amounts of ethylene: 1 to 10 µL kg^{-1} h^{-1} at 20 °C (68 °F). Tomatoes are sensitive to ethylene exposure: As little as 0.5 µL L^{-1} ethylene is sufficient to trigger ripening and other associated metabolic processes (Abeles et al. 1992). For commercial ripening, green tomatoes should be held at 20 to 21 °C (50 to 52 °F) with 90% RH and 50 µL L^{-1} ethylene; this will promote uniform ripening. Upon reaching breaker stage, tomatoes produce sufficient ethylene and no longer require gassing. Highest quality tomatoes are those reaching the breaker stage within 3 days of ethylene exposure. These fruit were harvested at the mature green stage and will ripen with quality similar to tomatoes harvested at the breaker stage or later (Maul et al. 1998).

Respiration Rates

Tomatoes are climacteric and show a pronounced increase in respiration during ripening. The intensity and duration of the climacteric varies among cultivars (Wills et al. 1998). Respiration also varies with temperature and atmospheric composition.

Temperature	Air*	3% O_2 /97% N_2†
	mg CO_2 kg^{-1} h^{-1}	
10 °C	13 to 16	6
15 °C	16 to 28	-
20 °C	28 to 41	12
25 °C	35 to 51	-

*Data from Scholz et al. (1963). Storage at 10 °C (50 °F) is only recommended for red-ripe tomatoes.
†Data from Robinson et al. (1975).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Blotchy ripening is characterized by randomized development of green or green-yellowish areas on the surface of red tomato fruit. Apparently the development of this disorder is related to the availability of potassium and inorganic nitrogen in the soil. Areas showing blotchy ripening have less organic acids, SSC, and starch (Moretti et al. 2000).

Sunburn is associated with excessive exposure to sunlight and the resultant elevated tissue temperature during fruit development, disrupting lycopene synthesis and resulting in the appearance of yellow areas that remain during ripening.

Blossom-end rot involves a calcium deficiency caused by either poor uptake or poor translocation into the fruit. Symptoms begin in the green fruit as a small discoloration at the blossom end that increases in size and becomes dry and dark brown. Occurrence increases dramatically when calcium levels in the soil system drop below 0.08% (Moretti et al. 2000). Eventually, secondary decay organisms colonize weakened tissues.

Graywall is noticeable as necrotic vascular tissue in the pericarp fruit wall (Jones et al. 1999). It begins developing at the green stage and has been associated with marginal growing conditions such as cool weather, low light levels, poor nutrition, saturated soils, tobacco mosaic virus, and bacteria; however, the cause is still undetermined. Graywall can be a serious disorder in both field and greenhouse production systems.

Irregular ripening is characterized by the appearance of nonuniform ripening and white internal tissue. It has been associated with feeding of sweetpotato whitefly *(Bemisia argentifolii)* on tomato fruit (Hanif-Khan et al. 1997).

Internal bruising is recognized by the appearance of yellow to green locular gel in ripe tomatoes. It is caused by an impairment of normal ripening of the locular gel following a physical impact at the green or breaker stage of ripeness (MacLeod et al. 1976). Fruit with internal bruising show significant reductions in vitamin C content, TA, consistency, and total carotenoids (Moretti et al. 1998). Besides altering quality attributes, internal bruising also affects flavor (Moretti et al. 2002). Breaker-stage tomatoes are more sensitive to internal bruising than those handled at the green stage (Sargent et al. 1992).

Postharvest Pathology

Tomatoes are susceptible to numerous fruit decays from the field through postharvest handling. Postharvest decay often develops in wounds and bruised tissue and during fruit softening. Sound tomatoes can be inoculated by plant pathogens via cross-contamination from diseased fruit, dirty harvest containers, and poorly sanitized water handling systems and packing line components. Populations of decay pathogens can be adequately controlled through a regular sanitation program in the field and during handling, packing, and ripening-storage operations.

Causes of bacterial decay include soft rot *(Bacillus* spp., *Erwinia carotovora* ssp., *Pseudomonas* spp., and *Xanthomonas campestris)* and lactic acid decay (bacterial sour rot) *(Lactobacillus* spp. and *Leuconostoc mesenteroides)* (Bartz et al. 1995, Conn et al. 1995).

Fungal decay sources include alternaria rot (black rot) *(Alternaria alternata),* fusarium rot (*Fusarium* spp.), gray mold rot *(Botrytis cinerea),* mucor rot *(Mucor mucedo),* phoma rot (*Phoma* ssp.), phomopsis rot (*Diaporthe* spp.), phytophthora rot (buckeye rot) (*Phytophthora* spp.), pleospora rot (*Pleospora herbarum, Stemphylium botryosum* imp. stage), rhizopus rot *(Rhizopus stolonifer, R. oryzae),* ring rot *(Myrothecium roridum),* sclerotium rot *(Sclerotium rolfsii),* sour rot *(Geotrichum candidum),* target spot *(Corynespora cassiicola),* and watery soft rot *(Sclerotinia minor, S. sclerotiorum).* Tomato spotted wilt virus induces a mottled coloration at red stage. (Information adapted from Jones et al. [1991] and Snowdon [1992].)

Quarantine Issues

Tomato fruit are a host for fruit flies and are subject to inspection in quarantined areas. Methyl bromide has been employed on a wide range of fruits and vegetables; however, its use is being phased out. Tomatoes have a phytotoxic response, characterized by delayed ripening and reduced sensitivity to exposure to ethylene (Brecht 1994). Vapor heat and hot water treatments are effective alternatives to treatment with methyl bromide.

Suitability as Fresh-Cut Product

Despite efforts to commercialize fresh-cut tomatoes, such products are still only available in limited quantities to the food-service industry, particularly fast-food restaurants and catering services. After processing, loss of the gel-like locule tissue, desiccation, water-soaking, and the development of decay are the principal constraints challenging the worldwide fresh-cut industry. Crossing commercial varieties with mutants that express delayed softening and slicing less ripe tomatoes (in the breaker stage, for instance) for subsequent application of ethylene are strategies being researched in different parts of the world to obtain a fresh-cut tomato with sufficient postharvest life to be readily commercialized. Mature-green sliced tomatoes ripen normally at 20 °C (68 °F) (Mencarelli and Saltveit 1988). Sliced red tomatoes maintain good quality for 14 days when stored in MAP at 5 °C (Hong and Gross 2001).

Special Considerations

Ethylene used to ripen tomatoes can be catalytically generated from ethanol using commercially available units or supplied from compressed cylinders. Because air mixtures of 3 to 32% ethylene are explosive (Abeles et al. 1992), ethylene for ripening rooms is supplied from a compressed cylinder containing a <3% ethylene in N_2. A metered flow of ethylene from either a catalytic unit or compressed cylinder is used to produce a diluted, active concentration of ethylene in the ripening room.

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References

Abeles, F.B., P.W. Morgan, and M.E. Saltveit. 1992. Ethylene in Plant Biology, 2nd ed. Acad. Press, Waltham, MA.

AMS [USDA Agricultural Marketing Service]. 2007. United States standards for grades of tomatoes on the vine. *At* http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5065392

AMS [USDA Agricultural Marketing Service]. 1991. United States standards for grades of fresh tomatoes. *At* http://www.ams.usda.gov/standards/tomatfrh.pdf.

Bartz, J.A., N.C. Hodge, Y. Perez, and D. Concelmo. 1995. Two different bacteria cause a decay in tomatoes that is similar to sour rot. Phytopathology 85:1123.

Brecht, J.K. 1994. Vegetables. *In* R.E. Paull and J.W. Armstrong, eds., Insect Pests and Fresh Horticultural Products: Treatments and Responses, pp. 309-328. CAB International, Wallingford, U.K.

Brecht, J.K. 1996. Tomato response to ethylene at high temperatures: are pressure ripening systems worth considering? *In* C.S. Vavrina, ed., Proceedings of the Florida Tomato Institute, pp. 11-13. Pub. no. PRO 108, University of Florida, Institute of Food and Agricultural Science, Gainesville, FL.

Conn, K.E., J.M. Ogawa, B.T. Manji, and J.E. Adaskaveg. 1995. *Leuconostoc mesenteroides* subsp. *mesenteroides,* the first report of a coccoid bacterium causing a plant disease. Phytopathology 85:593-599.

Goodenough, P.W., and T.H. Thomas. 1980. Comparative physiology of field grown tomatoes during ripening on the plant or retard ripening in controlled atmospheres. Ann. Appl. Biol. 94:445-455.

Hanif-Khan, S., R.C. Bullock, P.J. Stoffella, et al. 1997. Possible involvement of altered gibberellin metabolism in the induction of tomato irregular ripening in dwarf cherry tomato by silverleaf whitefly. J. Plant Growth Reg. 16(4):245-251.

Hong, J.H., and K.C. Gross. 2001. Maintaining quality of fresh-cut tomato slices through modified atmosphere packaging and low temperature storage. J. Food Sci. 66(7):960-965.

Jones, J.B., J. Jones, R. Stall, and T. Zitter. 1991. Compendium of Tomato Diseases. APS, St. Paul, MN.

Kader, A.A. 1986. Biochemical and physiological basis for effects of controlled and modified atmospheres on fruits and vegetables. Food Technol. 40(5):99-104.

Kader, A.A., and L.L. Morris. 1976. Correlating subjective and objective measurements of maturation and ripeness of tomatoes. *In* Proceedings of the 2nd Tomato Quality Workshop. Vegetable Crop Series no. 178, University of California, Davis, CA.

MacLeod, R.F., A.A. Kader, and L.L. Morris. 1976. Stimulation of ethylene and CO_2 production of mature-green tomatoes by impact bruising. HortScience 11(6):604-606.

Maul, F., S.A. Sargent, M.O. Balaban, et al. 1998. Aroma volatile profiles from ripe tomato fruit are influenced by physiological maturity at harvest: an application for electronic nose technology. J. Amer. Soc. Hort. Sci. 123(6):1094-1101.

Maul, F., S.A. Sargent, C.A. Sims, et al. 2000. Recommended commercial storage temperatures affect tomato flavor and aroma quality. J. Food Sci. 65(7):1228-1237.

Mencarelli, F., and M.E. Saltveit. 1988. Ripening of mature-green tomato fruit slices. J. Amer. Soc. Hort. Sci. 113(5):742-745.

Moretti, C.L., E.A. Baldwin, S.A. Sargent, and D.J. Huber. 2002. Internal bruising alters aroma volatile profiles in tomato fruit tissues. HortScience 37(2):378-382.

Moretti, C.L., A.G. Calbo, and G.P. Henz. 2000. Postharvest physiology and handling. *In* J.B.C. Silva and L.B. Giordano, eds., Processing Tomatoes, p.136-143. Embrapa/SCT, Brasilia, Brazil.

Moretti, C.L., S.A. Sargent, D.J. Huber, et al. 1998. Chemical composition and physical properties of pericarp, locule and placental tissues of tomatoes with internal bruising. J. Amer. Soc. Hort. Sci. 123(4):656-660.

Moretti, C.L., S.A. Sargent, D.J. Huber, et al. 1999. Delayed ripening does not alleviate symptoms of internal bruising in tomato fruit. Proc. Fla. State Hort. Soc. 112:169-171.

Nakhasi, S., D. Schlimme, and T. Solomos. 1991. Storage potential of tomatoes harvested at the breaker stage using modified atmosphere storage. J. Food Sci. 56(1):55-59.

Parsons, C.S., R.E. Anderson, and R.W. Penney. 1970. Storage of mature-green tomatoes in controlled atmospheres. J. Amer. Soc. Hort. Sci. 95:791-794.

Robinson, J.E., K.M. Browne, and W.G. Burton. 1975. Storage characteristics of some vegetables and soft fruits. Ann. Appl. Biol. 81:399-408.

Saltveit, M.E. 1997. A summary of CA and MA requirements and recommendations for harvested vegetables. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, July 13-18, 1997, University of California, Davis, vol. 4, pp. 98-117. University of California, Davis, CA.

Sargent, S.A., J.K. Brecht, and J.J. Zoellner. 1992. Sensitivity of tomatoes at mature-green and breaker ripeness stages to internal bruising. J. Amer. Soc. Hort. Sci. 117(1):119-123.

Sargent, S.A., and J.J. VanSickle. 1996. Premium-quality tomato program for Florida. *In* C.S. Vavrina, ed., Proceedings of the Florida Tomato Institute, pp. 8-9. Pub. no. PRO 108, University of Florida, Institute of Food & Agricultural Science, Gainesville, FL.

Scholz, E.W, H.B. Johnson, and W.R. Buford. 1963. Heat-evolution rates of some [Lower Rio Grande Valley] Texas-grown fruits and vegetables. J. Rio Grande Valley Hort. Soc. 17:170-175.

Snowdon, A.L. 1992. Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables. CRC Press, Boca Raton FL.

Wills, R.B.H., B. McGlasson, D. Graham, and D. Joyce. 1998. Postharvest: An Introduction to the Physiology and Handling of Fruits, Vegetables and Ornamentals. University of New South Wales Press, Sydney, Australia.

Truffle

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Scientific Name and Introduction

"Truffle" is the common name for several hypogous fungi—the most highly prized white truffle (*Tuber magnatum* Pico:Fr.), the black truffle (*Tuber melanosporum* Pico), and the least prized summer truffle (*Tuber æstivum* Vitt.). The market is concentrated in France, Italy, and Spain; but truffles are now being produced all over the world, with China as one of the biggest producers.

Quality Characteristics and Criteria

A high-quality truffle is characterized by a strong odor. No commercial standards exist, and only the kind of truffle and its geographical origin influence market price. The size (larger is more appreciated), soundness, regular shape, and uniform distribution of color are important quality characteristics.

Horticultural Maturity Indices

Maturity indices do not exist for truffles, but truffles harvested for immediate sale should be collected during the normal season because they are bigger and develop stronger smell. Truffles harvested at the beginning of the season store better because they have lower water content and are less prone to superficial mold development.

Grades, Sizes, and Packaging

No standards exist for grading, sizing, or packaging.

Precooling conditions

Only summer truffles or truffles grown in hot areas need precooling because of their higher metabolic rates. Hydrocooling at 0 °C (32 °F) is best, and must be done by immersion, which can be part of the washing procedure. After washing, excess water should be removed in a well-ventilated room at 4 to 5 °C (39 to 41 °F). Lowering the temperature helps maintain the characteristic aroma.

Optimum Storage Conditions

Truffles can be kept in good condition for 20 to 30 days at 0 ºC (32 °F) with 90 to 95% RH. Storage life is slightly reduced at 5 °C (41 °F) (Mencarelli et al. 1997). Attention must be paid to fluctuation of the refrigeration temperature around 0 °C (32 °F) that could freeze truffles and completely destroy their texture.

Controlled Atmosphere (CA) Considerations

Textural characteristics were maintained similar to fresh when stored in 60% CO_2 for 35 days at 5 °C (41 °F) (Massini and Landucci 1988). High CO_2 maintains aroma better than low O_2 and controls development of superficial molds. Quality characteristics and aroma can be maintained in low permeability plastic film packages. High CO_2 should be combined with low O_2 to avoid anoxic conditions.

Retail Outlet Display Considerations

The aroma compounds produced by truffles can contaminate other produce. Only those truffles that can be sold that day should be displayed unwrapped; the others should be kept sealed in impermeable plastic trays in the cold section.

Chilling Sensitivity

Truffles are not chilling sensitive and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Truffles produce only very low amounts of ethylene and are not sensitive to ethylene exposure (Mencarelli et al. 1997). Production of ethylene in storage can therefore be a good indicator of internal decay.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	20 to 36
5 °C	24 to 45
10 °C	30 to 60

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Drying of the epicarp caused by low RH can be a problem. Internal browning of white-fleshed truffles can be caused by overmaturity, while worms and growing conditions can cause sponginess.

Postharvest Pathology

Bacteria are present inside and on the surface, but they usually do not cause decay. The frequent presence of worms inside truffles is often undetectable from the outside.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

No current potential exists.

Special Considerations

Truffles need brushing during washing. Excess water must be removed before storage to avoid growth of superficial mold. Special care must used with mixed loads because truffles can significantly affect the aroma of other commodities.

References

Massantini, R., and A. Landucci. 1988. Trattamento e commercializzazione dei tartufi freschi e in conserva. Problemi normativi e sviluppo tecnologico. Proceedings of the 2nd International Symposium on Truffle, Spoleto, Italy, pp. 645-651.

Mencarelli, F., R. Massantini, and R. Botondi. 1997. Physiological and textural response of truffles during low-temperature storage. J. Hort. Sci. 72(3):407-414.

Turnip

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Scientific Name and Introduction

Turnip *(Brassica campestris,* Rapaceum group) is often confused with rutabaga or swede (*B. napus*, Napobrassica group). Turnips have a small, white-fleshed root, often with the surface of the top half purple. Leaves are hairy. Roots can be grown in warm soils, >25 °C (>77 °F) (Peirce 1987). (In contrast, rutabagas have large, yellow-fleshed roots and large, smooth leaves, and they grow in cool soils.) There are also yellow-fleshed turnips. Common turnip varieties are 'Purple Top,' 'White Globe,' 'White Egg,' and 'Golden Ball.'

Quality Characteristics and Criteria

High-quality turnips are firm and are free of growth cracks, woodiness, rot, injury, and pithiness.

Horticultural Maturity Indices

Root diameter and freedom from woodiness are maturity indices for turnips. If sold as topped turnips, roots should be at least 4.4 cm (1.75 in) in diameter.

Grades, Sizes, and Packaging

Grades of U.S. No. 1 and U.S. No. 2 are based primarily on external appearance, size, and defects. U.S. Grade 1 roots are well trimmed, firm, fairly smooth and clean, and free from injury, growth cracks, woodiness, water core, dry rot, and soft rot. The roots should have a minimum diameter of 4.4 cm (1.75 in). Turnips are sold bunched with tops not less than 15 cm (6 in) long, short-trimmed roots with tops not more than 10 cm (4 in) long, and topped turnips with tops removed to not more than 2 cm (0.75 in). Some roots are waxed, but most are packaged as fresh roots and leaves or topped, and packed in vented plastic film or mesh 11.4- or 22.7-kg (25- or 50-lb) bags or 0.45-kg (1-lb) bags packed 12 per carton.

Precooling Conditions

Turnips can be cooled in the wash water, but a temperature differential of 10 °C (50 °F) or more should be avoided to prevent cracking.

Optimum Storage Conditions

Turnips can be held 4 to 5 mo at 0 °C (32 °F) with 90 to 95% RH.

Controlled Atmosphere (CA) Considerations

Unknown.

Retail Outlet Display Conditions

Turnips should be stored and displayed under high RH and refrigerated to slow shrivel. They can be misted.

Chilling Sensitivity

Turnips are not sensitive to chilling and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Turnips produce no detectable ethylene and are insensitive to ethylene.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	6 to 9
5 to 6 °C	10
10 °C	13 to 19
15 to 16 °C	21 to 24
20 to 21 °C	24 to 25

Data from Smith (1957) and Scholz et al. (1963).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU per ton per day or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Turnips can develop growth cracks from overmaturity or boron deficiency, brown heart from boron deficiency, and pithiness from water stress (Snowdon 1992). Root shriveling and loss of firmness can occur from storage at >2 °C (36 °F) or at low RH.

Postharvest Pathology

Dry rot or phoma rot *(Leptospharia maculans)*, watery soft rot *(Sclerotina minor* or *S. scerotiorum)*, alternaria rot *(Alternaria brassicae)*, rhizoctonia rot *(Thanatephorus cucumeris)*, gray mold *(Botrytis cinerea)*, and bacterial soft rot *(Erwinia crotovora* ssp. *carotovora)* can occur in harvested roots, generally resulting from field infection.

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Turnips may be peeled and diced as a fresh market pre-cut product (Snowdon 1992).

Special Considerations

Turnips are susceptible to freezing damage when held at 0 °C (32 °F). Storage at warmer temperatures, >5 °C (41 °F), accelerates weight loss and development of soft rot. Waxing roots with a water-miscible, carnauba-based wax slightly delays weight loss and intensifies the purple color of the roots (Perkins-Veazie and Collins 1991).

References

Peirce, L.C. 1987. Root crops. *In* L.C. Peirce, Vegetables: Characteristics, Production, and Marketing, pp. 251-269. J. Wiley & Sons, New York, NY.

Perkins-Veazie, P., and J.K. Collins. 1991. Color changes in waxed turnips during storage. J. Food Qual. 14:313-319.

Scholz, E.W., H.B. Johnson, and W.R. Buford. 1963. Heat evolution rates of some Texas-grown fruits and vegetables. J. Rio Grande Valley Hort. Soc. 17:170-175.

Smith, W.H. 1957. The production of carbon dioxide and metabolic heat by horticultural produce. Modern Refrig. 60:493-496.

Snowdon, A.L. 1992. Diseases of swedes (rutabagas) and turnips. *In* A.L. Snowdon, Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables, pp. 339-343. CRC Press, Boca Raton, FL.

Waterchestnut

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Scientific Name and Introduction

Waterchestnut or matai (*Eleocharis dulcis* [Burm.] Trin. ex Hens.) is a member of the sedge family (Cyperaceae). It is primarily cultivated throughout tropical Asia for its edible corms. The plant is a hydrophyte (water-loving) and is grown under flooded conditions similar to paddy rice. There are two types: the sweet hon matai and the starchy sui matai, with the former more popular in the United States. *Eleocharis dulcis* corms differ from fruit of the dicot *Trapa* species *(T. bicornis* and *T. natans)*, which are also called water chestnut, in that they are toxic when eaten raw (Rubatzky and Yamaguchi 1997).

Quality Characteristics and Criteria

High-quality hon matai waterchestnuts are tender, crisp, and somewhat sweet with a white interior tissue. The corms may be eaten raw, but they maintain their crispness when cooked and are usually consumed cooked.

Horticultural Maturity Indices

Corms mature after plant tops have died or been killed by frost. Mature corms are recognized by their well-developed, lignified, dark, shell-like epidermis. Corms keep well underground, and harvest can be delayed for up to 4 mo after tops senesce (Hodge 1956). Sugar content is more than double in corms harvested in December versus October in the southeastern United States (Twigg et al. 1957). However, corms became less tender and more fibrous when harvest is delayed (Brecht et al. 1992).

Grades, Sizes, and Packaging

There are no USDA grade standards. However, mature, dark-skinned corms over 30 mm (1.25 in) in diameter with no physical injury from harvesting are considered marketable (DeRigo and Winters 1964), but corms over 40 mm (1.5 in) in diameter are more desirable (McGregor 1989). Corms are usually packed and stored in film bags with moist sphagnum moss.

Precooling Conditions

Though amenable to faster cooling methods such as hydrocooling and forced-air cooling, waterchestnuts are usually room-cooled for storage and prior to shipping. Immersion in cold, chlorinated water (see "Special Considerations" section) may be an effective precooling treatment.

Optimum Storage Conditions

When stored and packed in moist sphagnum moss, waterchestnuts can be stored for 1 to 2 mo at 0 to 2 °C (32 to 36 °F) with 98 to 100% RH (Ryall and Lipton 1979). They can be stored at least 10 mo at 0 °C (32 °F) and 8 mo at 5 °C (41 °F) if corms are free from damage and submerged in NaOCl solution soon after harvest. An initial concentration of about 1,000 $\mu L\ L^{-1}$ falls to essentially zero within 3 to 5 days. Anaerobiosis was not a problem when 23 kg (50 lb) lots were stored in open containers with the solution 60 cm (24 in) deep (Kanes and Vines 1977). However, the storage life of mechanically harvested corms was <2 mo in either aerated water or 1,000 $\mu L\ L^{-1}$ NaOCl at 1.5 °C (35 °F) (Kays and Sanchez 1984).

Controlled Atmosphere (CA) Considerations

There is no documented information on the use of CA.

Retail Outlet Display Considerations

Waterchestnuts should be displayed in refrigerated units with water spray or mist to keep them from shriveling.

Chilling Sensitivity

Chilling injury is only a concern with immature corms. Symptoms are water-soaking, internal browning, and external decay. Immature corms can become injured within 10 days at 1 °C (34 °F); by 21 days, they shrivel and become discolored (Brecht et al. 1992).

Ethylene Production and Sensitivity

There is no information on ethylene production or ethylene sensitivity of waterchestnuts.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	10.1
5 °C	25.4
10 °C	41.6
15 °C	78.7 (estimated by extrapolation)
20 °C	114.4

Data from Peiris et al. (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Damaged areas on corms turn brown, which detracts from their appearance and must be trimmed when the corms are peeled. Corms are susceptible to water loss, which causes loss of crispness and tenderness, but texture changes are minimal in refrigerated storage if water loss is minimized (Kays and Sanchez 1984, Brecht et al. 1992).

Postharvest Pathology

Decay, caused mainly by *Fusarium* and *Geotrichum* spp., is a problem at storage temperatures of >5 °C (41 °F) and in immature corms with chilling injury (Brecht et al. 1992). Black rot *(Cerastomella paradoxa)* and trichoderma rot *(Trichoderma viride)* have been reported, with black rot being controlled by curing at 30 to 32 °C (86 to 90 °F) with 100% RH for 3 days (Ryall and Lipton 1979).

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Fresh, peeled corms could be marketed if consumer demand is sufficient. A method has been developed to mechanically peel waterchestnut corms that involves cutting off the apical and basal ends, removing the peel with hot alkali followed by wet brushing, and bleaching with hydrogen peroxide (Leeper and Williams 1976).

Special Considerations

Following washing with water to remove adhering soil, corms should be treated with chlorinated water (1,000 µL L^{-1}, pH 7.0) to reduce decay. Waterchestnuts sweeten during low temperature storage, much like potato (*Solanum tuberosum* L.) tubers and parsnip (*Pastinaca sativa* L.) roots (DeRigo and Winters 1964). Starch to sugar conversion can result in doubling or tripling of sugar levels within 1 mo of storage, with no further increase over longer storage times; maximum sugar levels are reached at 10 °C (50 °F) and in early harvested, larger corms (Brecht et al. 1992), but decay can limit storage at 10 °C (50 °F) to 1 mo.

References

Brecht, J.K., K.A. Bergsma, C.A. Sanchez, and G.H. Snyder. 1992. Harvest maturity and storage temperature effects on quality of chinese water chestnuts *(Eleocharis dulcis)*. Acta Hort. 318:313-319.

DeRigo, H.T., and H.F. Winters. 1964. Effects of storage temperatures on physiological and chemical changes in chinese waterchestnut corms. Proc. Amer. Soc. Hort. Sci. 85:521-525.

Hodge, W. 1956. Chinese water chestnut or matai—a paddy crop of China. Econ. Bot. 10:49-65.

Kanes, C.A., and A.K. Vines. 1977. Storage conditions for chinese water chestnuts *(Eleocharis dulcis)*. Acta Hort. 62:151-160.

Kays, S.J., and M.G.C. Sanchez. 1984. Storage of chinese water chestnut (*Eleocharis dulcis* [Burm. F.] Trin.) corms. Acta Hort. 157:149-159.

Leeper, G.F., and A.K. Williams. 1976. Peeling of chinese waterchestnuts. J. Food Sci. 41:86-88.

McGregor, B.M. 1989. Tropical Products Transport Handbook. Agriculture Handbook 668, U.S. Department of Agriculture, Washington, DC.

Peiris, K.H.S., J.L. Mallon, and S.J. Kays. 1997. Respiratory rate and vital heat of some specialty vegetables at various temperatures. HortTechnology 7:46-49.

Rubatzky, V.E., and M. Yamaguchi. 1997. World Vegetables: Principles, Production, and Nutritive Values, 2nd ed. Chapman & Hall, New York, NY.

Ryall, A.L., and W.J. Lipton. 1979. Handling, Transportation and Storage of Fruits and Vegetables, vol. 1. AVI, Westport, CT.

Twigg, B.A., F.C. Stark, and A. Kramer. 1957. Cultural studies with matai (chinese water chestnut). Proc. Amer. Soc. Hort. Sci. 70:266-272.

Water Convolvulus

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Scientific Name and Introduction

Water convolvulus (*Ipomoea aquatica* Forsk.) is also called ung choi and kang kong. It is a member of the morning-glory family (Convolvulaceae) and is in the same genus as sweetpotato. It is thought to be native of India and is now widely consumed as a vegetable throughout Southeast Asia. Young stems and leaves are consumed after frying or boiling. It has high protein and carotenoid contents. It is grown both in ponds and in moist soil. Common varieties include types with large or small leaves, green or greenish-yellow leaves, and stems that are white or green. There are many common names besides the three given above: kong xin cai, water spinach, water cabbage, and pake boong.

Quality Characteristics and Criteria

Plants should have tender tips, and the diameter in the middle of the stem should be 8 mm (0.3 in) or more. There should be no insect or disease injury or blemishes; leaves should be uniformly dark-green, smooth, healthy, and turgid with no black streaks from folding or mechanical injury; and stems should be tender (Tisbe and Cadiz 1967). Plants should be free of dirt and residue, and stems should have a minimum of fibers.

Horticultural Maturity Indices

Young plants are either up-rooted or cut near the water surface (flooded culture) or ground level (moist soil culture) when about 30 cm (12 in) long. Then they are tied into bundles. Plants with roots attached are less perishable (Cornelis et al. 1985).

Grades, Sizes, and Packaging

There are no U.S. or international grades. Plants are sold in 0.45- to 0.9-kg (1- to 2-lb) bunches packed in fiberboard cartons holding 9 to 18 kg (20 to 40 lb).

Precooling Conditions

Room-cooling is normally used. Vacuum-cooling is possible.

Optimum Storage Conditions

Tentative data suggest a storage life of 10 to 12 days at 12 to 14 °C (54 to 57 °F) with 90 to 95% RH.

Controlled Atmosphere (CA) Considerations

Tissue browning is promoted by 3% CO_2 at 1 °C (33 °F) but is prevented by higher CO_2 concentrations at 20 °C (68 °F) (Ose et al. 1999).

Retail Outlet Display Considerations

Water convolvulus should be displayed at 10 to 14 °C (50 to 57 °F) with misting. Placing on ice or top-icing is not recommended.

Chilling Sensitivity

Water convolvulus is injured below 10 to 14 °C (50 to 57 °F). Symptoms include darkening and wilting of leaves, darkening of the stems, and increased susceptibility to bacterial disease. Darkening symptoms develop after about 4 days at 1 °C (34 °F).

Ethylene Production and Sensitivity

Water convolvulus produces about 2 µL kg^{-1} h^{-1} ethylene at harvest; the rate declines during storage. Production can then increase to about the same level when leaves senesce and turn yellow. Ethylene exposure induces premature leaf senescence and yellowing.

Respiration Rates

Respiration rate is 50 to 150 mg (28 to 85 µL) CO_2 kg^{-1} h^{-1} at 27 °C (81 °F). Heat production is 11,000 to 33,000 BTU ton^{-1} day^{-1} or 3,050 to 9,150 kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Chilling injury is the main disorder.

Postharvest Pathology

White rust can be a problem in Southeast Asia, as occasionally can alternaria rot *(Alternaria ipomoeae-aquaticae).* Cercospora leaf spots are also found (Ho and Edie 1969). Postharvest diseases are not generally a problem, though bacterial rot does occur. Rapid cooling, good temperature management, and sanitation reduce the problem significantly.

Quarantine Issues

Peach aphid is sometimes found. Though sweetpotato weevil may not be able to complete its life cycle in this vegetable, larvae have been found in the hollow stems, and therefore it is regarded as a host (Austin 1991).

Suitability as Fresh-Cut Product

Water convolvulus is sold in Southeast Asian markets as part of a meal pack for stir-frying.

References

Austin, D.F. 1991. Associations between the plant family Convolvulaceae and cylas weevils. *In* R.K. Jansson and K.V. Raman, eds., Sweet Potato Pest Management: A Global Perspective, pp. 45-78. Westview, Boulder, CO.

Cornelis, J., J.A. Nugteren, and E. Westphal. 1985. Kang kong (*Ipomoea aquatica* Forsk.): an important leaf vegetable in South-East Asia. Abst. Trop. Agric. 10:9-21.

Ho, B.W.C., and H.H. Edie. 1969. White rust *(Albergo ipomoeae-aquatica)* on *Ipomoea aquatica* in Hong Kong. Plant Dis. Rep. 53:959-962.

Ose, K., K. Chachin, and Y. Ueda. 1999. Relationship between the occurrence of chilling injury and the environmental gas concentration during storage of water convolvulus (*Ipomoea aquatica* Forsk.). Acta Hort. 483:303-310.

Tsay, L.M. 1987. Effects of holding posture on the respiration and ethylene production of eggplant and water convolvulus. J. Chinese Soc. Hort. Sci. 33:34-37.

Tisbe, V.O., and T.G. Cadiz. 1967. Convolvulus or kang kong. *In* J.E. Knott and J.R. Dean, eds., Vegetable Production in South-East Asia, pp. 285-289. University of the Philippines, Los Banos, Philippines.

Watercress

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Specific Name and Introduction

Watercress (*Nasturtium officinale* R.Br.) has been known in Europe and Asia for thousands of years, and it is now grown in many countries worldwide. It is a member of the Brassicaceae (Cruciferae) family and is used as a leafy salad vegetable. It has attractive dark green leaves, a strong flavor and is rich in vitamins. Watercress is typically grown in running water (Snowdon 1991).

Horticultural Maturity Indices

Leaves should be harvested when full size and still bright-green.

Quality Characteristics and Criteria

Watercress should be bright green and not limp. The leaves of watercress quickly become yellow and slimy when improperly handled.

Grades, Sizes, and Packaging

There are no U.S. grade standards. Watercress is sold in bunches and can be packed in waxed cartons with top ice (Hruschka and Wang 1979). It can also be packaged in boxes with plastic liners.

Precooling Conditions

Watercress should be precooled promptly after harvest either by hydrocooling or vacuum-cooling (Hruschka and Wang 1979).

Optimum Storage Conditions

Watercress can be stored for 2 to 3 weeks at 0 °C (32 °F) with >95% RH (Hruschka and Wang 1979). Shelf-life is reduced to 2 to 3 days if stored under low RH.

Controlled Atmosphere (CA) Considerations

The rate of yellowing can be reduced by storing in atmospheres >7% CO_2 with not less than 5% O_2 (Aharoni et al. 1989).

Retail Outlet Display Considerations

Contact with melting ice and water sprays help in preventing dehydration. Careful handling is necessary to avoid crushing or bruising the delicate leaves.

Chilling Sensitivity

Watercress is not sensitive to low temperature and should be stored as cold as possible without freezing.

Ethylene Production and Sensitivity

Watercress produces only low amounts of ethylene in response to wounding: <0.1 µL kg^{-1} h^{-1} at 20 °C (68 °F). However, exposure to ethylene reduces shelf-life due to increased rate of yellowing (Philosoph-Hadas et al. 1989).

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	16 to 28
5 °C	47 to 53
10 °C	95 to 125
15 °C	139 to 210
20 °C	300 to 344
25 °C	334 to 420

Data from Smith (1957) and Hruschka and Wang (1979).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Watercress is very susceptible to dehydration and crushing of leaves.

Postharvest Pathology

Harvested watercress is highly perishable. In warm conditions, the stems can become slimy as a result of bacterial soft rot caused by *Erwinia carotovora*. It is therefore important that watercress be cooled promptly after harvest (Snowdon 1991).

Quarantine Issues

There are no known quarantine issues.

Suitability as Fresh-Cut Product

Watercress can be used as part of mixed salads.

Special Considerations

Care must be taken to maintain high RH or storage life is substantially shortened.

References

Aharoni, N., A. Reuveni, and O. Dvir. 1989. Modified atmospheres in film packages delay senescence and decay of fresh herbs. Acta Hort. 258:255-263.

Hruschka, H.W., and C.Y. Wang. 1979. Storage and shelf life of packaged watercress, parsley and mint. Market Research Report 1102, U.S. Department of Agriculture, Washington, DC.

Philosoph-Hadas, S., E. Pesis, S. Meir, et al. 1989. Ethylene-enhanced senescence of leafy vegetables. Acta Hort. 258:37-45.

Smith, W.H. 1957. The production of carbon dioxide and metabolic heat by horticultural produce. Modern Refrig. 60:493-496.

Snowdon, A.L. 1991. A Colour Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables, p. 219. Wolfe Scientific, London, U.K.

Watermelon

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Scientific Name and Introduction

Watermelon, *Citrullus lanatus* (Thunb.) Matsum. and Nakai, is an annual plant of the Cucurbitaceae family. The edible fruit is produced on trailing vines that may reach 15 ft. (4.6 m) or more in length. Fruit vary in shape from globular to oblong. The color of the hairless skin varies in shades of green from pale yellowish to almost black and may be solid, striped, or marbled. Fruit have a thin, firm outer rind, a layer of white-fleshed inner rind that may be up to about one inch thick, and an interior edible pulp containing seeds unless the variety is triploid. Pulp color of most commercial varieties is some shade of yellow or red (Sackett 1974).

Quality Characteristics and Criteria

High-quality watermelons are well formed, symmetrical, and uniform in shape and have a waxy, bright appearance. The rind should be free of scars, sunburn, and abrasions with no bruising or other physical injury; free from anthracnose or other decay; and not overripe (AMS 1978, Suslow 1999).

Horticultural Maturity Indices

As watermelons reach horticultural maturity, the ground spot changes from white to pale yellow, tendrils nearest the fruit may turn brown and dry, and the fruit surface may become irregular and dull rather than bright or glossy. Experienced harvest managers may note that when the fruit is thumped or rapped with the knuckles, immature fruit gives off a metallic ringing sound while mature fruit sounds dull or hollow. The most reliable method of determining maturity within a given field is to visually examine the fruit for the changes described above, then cut some fruit in random sectors of the field to check flavor and internal color development. Some buyers require that fruit have some minimum SSC, which is easily measured with a refractometer (Sackett 1974, Rushing et al. 2000).

Grades, Sizes, and Packaging

Watermelon grades are U.S. Fancy, U.S. No. 1., and U.S. No. 2. Grade is subjectively based on the quality characteristics and criteria described above. Size may be specified in terms of average weight, minimum weight, or minimum and maximum weight (AMS 1978). Watermelons may be shipped in bulk, placed on corrugated bins with a capacity of approximately 1,000 lb (454 kg), or packed into cartons containing 3 to 6 watermelons depending on fruit size. Cartons should have specially designed inserts to help support the weight of the fruit (Close et al. 1971).

Precooling Conditions

Watermelons generally are not precooled and some are shipped in unrefrigerated trucks (Suslow 1999). If precooling is implemented, forced-air cooling would be the method of choice. In common room-cooling, good air circulation between palletized boxes is essential. Fruit that are placed in bulk fiberboard bins will cool slowly because of poor air circulation within the bin.

Optimum Storage Conditions

Some variability is noted in watermelon varieties and types, such as seeded vs. seedless; but in general none are suited to very-long-term storage. The ideal storage temperature is in the range of 10 to 15 °C (50 to 59 °F) with approximately 90% RH. Fruit should be consumed within 2 to 3 weeks following harvest (Hardenburg et al. 1986).

Controlled Atmosphere (CA) Conditions

Watermelons generally do not respond well to CA or to MAP. Studies with shrink-wrap packaging of individual fruits, a form of MAP, was not beneficial, and in some cases decay in MAP was higher (Biglete 1992).

Retail Outlet Display Considerations

Watermelons are usually sold from unrefrigerated displays. Bulk fiberboard bins with colorful graphics have been a popular method of displaying watermelons for retail sale.

Chilling Sensitivity

Watermelons develop chilling injury when stored below about 10 °C for more than a few days. Lower temperatures will hasten the onset of injury. Symptoms appear as brown-staining of the rind, surface pitting, deterioration of flavor, fading of flesh color, and increased incidence of decay after being returned to room temperatures (Hardenburg et al. 1986, Suslow 1999, Rushing et al. 2000). Conditioning fruit at 30 °C (86 °F) for about 4 days prior to cooling has been shown to induce some tolerance to chilling, but it does not completely alleviate the problem (Picha 1986).

Ethylene Production and Sensitivity

Watermelons are classified as low-ethylene producers, with production rates in the range of 0.1 to 1.0 µL kg^{-1} h^{-1} at 20 °C. Though production rates are low, fruit are extremely sensitive to ethylene. Exposure to as little as 5 µL L^{-1} ethylene causes softening, rind thinning, fading of flesh color, and over-ripeness (Elkashif et al. 1989, Suslow 1999). Interactions between ethylene concentration, temperature, and duration of exposure are not well defined. The recommended management protocol is to avoid any exposure to ethylene in storage.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
4 to 5 ºC	3 to 4
10 ºC	6 to 9
20 to 21 ºC	17 to 25

Data from Hardenburg et al. (1986).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Refer to above sections on "Chilling Injury" and "Ethylene Sensitivity." A disorder of preharvest origin that can have serious postharvest consequences for marketing is hollowheart.

Postharvest Pathology

A variety of pathogens may cause postharvest decay of watermelon, but in the absence of any approved chemical control measures, the primary defense against decay is the exclusion of diseased fruit from the marketing chain through careful selection at harvest and appropriate grading before shipment. Postharvest rot caused by *Fusarium* spp. and *Phytophthora capsici* are of concern because control measures for these fungi in the field often are inadequate. With good disease control in the field, anthracnose *(Colletotrichum orbiculare)* and black rot *(Didymella bryoniae)* rarely develop on watermelon (Snowdon 1992, Rushing et al. 2001).

In production areas with high RH and temperature, an extensive list of rind lesions, stem-end or blossom-end rots, and surface lesions may be caused by *Erwinia* or an assortment of fungi (Snowdon 1992, Suslow 1999). Watermelon fruit blotch *(Acidovorax avenae* subsp. *citrulli)* was a postharvest problem for several years, but research demonstrated the disease is not easily transmitted from fruit to fruit after harvest. Appropriate grading and temperature management can virtually eliminate its presence in the marketing chain (Rushing et al. 1999).

Quarantine Issues

Watermelons destined for export must be free of disease, insects, soil, or vegetative debris. Phytosanitary requirements in the receiving country should be reviewed prior to shipment.

Suitability as Fresh-Cut Product

The fresh-cut market for watermelon cubes and slices has grown dramatically, but most processing is done near the point of sale. Some benefits may be derived from MAP. Fresh-cut watermelon is badly damaged by rough handling during distribution (Sargent 1998).

Special Considerations

Special care should be given to avoid rough handling injury of watermelon fruit during harvesting and handling. Fruit that are inadvertently dropped during harvest or handling should not be shipped. Injury that may not be obvious at the moment it occurs can develop into bruised areas and damage to the flesh in transit.

References

AMS [Agricultural Marketing Service]. 1978. United States standards for grades of watermelons. At http://www.ams.usda.gov/AMSv1.0/standards.

Biglete, N.A. 1992. Packaging And Storage of Watermelon Using Different Shrink-Wrap Techniques. M.S. thesis, Clemson University, Clemson, SC.

Close, E.G., J. Varick, and L.A. Risse. 1971. Comparative methods of handling watermelons—bulk and cartons. Series MA 1-71, Florida Department of Agriculture and Consumer Services, Tallahassee, FL.

Elkashif, M.E., D.J. Huber, and J.K. Brecht. 1989. Respiration and ethylene production in harvested watermelon fruit: evidence for non-climacteric respiratory behavior. J. Amer. Soc. Hort. Sci. 114:81-85.

Hardenburg, R.E., A.E. Watada, and C.Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, pp. 12,62. Agricultural Handbook 66, U.S. Department of Agriculture, Washington, DC.

Picha, D.H. 1986. Postharvest fruit conditioning reduces chilling injury in watermelons. HortScience 21:1407-1409.

Rushing, J.W., J.M. Fonseca, and A.P. Keinath. 2001. Harvesting and postharvest handling, pp. 156-164. *In* Watermelons - Characteristics, Production, and Marketing, D.N. Maynard, ed., American Society for Horticultural Science Press, Alexandria, VA.

Rushing, J.W., A.P. Keinath, and W.P. Cook. 1999. Postharvest development and transmission of watermelon fruit blotch. HortTechnology 9:33-35.

Sackett, C. 1974. Watermelons. Fruit and Vegetable Facts and Pointers. United Fresh Fruit and Vegetable Association, Alexandria, VA.

Sargent, S.A. 1998. Fresh-cut watermelon. Citrus and Veg. Mag. 62:26-28,44.

Snowdon, A.L. 1992. Color Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2, Vegetables. pp. 18,51. CRC Press, Boca Raton, FL.

Suslow, T.V. 1999. Watermelon. Recommendations for maintaining postharvest quality. *At* http://postharvest.ucdavis.edu/produce_information.

Wax Apple

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Scientific Name and Introduction

Wax apple (*Syzygium samarangense* [Blume] Merrill & L. M. Perry) is the main species in this Southeast Asian genus that is consumed fresh. Other species with similar fruits are *S. aqueum*, rose water apple; *S. aimini*, java plum; *S. jambos*, rose apple; and *S. malaccense*, Malay apple. The spice clove is *S. aromaticum*.

The fruit is broad, bell-shaped or sometimes oval, 5 to 6 cm (2 to 2.5 in) long, and 4 to 5 cm (1.5 to 2 in) wide. It has one to four seeds. The skin can be green to light red to dark red and has a waxlike high gloss sheen. The low-acid flesh is white and juicy (Nakasone and Paull 1998).

Quality Characteristics and Criteria

Criteria are skin color; waxy glossy appearance; large size with small seeds; crunchy, watery, sweet taste; and subtle flavor.

Horticultural Maturity Indices

Wax apples are ready for harvest when the blossom-end is fully expanded and the skin shows desired market color. Green-skin varieties are harvested when they reach full size.

Grades, Sizes, and Packaging

There are no U.S. or international standards. Fruit are generally graded by size and color. They are generally marketed in single-layer fiberboard cartons of 2.25 kg (5 lb) with padding, sometimes in trays.

Precooling Conditions

Room-cooling is normally used because of the risk of excessive moisture loss with forced-air cooling.

Optimum Storage Conditions

Storage at 2 to 10 °C (36 to 50 °F) is recommended. However, chilling injury is a problem at these temperatures. A conservative recommendation would be 12 to 14 °C (54 to 57 °F) with 90 to 95% RH, which should result in a shelf-life of 10 to 14 days.

Controlled Atmospheres (CA) Consideration

No CA studies have been reported. MAP in sealed polyethylene film bags reduces chilling injury and decay (Horng and Peng 1983). Waxing is less effective, partly due to RH control.

Retail Outlet Display Considerations

Fruit should be displayed in overwrapped trays or closed polystyrene clamshell containers with no perforations at 10 °C (50 °F). They should not be misted.

Chilling Sensitivity

Wax apples show pitting and skin scald after 4 days at 2 °C (36 °F), while slight injury occurs after 4 days at 10 °C (50 °F) (Horng and Peng 1983).

Ethylene Production and Sensitivity

Wax apples produce very low ethylene. It is a nonclimacteric fruit (Akamine and Goo 1979). There are no reported responses to ethylene, but ethylene treatment may lead to premature senescence.

Respiration Rates

Respiration declines after harvest (Liao et al. 1983).

Temperature	mg CO_2 kg^{-1} h^{-1}
10 °C	4 to 5
20 °C	8 to 11

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Chilling injury, mechanical injury, and water loss are the three major disorders. Chilling injury symptoms are pitting and scalding of the skin, while mechanical injury (impact and abrasion) leads to development of sunken areas and some darkening of affected flesh. Though fruit have a bright waxy coating, water loss is rapid, leading to shriveling on the skin and loss of crisp texture. At 2% moisture loss, fruit become slightly shriveled; and at 6%, fruit are shrunken and lose turgidity (Horng and Peng 1983).

Postharvest Pathology

There are no published reports. Wax apple may be susceptible to anthracnose.

Quarantine Issues

Wax apple is a fruit fly host; irradiation at 300 Gy may have potential for disinfestation.

Suitability as Fresh-Cut Product

Wax apple is often available as a fresh-cut product in Southeast Asian markets in trays with overwrap. It has some potential as a fresh-cut product.

References

Akamine, E.K., and T. Goo. 1979. Respiration and ethylene production of fruits of species and cultivars of *Psidium* and species of *Eugenia*. J. Amer. Soc. Hort. Sci. 104:632-635.

Horng, D., and C. Peng. 1983. Studies on package, transportation and storage of wax apple fruits *(Syzygium samarangense)*. Natl. Chung Hsing Univ. Hort. J. 8:31-39.

Liao, M.L., M.S. Liu, and J.S. Yang. 1983. Respiration measurement of some important fruits in Taiwan. Acta Hort. 138:227-246.

Nakasone, H.Y., and R.E. Paull. 1998. Tropical Fruits. CAB Intl., Wallingford, U.K

Fresh-Cut Fruits

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Introduction and Overview

Fresh-cut fruit products for both retail and food service applications have enjoyed an increasing presence in the marketplace due to demand by the consumer. In the coming years, it is commonly perceived that the fresh-cut fruit industry will have unprecedented growth. For this reason, many leading fresh-cut salad manufacturers have targeted development of fresh-cut fruit products as part of their long-term business plans. However, processors of fresh-cut fruit products face numerous challenges not commonly encountered during fresh-cut vegetable processing. The difficulties encountered with fresh-cut fruit, while not insurmountable, require a new and higher level of technical and operational sophistication.

Fresh-Cut Defined for Fruits

The USDA and FDA definitions for “fresh” and “minimally processed” fruits and vegetables imply that fresh-cut (precut) products have been freshly cut, washed, packaged, and maintained with refrigeration. Fresh-cut products are raw, and even though processed (physically altered from the original form), they remain in a fresh state, ready to eat or cook, without freezing, thermal processing, or treatments with additives or preservatives (AMS 1998, Anonymous 1998). The United Fresh Produce Association defines a fresh-cut product as fruits or vegetables that have been trimmed and/or peeled and/or cut into 100% usable product that is bagged or prepackaged to offer consumers high nutrition, convenience, and flavor while still maintaining freshness. Several commodities, although botanically fruits (for example, cucumber, pepper, and tomato), will not be covered in this section since they are commonly classified as vegetables.

Fresh-Cut Physiology and Physiological Concerns

Once harvested, fruits are removed from their source of water, minerals, and sustenance. Fruit tissues continue to respire, using available and stored sugars and organic acids, and they begin to senesce rapidly. Postharvest quality loss is primarily a function of respiration, onset or progression of ripening (climacteric fruit), water loss (transpiration), enzymatic discoloration of cut surfaces, decay (microbial), senescence, and mechanical damage suffered during preparation, shipping, handling, and processing (Schlimme and Rooney 1994, Watada et al. 1996). Fruits destined for fresh-cut processors should be harvested as ripe as possible. This makes it critical that temperature-dependent events related to respiration, water loss, pathological decay, and ethylene production be strictly regulated during shipment (or storage) of the fruit.

During the climacteric ripening stage of many fruits, there is a dramatic increase in respiratory production of CO_2 and ethylene. Non-climacteric fruit, leafy vegetables, non-fruit vegetables, and roots and tubers do not have a surge in ethylene production and generally have only slightly increased respiration as senescence approaches. However, if severely wounded (for example, by fresh-cut processing), significant stress-induced production of CO_2, and often ethylene, occurs (Abeles et al. 1992, Brecht 1995). Fresh-cut processing increases respiration rates and causes major tissue disruption as enzymes and substrates, normally sequestered within the vacuole, become mixed with other cytoplasmic and nucleic substrates and enzymes. Processing also increases wound-induced ethylene, water activity, and surface area per unit volume, which may accelerate water loss and enhance microbial growth since sugars also become readily available

(King and Bolin 1989, Watada et al. 1990, Wiley 1994, Watada and Qi 1999).

These physiological changes may be accompanied by flavor loss, cut surface discoloration, color loss, decay, increased rate of vitamin loss, rapid softening, shrinkage, and a shorter storage life. Increased water activity and mixing of intracellular and intercellular enzymes and substrates may also contribute to flavor and texture loss during and after processing. Therefore, proper temperature management during product preparation and refrigeration throughout distribution and marketing are essential for maintenance of quality.

Physical alterations and potential low-O_2 atmospheres in packages may create significant negative changes in flavor, aroma, and "mouth-feel." There are also synergistic interactions between numerous factors such as variety, source, season, initial maturity, optimum processing maturity, slicing and cutting equipment, sanitation and GRAS chemical treatments, packaging (including MAP), temperature management, shipping, handling, and length of shelf-life. The combined effect of these factors may have negative consequences on postharvest shelf-life and sensory quality. Therefore, improperly preparing, packaging, and handling fresh-cut fruit may compromise overall quality and decrease consumer acceptability.

Defining Fresh-Cut Fruit Quality

Postharvest quality and post-cutting quality are unfortunately ambiguous or confused terms. Harvest indices used to deliver optimum quality whole fruits to storage facilities, terminal markets, and the fresh markets oftentimes may not be appropriate for fruits destined to be processed (see also *Factors Affecting Fresh-Cut Fruit Quality*). Growers often destructively sample fruit before making a decision to harvest. Processor assessment of fruit maturity before cutting either upon receipt or after in-house storage is also advisable. For example, a lot of peaches that are optimally mature for fresh market may be shipped to a processor and rejected because the fruit are too soft or ripe for cutting. Determination of optimum maturity depends on the commodity and the use. The processor must understand the physiology of the fruit and the finished product (and packaging) to accurately determine when fruit is at the appropriate maturity stage to process. Choice of variety, harvest condition, maturity, storage, and shelf-life for various fresh-cut fruits are active areas of research.

Proper initial maturity of fruit is essential. However, once processed, quality is most commonly, and sometimes only, assessed visually. Visual appearance is generally the determinant for commercial shelf-life. Although some studies have found that vitamin C and carotene degrade very little during short-term (about 1 week) refrigerated storage in some fresh-cut fruits (Wright and Kader 1997a,b), other researchers are attempting to retain fresh-cut quality for 3 to 4 weeks. Although some quality attributes may still be acceptable, overall quality in terms of aroma, taste, and texture may be jeopardized (Anonymous 2000a).

Firmness and Texture

Tissue softening is a very serious problem with fresh-cut fruit products and can limit shelf-life. Fresh-cut fruit firmness is an important quality attribute that can be affected by cell softening enzymes present in the fruit tissue (Varoquaux et al. 1990) and by decreased turgor due to water loss. For example, there was 26 to 49% firmness loss in four varieties of fresh-cut cantaloupe processed from three-quarters to full-slip maturity fruit when stored in air at 4 °C (39 °F) (Beaulieu 2002, unpublished data). Unwrapped watermelon slices lost 47% of their firmness after 4 days at 5 °C (41 °F) (Abbey et al. 1988), and firmness decreased in stored cantaloupe cubes (12 days in air at 5 °C) by more than 25% (Cantwell and Portela 1997).

Flesh firmness of fresh-cut fruit products can be maintained by application or treatment with calcium compounds. Dipping fresh-cut products in solutions of 0.5 to 1.0% calcium chloride is very effective in maintaining product firmness (Ponting et al. 1971, 1972). However, calcium chloride may leave bitter off flavors on some products. Firmness of slices from 12 untreated apple cultivars stored at 2 °C (36 °F) decreased steadily for 7 days and more rapidly thereafter (Kim et al. 1993). However, mild heat treatment of whole apples before processing maintained firmness during storage in some fresh-cut apple cultivars (Kim et al. 1994).

Firmness can sometimes be maintained by CA storage. Firmness loss averaged 2.2 lb (10 N) in honeydew cylinders after 12 days of storage in air at 5 °C (41 °F), while CA storage (air + 15% CO_2) reduced the loss significantly in one of four cultivars tested (Portela and Cantwell 1998). CA treatments (2% O_2 + 10% CO_2 at 5 °C [41 °F] and 4 % O_2 + 10% CO_2 at 10 °C [50 °F]) were more beneficial than air storage in maintaining honeydew cube quality for up to 6 days at 5 °C (41 °F) (Qi et al. 1999).

Color at the Cut Surface

An important issue in fresh-cut fruit processing is the control of discoloration (pinking, reddening, or blackening) or browning on cut surfaces. Oxidative browning is usually caused by the enzyme polyphenol oxidase (PPO), which in the presence of O_2 converts phenolic compounds in fruits and vegetables into dark-colored pigments. Outlined below are a number of strategies that may be used to reduce PPO-mediated cut-surface discoloration.

Reduced O_2

Because PPO requires O_2 to induce cut surface discoloration, reducing the amount of O_2 in a package of fresh-cut product by vacuum MAP or gas flushing may reduce cut surface discoloration, but not completely stop it. Careful design of a fresh-cut package is essential to assure that the proper amount of O_2 is present. Excessive levels of O_2 in a package may allow for cut surface discoloration to occur, while too little O_2 may cause anaerobic metabolism and production of off flavors and odors.

Acidification

PPO most effectively catalyzes cut surface discoloration at a neutral pH of approximately 7. Therefore, browning can be slowed by dipping products in mildly acidic food grade solutions of acetic, ascorbic, citric, tartaric, fumaric, or phosphoric acid. However, these acids may leave off flavors and promote tissue softening and therefore must be used with care.

Reducing Agents

Ascorbic acid or erythorbate (an isomer of ascorbic acid) are two common compounds used in the food industry to prevent PPO-mediated cut-surface discoloration. Ascorbic acid and erythorbate reduce PPO-induced discoloration at the cut surface by converting quinones (formed by PPO from phenolics) back to phenolic compounds. Unfortunately, once all the ascorbic acid or erythorbate is exhausted, PPO browning will proceed uninhibited. Ascorbic acid or erythorbate are commonly used as 1% solutions to prevent browning and discoloration of cut surfaces. These compounds are organic acids, so they may also reduce surface pH of commodities, further slowing browning.

Sensory Aspects

Fresh-cut vegetable salads have great consumer appeal because of their convenience, flexibility of use, and probably the fact that their desirable flavor often comes about via condiments (croutons, spices, or dressing) or because numerous products make up a medley mixture. However, consumer acceptance of fresh-cut fruits most often relies on the inherent flavor and texture quality of the product, seldom with accompaniments. It is generally and unfortunately assumed that “if it looks good, it tastes good.” Improving consistency in fresh-cut fruit product flavor and texture may enhance consumers desire to repeatedly purchase such products.

Soluble Solids Content (SSC) and Titratable Acidity (TA)

Sweetness, flesh firmness, and taste are very important characteristics for fresh-cut melon quality. In a midseason trial of 17 western cantaloupe varieties, there was an average 5% decrease in SSC (range 0 to 11%) and an average 8% decrease in sugar (range 0 to 21%) when cubes were stored 12 days (in air) at 5 °C (41 °F) (Cantwell and Portela 1997). After 9 days at 10 °C (50 °F) or 15 days at 5 °C (41 °F), SSC in CA-stored melon pieces were higher than in air: 10.3 vs. 9.5% and 10.2 vs. 9.1% at 10 and 5 °C (50 and 41 °F), respectively (Cantwell and Portela 1997). Cantaloupe balls prepared from four eastern varieties stored 8 days at 0 °C (32 °F) had an average SSC decrease of 9.7% with a range of 2.3 to 13% (Lange 1998). SSC remained somewhat constant for 7 days storage at 4 °C (39 °F) in fresh-cut cantaloupe when harvest maturity was at least half-slip, and cubes prepared from fruit harvested at quarter-slip had significantly lower initial SSC, which rapidly declined after only 5 days storage (Beaulieu and Baldwin 2002). It is well established in the food industry that sugar content (SSC) is generally positively correlated with desirable flavor quality. However, occasionally too much sugar is perceived negatively. The best sugar range for storage of fresh-cut cantaloupe was 10 to 13 °Brix. However, some judged the 13 °Brix fruit as too sweet (Anonymous 2000b).

TA and SSC have also been used to assess quality via the SSC:TA ratio in some fresh-cut fruits. Changes in TA, pH, and SSC in apple slices from 12 cultivars that were stored at 2 °C (36 °F) for 12 days were small and varied by cultivar (Kim et al. 1993). Likewise, there were changes in SSC in fresh-cut strawberries stored under various CA for 7 days at 5 °C (41 °F). However, pH increased over time (Wright and Kader 1997b). Fresh-cut persimmons stored under various CA had increased SSC for 3 days, then decreased SSC by day 8; pH tended to increase through storage (except when stored under 2% O_2) (Wright and Kader 1997b). In cantaloupe slices, a 17% loss in SSC and a 2-fold increase in TA occurred after only 2 days storage at 20 °C (68 °F), but the acidity change was attributed to lactic acid bacteria (Lamikanra et al. 2000). TA in fresh-cut oranges stored 8 days at 4 °C (39 °F) decreased 36% (Rocha et al. 1995).

Aroma and Flavor

An acceptable post-cutting visual appraisal does not necessarily imply that a product has satisfactory flavor quality. Excellent visual quality and acceptance by retailers and consumers often occur with fruits processed when immature. For example, immature peaches and nectarines will process and hold visual quality for extended periods, but rehardening and poor eating-quality limit their use (Gorny et al. 1998b, Beaulieu et al. 1999). A mature green cantaloupe at less than half-slip delivers a fresh-cut product with optimum visual shelf-life but insufficient sugar or volatile composition compared to a desirable ripe whole melon (Pratt 1971, Beaulieu and Grimm 2001, Beaulieu and Baldwin 2002). 'Makdimon' melons harvested 2 days before fully-ripe (full-slip) developed only about 25% the total volatiles as 3 day-old, fully-ripe fruit (Wyllie et al. 1996). Volatiles increased with harvest maturity, and cubes prepared from quarter-slip fruit contained only 25 to 33% of the total volatiles of full-slip fruit (Beaulieu and Baldwin 2002). Furthermore, these trends were conserved during 10 days at 4°C (39 °F) in fresh-cut products.

Flavor and aroma quality are important attributes for consumers, and these attributes should be seriously examined when determining the shelf-life of fresh-cut fruit products. Nevertheless, the quality of intact vegetables and fruits is often determined almost exclusively based on appearance, sometimes to the exclusion of flavor and texture (Sapers et al. 1997). Much variability exists in the literature regarding acceptability based on sensory evaluations, and this variability oftentimes can be attributed to different experimental designs or sensorial analyses and cultural bias. For example, sensory evaluation determined that fresh-cut honeydew, kiwi fruit, papaya, pineapple, and cantaloupe stored at 4 °C (39 °F) were unacceptable after 7, 4, 2, about 7, and 4 days, respectively (O'Connor-Shaw et al. 1994). However, fruit were not sanitized, nor were gloves worn during preparation and subsequent microbial decay and associated texture loss most likely limited post-cutting life. Sterilized, diced cantaloupe stored at 4 °C (39 °F) in various controlled atmospheres were acceptable from a sensory quality standpoint after 28 days (O'Connor-Shaw et al. 1996). Cantaloupe pieces stored at 2 °C (36°F) in ready-to-serve tray-packs were visually acceptable after 19 days, but flavor scores fell after 13 days storage (Silva et al. 1987). An informal taste panel determined that fresh-cut honeydew melon stored in air at 5 °C (41 °F) for 6 days lacked acceptable textural characteristics and were flat in flavor (Qi et al. 1998).

Fresh-cut pineapple stored at 4 °C (39 °F) had excellent visual appearance after 7 to 10 days storage; however, fruit in the lower portion of containers developed off flavors associated with microbial fermentation (Spanier et al. 1998). Fresh-cut orange segments that had acceptable appearance after 14 days storage were found to have unacceptable flavor quality after only 5 days at 4 °C (39 °F) (Rocha et al. 1995). Likewise, undesirable flavor was the limiting factor in sliced wrapped watermelon stored 7 days at 5 °C (41 °F), even though aroma was still acceptable and microbial populations were not problematic until after 8 days (Abbey et al. 1988).

Establishing overall shelf-life limits for fresh-cut fruit, taking flavor quality into consideration, is difficult since initial product variability, potential post-cutting treatments, and packaging affect flavor attributes differently. Washing whole products prior to processing and other proper sanitation practices, in combination with optimum storage temperature, are critical to maintaining quality and prolonging product life. Little is known concerning what effect storage temperature has on volatile production and little flavor and sensory work has been performed on fresh-cut fruits.

Microbiology

Microbial decay can be a major source of spoilage of fresh-cut produce (Brackett 1994). Microbial decay of fresh-cut fruit may occur much more rapidly than in vegetable products because of the high levels of sugars found in most fruit. The acidity of fruit tissue usually helps suppress bacterial growth but not growth of yeast and molds. There is no evidence to suggest that lower aerobic plate counts (APC) or total plate counts (TPC) immediately after processing correlate with increased shelf-life in fresh-cut vegetables. However, for fresh-cut fruit, very low APC, TPC, and especially yeast and mold counts correlate with increased shelf-life.

The dominant microorganisms associated with spoilage of fresh-cut vegetables are bacteria (for example, *Pseudomonas* spp.), whereas the dominant microorganisms associated with the spoilage of fresh-cut fruit products are yeasts and molds. In fresh-cut vegetables the proliferation of bacteria may be a symptom associated with tissue senescence and may not be a true cause of spoilage except in a few rare exceptions when pectinolytic *Pseudomonas* are present. However, in acidic fresh-cut fruit products, yeasts and molds are typically associated with product spoilage. Reducing initial yeast and mold counts, as well as slowing growth by low temperature storage at <5 °C (41 °F), affects product shelf-life (O'Connor-Shaw et al. 1994, Qi et al. 1999). In fresh-cut fruit with a neutral pH, such as cantaloupe, bacteria were the main source of spoilage (Lamikanra et al. 2000), and bacterial development was inhibited in fresh-cut watermelon by CA (3% O_2 and 15 or 20% CO_2). However, visual quality was compromised (Cartaxo et al. 1997).

Little research has been performed on foodborne human pathogens on fresh-cut fruits. Conway et al. (2000) determined that *Listeria monocytogenes* survived and proliferated on 'Delicious' apple slices stored at 10 or 20 °C (50 or 68 °F) in air or CA (0.5% O_2 + 15% CO_2) but did not grow at 5 °C (41 °F). CA had no significant effect on the survival or growth of *L. monocytogenes* at elevated temperatures. Botulinal toxin was not recovered in fresh-cut cantaloupe or honeydew inoculated with a 10-strain mixture of proteolytic and nonproteolytic *Clostridium botulinum* after 21 days at 7 °C (45 °F). However, toxin was recovered in some inoculated honeydew samples stored 9 days at 15 °C (59 °F) in hermetically sealed packages (Larson and Johnson 1999).

Factors Affecting Fresh-Cut Fruit Quality

Major factors affecting fresh-cut fruit quality are cultivar (Kim et al. 1993, Romig 1995), preharvest cultural practices (Romig 1995), harvest maturity (Gorny et al. 1998b), physiological status of the raw product (Brecht 1995), postharvest handling and cold storage (Watada et al. 1996), processing technique (Bolin et al. 1977, Saltveit 1997, Wright and Kader 1997b), sanitation (Hurst 1995), and packaging (Solomos 1994, Cameron et al. 1995).

General Fresh-Cut Physiology and Physiological Concerns

Most fruit are very susceptible to bruising and mechanical injury. This is very different from most fresh-cut vegetables, which may be derived from very durable root tissues (carrots, radishes) or pliable leaf tissue (iceberg lettuce, cabbage). Fresh-cut processing removes the fruit's natural cuticle, or skin barrier, to gas diffusion and microbial invasion, and severe disruption of the tissue often provokes increased respiration, ethylene production, and enhanced susceptibility to water loss and microbial decay. All of these factors may contribute to decreased shelf-life via browning, off color, softening, or decay.

Subsequently, methods for cutting and peeling fruit differ from those for vegetables. Therefore, mechanical size reduction (trimming, peeling, deseeding, etc.) by high-speed cutting equipment may not be appropriate for some fresh-cut fruit products. Knife sharpness has a significant effect on shelf-life of fresh-cut lettuce products (Bolin et al. 1977, Bolin and Huxsoll 1991), and this also applies to fresh-cut fruits. Pear slices cut with a freshly sharpened knife retained visual quality longer than fruit cut with a dull hand-slicer (Gorny and Kader 1996). Sharpening of machine and hand knives as often as possible prolongs shelf-life of fresh-cut fruit because there is less tissue injury.

Chilling Injury and Holding Temperatures

A significant number of fresh-cut fruits are not as chilling injury (CI) sensitive as the corresponding intact fruit before processing. Examples include pineapple, cantaloupe, honeydew, watermelon, peach, nectarine, and mango. If these intact fruits are stored at chilling temperatures, typically <12 °C (54 °F), accelerated physiological breakdown and increased incidence of pathological decay occurs. CI symptoms are often manifested when fruit are subsequently placed at non-chilling temperatures and may not be visible if maintained at chilling temperatures (Saltveit and Morris 1990). Nonetheless, precooling whole cantaloupe to below their optimal long-term storage temperature shortly before cutting is effective at increasing product shelf-life (Cantwell and Portela 1997, Lange 1998).

Fruit tissues normally damaged by storage at chilling temperatures are the inedible outer rind or skin portions. During fresh-cut processing, these tissues are normally removed and discarded. Although the optimal storage temperature for many whole CI-sensitive fruit is above 10 °C (50 °F), after processing storage at 0 °C (32°F) is almost always the temperature that provides optimal shelf-life by reducing growth of spoilage microorganisms. However, the edible flesh of CI-sensitive fruits may still be susceptible to chilling injury, and no studies have indicated if flavor biosynthesis is inhibited or negatively affected by chilling.

Variety, Growing Region, and Season

Seed companies and numerous fresh-cut processors are already aware that a given variety performs optimally in certain growing regions and oftentimes has variable postharvest quality attributes depending on cultural practices, climate, season, and harvest maturity. For example, the desirable volatile oil content of pineapple flesh is higher in summer fruit (Haagen-Smit et al. 1945), and the proportions of dominant apple volatiles vary by season (López et al. 1998). The aforementioned interactions, in concert with breeding against or for specific traits to optimize shelf-life, must be considered when developing cultivars tailored for the fresh-cut industry (Romig 1995). Several reports have documented that certain cultivars out-perform others with regard to fresh-cut shelf-life and quality (Kim et al. 1993, Cantwell and Portela 1997, Lange 1998, Gorny et al. 1999, Anonymous 2000b). However, no single study can encompass all desirable varieties, and singling out a "winner" can be compromised by seed source and seasonal/climactic variations. Furthermore, the industry may also be historically driven toward specific varieties (such as western cantaloupes) when indeed optimum alternatives exist for local seasonal production (such as eastern cantaloupes) (Lange 1998).

Gorny et al. (1999) determined the shelf-life of peach and nectarine slices made from 13 cultivars of peaches and eight cultivars of nectarines that had been ripened to between 4 to 7 lb (18 to 31 N) firmness, cut, and then held at 0 °C (32 °F) with 90 to 95% RH. Shelf-life was 2 to 12 days among the cultivars tested. Of the peach cultivars tested, 'Cal Red,' 'Red Cal,' and 'Elegant Lady' had the longest marketable shelf-life of 7.4, 7.2, and 6.7 days, respectively; while 'Summer Lady' and 'Ryan Sun' had the shortest (<2 days). Among nectarines, 'Sparkling Red,' 'Arctic Queen,' and 'Zee Grand' had the longest shelf-life of 12, 8, and 8 days, respectively, while the other cultivars had a shelf-life of 4 to 6 days. White-flesh peaches and nectarines had a comparable shelf-life to yellow-fleshed cultivars, with similar browning characteristics.

Based on visual quality, fresh-cut pear slices prepared from partially ripened 'Bosc' and 'Bartlett' fruit had the longest shelf-life in air at 10 °C (50 °F), being 3 and 4 days, respectively (Gorny et al. 1998a). d'Anjou' and 'Red Anjou' pear slices had a very short shelf-life of <2 days each, due to severe enzymatic browning on cut surfaces (Gorny et al. 1998a). However, 'Bartlett' and 'Bosc' pear slices experienced a much greater loss in firmness after slicing and storage in air at 10 °C (50 °F) than d'Anjou' and Red d'Anjou' slices.

Fruit Size and Yield

Typically, fresh-cut fruit processors will use either very large or very small fruit to maximize yields or to reduce the cost of raw ingredients. For example, fresh-cut melon processors will typically use very large 9-count-per-box fruit. This is because large melons are often available at lower prices in the marketplace, the yield from larger melon fruits is almost always higher, and the labor to process one large fruit is often less than processing many smaller fruit. Very little research has been done to document the effects of fruit size on post-cutting shelf-life and quality. One study by Gorny et al. (2000) found that 'Bartlett' pear fruit size did not have a significant effect on fresh-cut slice shelf-life, based on flesh color and firmness, if slices were treated after cutting with 2% ascorbate + 1% calcium lactate + 0.5% (w/v) cysteine, pH 7. However, if slices were not treated, smaller fruit discolored at their cut surface more rapidly than slices from large fruit. Small fruit also had lower SSC than large fruit, which may affect eating quality. These findings demonstrate that, in some cases, smaller whole fruit, which often receive lower prices in the marketplace, should be avoided for value-added fresh-cut products.

Physical Treatments

Many physical and chemical techniques have been studied as alternatives or adjuncts to MAP, especially for fresh-cut fruit: edible coatings (Baldwin et al. 1995a,b, 1996, Howard and Dewi 1996, Li and Barth 1998), disinfection (Hong and Gross 1998, Sapers and Simmons 1998), natural plant products (Kato-Noguchi and Watada 1997, Leepipattanawit et al. 1997, Buta et al. 1999, Moline et al. 1999), ethylene absorbents (Abe and Watada 1991), gamma irradiation (Chervin and

Boisseau 1994, Hagenmaier and Baker 1997), heat treatments or heat shock (Loaiza-Velarde et al. 1997), microbial competition (Liao 1989, Breidt and Fleming 1997), non-thermal physical treatments (Hoover 1997), and pulsed-microwave irradiation (Shin and Pyun 1997).

Storage Time, Temperature, and Atmosphere

The beneficial effects of CA storage for whole fruit have been well documented, and CA is widely employed throughout the industry. However, CA storage markedly inhibits apple volatile production (Yahia 1991, 1994, Mattheis et al. 1995). Furthermore, fruit maturity at harvest has been shown to be important in terms of volatile production in melons (Pratt 1971, Wyllie et al. 1996, Beaulieu and Grimm 2001, Beaulieu and Baldwin 2002) and in apples (Hansen et al. 1992, Brackmann et al. 1993, Yahia et al. 1990), especially once apple fruit were removed from CA and ripened 10 days at 20 °C (68 °F) (Mattheis et al. 1995). In fresh-cut 'Gala' apples stored for 14 days at 1 °C (34 °F) in sealed pouches, sugars remained constant during storage, pH decreased, and TA, sweetness, and sweet aromatic flavor all increased and then decreased (Bett et al. 2001). Therefore, certain packaged fresh-cut products may require active modification of the atmosphere to ensure desirable flavor during consumption.

Gorny et al. (2002) determined that, compared to air storage, CA (2% O_2 + 98% N_2) storage at -1 °C (30 °F) of whole mature-green pears extended shelf-life of slices 1 to 2 days. There was a significant reduction in shelf-life of pear slices stored at -1 °C (30 °F) in air or CA compared to slices from freshly harvested pears. Therefore, it seems beneficial to use CA for off-season pears (as opposed to air-stored) to maximize post-cutting life of slices. However, research is needed to determine if volatile synthesis is impaired, as in CA-stored apples.

Modified Atmosphere Packaging (MAP)

MAP is widely used for fresh-cut vegetables, but with fruits occasionally undesirable atmospheres can reduce quality due to off flavor and discoloration (Gil et al. 1998).

Heat Treatment

Slices prepared from heat-treated apples at 45 °C (113 °F) for 105 min, that did not display browning after treatment ('Delicious,' 'Empire,' 'Golden Delicious,' 'McIntosh' and 'New York 674'), were firmer (differences ranging from 12% for 'McIntosh' to 48% for 'Delicious') after 8 days storage at 2 °C (36 °F) than those prepared from untreated apples (Kim et al. 1994). However, heat treatments often led to undesirable flesh browning in many other cultivars tested (Kim et al. 1994).

Irradiation

Irradiation of fresh-cut fruit products may be beneficial in reducing the number of bacteria present on the product. The current FDA limit for irradiation on fresh produce is 1.0 kGy, but to destroy yeasts and molds that may exist as spores, irradiation levels of 1.5 to 20 kGy are necessary (Brackett 1987); and these levels are damaging to fruit tissues. Irradiation reduced ethylene production of all pre- versus post-climacteric apple slices and irradiation doses of up to 2.4 kGy had minimal effect on the respiratory physiology of tissues (Gunes et al. 2000). However, tissue softening occurred at doses above 0.4 kGy. Therefore, the use of irradiation to extend the shelf-life of fresh-cut fruit products has only limited benefits since the main spoilage microorganisms on fresh-cut fruit products are yeasts and molds.

Chemical Treatments

Retention of fresh-cut product firmness and inhibition of browning are common measures used to determine efficacy of chemical treatments. Calcium has been used as an agent for maintaining firmness of whole produce (Poovaiah 1986), and its use in fresh-cut was inevitable. Other chemical treatments have also been explored, and most GRAS applications used today involve chlorine, ascorbic acid, or calcium salts for preservation.

Chlorination and Washes

In general, fresh-cut fruit should be rinsed just after cutting with cold (0 to 1°C, 32 to 34 °F) chlorinated water at pH 7.0. This may help extend product shelf-life by reducing microbial load, removing cellular juices at cut surfaces that may promote cut surface discoloration, and actually inhibiting the enzymatic reactions involved in fruit browning (Brecht et al. 1993, Hurst 1995).

Chlorination, as commonly used for fresh-cut salad sanitation (not exceeding 200 $\mu L\ L^{-1}$ total chlorine), may not be desirable for all fresh-cut fruits. Post-cutting washing or dipping may have negative consequences regarding increased water activity and "washing away" of desirable flavor attributes. Processors may or may not wash freshly cut commodities that develop little or no browning (cantaloupe and honeydew, for example), since chemical treatments are seldom applied and because removal of free surface water (centrifugation or spinning) from the cut fruit can be damaging. On the other hand, honeydew and cantaloupe pieces dipped in hypochlorite (pH 6, 50 $\mu L\ L^{-1}$) prior to packaging in 95% N_2 + 5% O_2 at 2 °C (36 °F) had no deleterious effect and microbial counts were lowered throughout storage (Ayhan et al. 1998).

Hydrogen peroxide (H_2O_2) is a strong oxidizing agent and a powerful surface-contact sterilizer. It has been shown experimentally to reduce microbe populations on the surface of many produce items with minimal to no residue (Bolin and Huxsoll 1989, Sapers and Simmons 1998). However, the GRAS status regarding use on fresh-cut products is currently unclear.

Calcium Compounds and Firmness Retention

Application of aqueous calcium compounds (generally 1% $CaCl_2$ dips) helps maintain firmness of fresh-cut apples, pears, and strawberries (Ponting et al. 1971, 1972, Morris et al. 1985, Rosen and Kader 1989, Gorny et al. 1998a). Softening of muskmelon sections was affected differently depending on calcium concentration (Lester 1996). Softening was the major factor in quality loss in kiwifruit slices. However, these slices had a shelf-life of 9 to 12 days if treated with 1% $CaCl_2$ or 2% calcium lactate and stored at 0 to 2 °C with >90% RH in 2 to 4% O_2 and/or 5 to 10% CO_2 (Massantini and Kader 1995, Agar et al. 1999). Cantaloupe cylinders treated with 1, 2.5, and 5% $CaCl_2$ for 1 to 5 min and stored 10 days at 5 °C (41 °F) generally increased in firmness (Luna-Guzmán et al. 1999).

Calcium lactate has been shown to be as effective as the chloride form without imparting a bitter flavor at higher concentrations (Luna-Guzmán and Barrett 2000). A 1% calcium lactate dip was an effective alternative to ascorbate in fresh-cut 'Bartlett' pears stored 1 to 2 days at 20 °C (68 °F), and 1% calcium lactate with 2% ascorbate was most effective (Gorny et al. 1998a).

Antibrowning Compounds

Many fruits brown rapidly after cutting, and extensive work has been performed to address this quality loss. Cut surface discoloration or enzymatic browning, caused by formation of quinones in the presence of O_2 and PPO, has been the subject of much research (Vámos-Vigyázó 1981, Sapers 1993). Since sulfite use as an anti-browning agent in the United States requires labeling for fresh produce, alternative GRAS and experimental compounds have been investigated. Nevertheless, enzymatic browning still represents a major challenge with fresh-cut fruit (Weller et al. 1997, Sapers and Miller 1998).

Ascorbate, citrate, isoascorbate, and sodium erythorbate are some of the most commonly used agents to reduce or eliminate cut-surface discoloration. Ascorbate was more effective than erythorbate in preventing surface browning in 'Winesap' and 'Red Delicious' apple plugs stored 24 h, and 1% citric acid enhanced their effectiveness (Sapers and Zoilkowski 1987). Cut surface discoloration was restricted in vacuum-packed carambola slices stored at 4 °C (39 °F) that were treated with 1 or 2.5% citrate plus 0.25% ascorbate (Weller et al. 1997). Ascorbate-2-phosphate and ascorbate-2-triphosphate also decreased cut surface discoloration in 'Red Delicious' apple plugs for 24 h (Sapers et al. 1989). 'Fuji' apple slices treated with 2% ascorbate had no browning or loss of visual quality for up to 15 days when stored at 10 °C (50 °F) in 0.25% O_2 (Gil et al. 1998). Calcium, in combination with ascorbate, was effective in preventing discoloration of fresh-cut apples (Ponting et al. 1972) and pears (Rosen and Kader 1989, Gorny et al. 1998a). Browning was also reduced in fresh-cut 'Carnival' peaches treated with 1% calcium lactate plus 2% ascorbate (Gorny et al. 1999).

Browning was retarded in slightly under-ripe 'Bartlett' and 'd'Anjou' pears treated with a combination of sodium erythorbate, $CaCl_2$, and 4-hexylresorcinol after 14 days storage at 4 °C (39 °F). However, fresh-cut 'Bosc' pears browned severely irrespective of inhibitor treatment (Sapers and Miller 1998). On the other hand, a combination dip with 0.01% 4-hexylresorcinol, 0.5% ascorbate, and 1% calcium lactate extended shelf-life of 'Anjou,' 'Bartlett,' and 'Bosc' pear slices for 15 to 30 days (Dong et al. 2000). Furthermore, combined treatments with 1 mM 4-hexylresorcinol, 0.5 M isoascorbate, 50 mM potassium sorbate, and 25 mM *N*-acetylcysteine decreased browning in fresh-cut 'Anjou,' 'Bartlett,' and 'Bosc' pears for 14 days. The preservative effect was unaffected by initial firmness (4.7 to 11.7 lb, 21 to 52 N) for 'Anjou' slices (Buta and Abbott 2000).

'Red Delicious' apple slices treated with a combined antibrowning dip (4-hexylresorcinol, isoascorbic acid, *N*-acetylcysteine, and calcium propionate) and held at 5 °C (41 °F) maintained visual quality for 5 weeks, yet microbial decay was evident after 4 weeks (Buta et al. 1999). Analyses of organic acids and sugars revealed that slices treated with combinations of antibrowning compounds retained higher levels of malate and had no decrease in sugar levels at 5 and 10 °C (41 and 50 °F), indicating that higher quality was maintained during storage. Fresh-cut mangoes treated with 1 mM 4-hexylresorcinol, 50 mM potassium sorbate, and 500 mM ascorbic acid in MAP at 10 °C (50 °F) maintained color and sensory characteristics, with low microbial growth, for 14 days (Gonzalez-Aguilar et al. 2000). Cut-surface discoloration was significantly reduced in fresh-cut banana slices treated with 500 mM citrate and 50 mM *N*-acetylcysteine and stored at 5 °C (41 °F) or 15 °C (59 °F) for 7 days, and no microbial decay was observed (Moline et al. 1999). A combination of 0.5% carrageenan and 0.5% citrate also inhibited browning in diced 'Granny Smith' and 'Red Delicious' apples for 7 to 9 days at 3 °C (37 °F) (Tong and Hicks 1991).

Cysteine inhibits PPO-mediated enzymatic browning (Joslyn and Ponting 1951, Molnar-Perl and Friedman 1990, Gunes and Lee 1997). Three mechanisms have been proposed to explain how thiol compounds inhibit enzymatic browning: reduction of *o*-quinone back to *o*-dihydroxyphenol (Kahn 1985); direct inhibition of PPO (Dudley and Hotchkiss 1989, Robert et al. 1996); and formation of a colorless cys-quinone adduct (Richard et al. 1991).

When cysteine is used as an inhibitor of enzymatic browning on sliced apples (Walker and Reddish 1964) or pears (Sapers and Miller 1998), pinkish-red off-colored compounds are formed due to phenol regeneration with deep color formation (Richard-Forget et al. 1992). If off-color formation can be prevented, cysteine may prove to be an effective replacement to bisulfites. Cysteine is a naturally occurring amino acid that has GRAS status for use as a dough conditioner (Code of Federal Regulations 21:184.1271 and 21:184.1272). Development of cut surface discoloration was reduced for only

1 day at 0 °C (32 °F) in 'Golden Delicious' fresh-cut apples treated with 0.1% cysteine (Nicoli et al. 1994). Ineffectiveness of the cysteine treatment was attributed to oxidation in the package and likely was due to the low concentration applied. Gorny et al. (2002) reported that a post-cutting dip (pH 7.0) of 2% ascorbate, 1% calcium lactate, plus 0.5% (weight by volume) cysteine significantly extended shelf-life of 'Bartlett' pear slices by inhibiting loss of firmness and preventing browning. Consumer panelists could not distinguish between pear slices treated with the preservative and controls. After 10 days in air at 0 °C (32 °F), 82 and 70% of consumers judged treated pear slices to be acceptable in appearance and flavor, respectively.

When used in combination with ascorbic acid, 4-hexylresorcinol is an effective inhibitor of cut discoloration on many fresh-cut fruit, including apples and pears especially (Monslave-Gonzalez et al. 1993, Luo and Barbosa-Cánovas 1996, 1997, Sapers and Miller 1998, Moline et al. 1999, Buta and Abbott 2000, Dong et al. 2000). Between 1 and 7 µL L^{-1} of residual 4-hexylresorcinol was necessary to prevent browning on fresh-cut pear slices stored up to 14 days at 2 to 5 °C (36 to 41 °F) (Dong et al. 2000). Although it is effective in preventing cut surface browning, it is not currently considered GRAS by the FDA and may not be used on fresh-cut fruit. It may also impart an unacceptable off flavor on fruit products.

Antimicrobials, Edible Coatings, and Other Treatment Compounds

Hexanal is a natural aroma precursor in apples that is readily converted to aroma volatiles in vivo by fresh-cut apple slices (Song et al. 1996). Hexanal can not only enhance aroma, but it also reduced enzymatic browning at cut surfaces, as well as inhibiting molds, yeasts, and mesophilic and psychrotrophic bacteria in 'Granny Smith' slices stored at 15 °C (59 °F) (Lanciotti et al. 1999). The inclusion of hexanal and *(E)*-hexenal in the MAP (70% N_2 + 30% CO_2) of sliced 'Granny Smith' apples reduced spoilage microbe populations and increased color stability for up to 16 days at abusive storage temperatures (Corbo et al. 2000). Research is currently in the initial stages for the use of volatile compounds on fresh-cut products; hexanal is not currently approved for use.

Methyl jasmonate is a naturally occurring volatile compound, found in many plants, that has hormonelike activity at low concentrations. Exogenously applied methyl jasmonate is effective in reducing mold growth on fresh-cut celery and peppers and may have applications as a naturally derived fungicide (Buta and Moline 1998).

Edible coatings have been used in an attempt to preserve fresh-cut products because the coatings act as barriers to water loss and gas exchange, creating a micromodified atmosphere around products, and can serve as carriers for other GRAS compounds (Baldwin et al. 1995a). Ethylene production and CO_2 evolution were reduced in apple slices coated with double layers of buffered polysaccharide/lipid, stored at 23 °C (73 °F) (Wong et al. 1994). Use of a cellulose-based edible coating on fresh-cut apple cylinders stored in overwrapped trays at 4 °C (39 °F) increased shelf-life by about 1 week (Baldwin et al. 1996). The effectiveness of ascorbate to reduce browning and potassium sorbate to decrease microbial growth was superior when incorporated into this edible coating. A commercially available sucrose ester edible coating also inhibits browning of fresh-cut fruit by acting as an O_2 barrier.

Peeled, packaged citrus products have a shelf-life of approximately 17 to 21 days, but fluid leakage can be problematic. Edible wax microemulsion coatings (up to 12% SSC) reduced leakage of dry-packed grapefruit segments by 80% after 2 weeks and by 64% after 4 weeks (Baker and Hagenmaier 1997). Coatings could be made with polyethylene, candelilla, or carnauba wax with lauric, stearic, palmitic, oleic, or myristic acids. Carnauba wax was most effective, and coatings were not detected by informal taste panels (Baker and Hagenmaier 1997).

Compendium of Recommendations and Data Related to Fresh-Cut Fruit Products

Proper storage temperature and atmosphere are the two most important factors that influence post-cutting shelf-life of fresh-cut fruit. Tables 1 and 2 identify optimum storage atmospheres, temperatures, and respiration rates for a range of fresh-cut fruits. This information may be used as a starting point for design and testing of MAP for fresh-cut fruit products. Fresh-cut fruit respiration rates, as well as responding to atmospheric modification, will vary depending on many factors, including variety and maturity of fruit at cutting.

Table 1. Respiration rates for fresh-cut fruits in air at various storage temperatures

Fresh-cut product	**Temperature (°C)**				
	0 to 2.5	**4 to 5**	**10**	**15**	**20 to 23**
	mg CO_2 kg^{-1} h^{-1}				
Apple, sliced					
‘Fuji’	—	—	6.7-19.0	—	—
Cantaloupe, cubed	4.0-16.0	5.9-31.2	11.4	—	54.0
Honeydew, cubed	3.6-10.2	—	—	18.9-85.1	—
Kiwifruit, sliced	2.0-6.0	—	—	—	32.4-46.8
Orange, sliced	—	5.3-5.7	—	—	30.8-32.9
Peach, sliced	6.0-12.0	11.7-44.9	32.3-100.7	—	—
Pear, sliced					
‘Bartlett’	0.0-10.0	—	22.8-30.4	—	90.0
‘Bosc’	—	—	15.2-26.6	—	—
‘d’Anjou’	—	—	13.3-26.6	—	—
‘Red d’Anjou’	—	—	11.4-26.6	—	—
Pineapple, cubed					
mature green	4.0-5.0	—	6.7-15.2	—	—
Golden	11.0-14.0	—	24.7-30.4	—	—
Pomegranate, arils	1.0-4.0	2.9-5.9	5.7-11.4	—	—
Strawberry, sliced	—	11.1	—	—	315.0

From Gorny (1998), updated based on references cited in this chapter.

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Table 2. Storage atmosphere recommendations for selected fresh-cut fruits

Fresh-cut product	Temperature	Atmosphere O_2	Atmosphere CO_2	Efficacy
	ºC	*%*		
Apple, sliced	0-5	<1	—	moderate
Cantaloupe, cubed	0-5	3-5	6-15	good
Honeydew, cubed	0-5	2	10	good
Kiwifruit, sliced	0-5	2-4	5-10	good
Mango, cubed	5	2-4	10	moderate
Orange, sliced	0-5	14-21	7-10	moderate
Peach, sliced	0	1-2	5-12	poor
Pear, sliced	0-5	0.5	<10	poor
Persimmon, sliced	0-5	2	12	poor
Pomegranate, arils	0-5	-	15-20	good
Strawberry, sliced	0-5	1-2	5-10	good
Watermelon, sliced	3	3	10-20	poor

From Gorny 1998, updated based on references cited in this chapter such as Rattanapanone and Watada 2000.

References

Abbey, S.D., E.K. Heaton, D.A. Golden, and L.A. Beuchat. 1988. Microbiological and sensory quality changes in unwrapped and wrapped sliced watermelon. J. Food Prot. 51:531-533.

Abe, K., and A.E. Watada. 1991. Ethylene absorbent to maintain quality of lightly processed fruits and vegetables. J. Food Sci. 56:1589-1592.

Abeles, F.B., P.W. Morgan, and M.E. Saltveit. 1992. Ethylene in Plant Biology, 2nd Edition, Academic Press, San Diego.

Agar, I.T., B. Hess-Pierce, and A.A. Kader. 1999. Postharvest CO_2 and ethylene production and quality maintenance of fresh-cut kiwifruit slices. J. Food Sci. 64(3):433-440.

AMS [U.S. Department of Agriculture, Agricultural Marketing Service]. 1998. Quality through verification program for the fresh-cut produce industry. Federal Register 63:47220-47224.

Anonymous. 1998. Food and Drugs. Food labeling. Code of Federal Regulations, 21CFR101.95.

Anonymous. 2000a. No substitute for flavor in fresh-cut. Fresh Cut, May, pp. 22-28.

Anonymous. 2000b. Supplying quality cantaloupe for fresh-cut processing. Fresh Cut, Jan, pp. 6-12.

Ayhan, Z., G.W. Chism, and E.R. Richter. 1998. The shelf-life of minimally processed fresh cut melons. J. Food Qual. 21:29-40.

Baker, R.A., and R.D. Hagenmaier. 1997. Reduction of fluid loss from grapefruit segments with wax microemulsion coatings. J. Food Sci. 62:789-792.

Baldwin, E.A., M.O. Nisperos, X. Chen, and R.D. Hagenmaier. 1996. Improving storage-life of cut apple and potato with edible coating. Postharv. Biol. Technol. 9:151-163.

Baldwin, E.A., M.O. Nisperos-Carriedo, and R.A. Baker. 1995a. Edible coatings for lightly processed fruits and vegetables. HortScience 30:35-38.

Baldwin, E.A., M.O. Nisperos-Carriedo, and R.A. Baker. 1995b. Use of edible coatings to preserve quality of lightly (and slightly) processed products. CRC Crit. Rev. Food Sci. Nutr. 35:509-524.

Beaulieu, J.C., and E.A. Baldwin, 2002. Flavor and aroma of fresh-cut fruits and vegetables. *In* O. Lamikanra, ed., Fresh-Cut Fruits and Vegetables. Science, Technology and Market, pp. 391-425. CRC Press, Boca Raton, FL.

Beaulieu, J.C., K.L. Bett, E.T. Champagne, et al. 1999. Flavor, sensory and postharvest evaluations of commercial versus tree-ripe fresh-cut ‘Bounty’ peaches. HortScience 34:504.

Beaulieu, J.C., and C.C. Grimm. 2001. Identification of volatile compounds in cantaloupe at various developmental stages using solid phase microextraction. J. Agric. Food Chem. 49:1345-1352.

Bett, K.L., D.A. Ingram, C.C. Grimm, et al. 2001. Flavor of fresh-cut ‘Gala’ apples in modified atmosphere packaging as affected by storage time. J. Food Qual. 24:141-156.

Bolin, H.R., and C.C. Huxsoll. 1989. Storage stability of minimally processed fruit. J. Food Proc. Preserv. 13:281-292.

Bolin, H.R., and C.C. Huxsoll. 1991. Effect of preparation procedures and storage parameters on quality retention of salad-cut lettuce. J. Food Sci. 56:60-62,67.

Bolin, H.R., A.E. Stafford, A.D. King Jr., and C.C. Huxsoll. 1977. Factors affecting the storage stability of shredded lettuce. J. Food Sci. 42:1319-1321.

Brackett, R.E. 1987. Microbiological consequences of minimally processed fruits and vegetables. J. Food Qual. 10:195-206.

Brackett, R.E. 1994. Microbiological spoilage and pathogens in minimally processed refrigerated fruits and vegetables. *In* R.C. Wiley, ed., Minimally Processed Refrigerated Fruits and Vegetables, pp. 269-312. Chapman and Hall, London, U.K.

Brackmann, A., J. Streif, and F. Bangerth. 1993. Relationship between a reduced aroma production and lipid metabolism of apples after long-term controlled-atmosphere storage. J. Amer. Soc. Hort. Sci. 118:243-247.

Brecht, J.K. 1995. Physiology of lightly processed fruits and vegetables. HortScience 30:18-22.

Brecht, J.K., A.U.O. Sabaa-Srur, S.A. Sargent, and R.J. Bender. 1993. Hypochlorite inhibition of enzymatic browning of cut vegetables and fruit. Acta Hort. 343:341-344.

Breidt, F., and H.P. Fleming. 1997. Using lactic acid bacteria to improve the safety of minimally processed fruits and vegetables. Food Technol. 51:44-46, 48-51.

Buta, J.G., and J.A. Abbott. 2000. Browning inhibition of fresh-cut ‘Anjou’, ‘Bartlett’, and ‘Bosc’ pears. HortScience 35:1111-1113.

Buta, J.G., and H.E. Moline. 1998. Methyl jasmonate extends shelf-life and reduces microbial contamination of fresh-cut celery and peppers. J. Agric. Food Chem. 46:1253-1256.

Buta, J.G., H.E. Moline, D.W. Spaulding, and C.Y. Wang. 1999. Extending storage-life of fresh-cut apples using natural products and their derivatives. J. Agric. Food Chem. 47:1-6.

Cameron, A.C., P.C. Talasila, and D.W. Joles. 1995. Predicting film permeability needs for modified-atmosphere packaging of lightly processed fruits and vegetables. HortScience 30:25-34.

Cantwell, M., and Portela, S. 1997. Comparing varieties and storage method. FreshCut, Oct., pp. 14-18.

Cartaxo, C.B.C., S.A. Sargent, and D.J. Huber. 1997. Controlled atmosphere storage suppresses microbial growth on fresh-cut watermelon. Proc. Fla. Sta. Hort. Soc. 110:252-257.

Chervin, C., and P. Boisseau. 1994. Quality maintenance of "ready-to-eat" shredded carrots by gamma irradiation. J. Food Sci. 59:359-361.

Conway, W.S., B. Leverentz, R.A. Saftner, et al. 2000. Survival and growth of *Listeria monocytogenes* on fresh-cut apple slices and its interaction with *Glomerella cingulata* and *Penicillium expansum*. Plant Dis. 84:177-181.

Corbo, M.R., R. Lanciotti, F. Gardini, et al. 2000. Effects of hexanal, trans-2-hexenal, and storage temperature on shelf-life of fresh sliced apples. J. Agric. Food Chem. 48:2401-2408.

Dong, X., R.E. Wrolstad, and D. Sugar. 2000. Extending shelf-life of fresh-cut pears. J. Food Sci. 65:181-186.

Dudley, E.D., and J.H. Hotchkiss. 1989. Cysteine as an inhibitor of polyphenol oxidase. J. Food Biochem. 13:65-75.

Gil, M.I., J.R. Gorny, and A.A. Kader. 1998. Responses of 'Fuji' apple slices to ascorbic acid treatments and low-oxygen atmospheres. HortScience 33:305-309.

Gonzalez-Aguilar, G.A., C.Y. Wang, and J.G. Buta. 2000. Maintaining quality of fresh-cut mangoes using antibrowning agents and modified atmosphere packaging. J. Agric. Food Chem. 48:4204-4208.

Gorny, J.R. 1998. A summary of CA and MA requirements and recommendations for fresh-cut (minimally processed) fruits and vegetables. *In* J.R. Gorny, ed., Fresh-cut Fruits and vegetables and MAP, vol. 5, 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, pp. 30-66. University of California Postharvest Horticulture Series no. 19, University of California, Davis, CA.

Gorny, J.R., R.A. Cifuentes, B. Hess-Pierce, and A.A. Kader. 2000. Quality changes in fresh-cut pear slices as affected by cultivar, ripeness stage, fruit size, and storage regime. J. Food Sci. 65:541-544.

Gorny, J.R., M.I. Gil, and A.A. Kader. 1998a. Postharvest physiology and quality maintenance of fresh-cut pears. Acta Hort. 464:231-236.

Gorny, J.R., B. Hess-Pierce, R.A. Cifuentes, and A.A. Kader. 2002. Quality changes in fresh-cut pear slices as affected by controlled atmospheres and chemical preservatives. Postharv. Biol. Technol. 24(3):271-278.

Gorny, J.R., B. Hess-Pierce, and A.A. Kader. 1998b. Effects of fruit ripeness and storage temperature on the deterioration rate of fresh-cut peach and nectarine slices. HortScience 33:110-113.

Gorny, J.R., B. Hess-Pierce, and A.A. Kader. 1999. Quality changes in fresh-cut peach and nectarine slices as affected by cultivar, storage atmosphere and chemical treatments. J. Food Sci. 64:429-432.

Gorny, J.R., and A.A. Kader. 1996. Fresh-cut fruit products. *In* M. Cantwell, ed., Fresh-Cut Products: Maintaining Quality and Safety. Postharvest Horticulture Series no. 10, University of California, Davis, CA.

Gunes, G., and C.Y. Lee. 1997. Color of minimally processed potatoes as affected by modified atmosphere packaging and antibrowning agents. J. Food Sci. 62:572-575,582.

Gunes, G., C.B. Watkins, and J.H. Hotchkiss. 2000. Effects of irradiation on respiration and ethylene production of apple slices. J. Sci. Food Agric. 80:1169-1175.

Haagen-Smit, A.J., J.G. Kirchner, A.N. Prater, and C.L. Deasy. 1945. Chemical studies of pineapple (*Ananas sativa* Lindl). I. The volatile flavor and odor constituents of pineapple. J. Amer. Chem. Soc. 67:1646-1652.

Hagenmaier, R.D., and R.A. Baker. 1997. Low-dose irradiation of cut iceberg lettuce in modified atmosphere packaging. J. Agric. Food Chem. 45:2864-2868.

Hansen, K., L. Poll, and M.J. Lewis. 1992. The influence of picking time on the postharvest volatile ester production of 'Jonagold' apples. Lebensm. Wiss. Technol. 25:451-456.

Hong, J.H., and K.C. Gross. 1998. Surface sterilization of whole tomato fruit with sodium hypochlorite influences subsequent postharvest behavior of fresh-cut slices. Postharv. Biol. Technol. 13:51-58.

Hoover, D.G. 1997. Minimally processed fruits and vegetables: reducing microbial load by non-thermal physical treatments. Food Technol. 51:66-69,71.

Howard, L.R., and T. Dewi. 1996. Minimal processing and edible coating effects on composition and sensory quality of mini-peeled carrots. J. Food Sci. 61:643-645,651.

Hurst, W.C. 1995. Sanitation of lightly processed fruits and vegetables. HortScience 30:22-24.

Joslyn, M.A., and J.D. Ponting. 1951. Enzyme-catalyzed oxidative browning of fruit products. Adv. Food Res. 3:44.

Kahn, V. 1985. Effect of proteins, protein hydolyzates and amino acids on *o*-diphenolase activity on polyphenol oxidase of mushroom, avocado and banana. J. Food Sci. 50:111-115.

Kato-Noguchi, H., and A.E. Watada. 1997. Citric acid reduces the respiration of fresh-cut carrots. HortScience 32:136-136.

Kim, D.M., N.L. Smith, and C.Y. Lee. 1993. Quality of minimally processed apple slices from selected cultivars. J. Food Sci. 58:1115-1117,1175.

Kim, D.M., N.L. Smith, and C.Y. Lee. 1994. Effect of heat treatment on firmness of apples and apple slices. J. Food Proc. Preserv. 18:1-8.

King, A.D. Jr., and H.R. Bolin. 1989. Physiological and microbiological storage stability of minimally processed fruits and vegetables. Food Technol. 43:132-135.

Lamikanra, O., J.C. Chen, D. Banks, and P.A. Hunter. 2000. Biochemical and microbial changes during the storage of minimally processed cantaloupe. J. Agric. Food Chem. 48:5955-5961.

Lanciotti, R., M.R. Corbo, F. Gardini, et al. 1999. Effect of hexanal on the shelf-life of fresh apple slices. J. Agric. Food Chem. 47:4769-4776.

Lange, D. 1998. Eastern cantaloupe varieties and their potential for fresh-cut melon products. FreshCut, Aug., pp. 17-18.

Larson, A.E., and E.A. Johnson. 1999. Evaluation of botulinal toxin production in packaged fresh-cut cantaloupe and honeydew melons. J. Food Prot. 62:948-952.

Leepipattanawit, R., R.M. Beaudry, and R.J. Hernandez. 1997. Control of decay in modified atmosphere packages of sliced apples using 2-nonanone vapor. J. Food Sci. 62:1043-1047.

Lester, G.E. 1996. Calcium alters senescence rate of postharvest muskmelon fruit disks. Postharvest Biol. Technol. 7:91-96.

Li, P., and M.M. Barth. 1998. Impact of edible coatings on nutritional and physiological changes in lightly processed carrots. Postharvest Biol. Technol. 14:51-60.

Liao, C.H. 1989. Antagonism of *Pseudomonas putida* strain PP22 to phytopathogenic bacteria and its potential use as a biocontrol agent. Plant Dis. 73:223-226.

Loaiza-Velarde, J.G., F.A. Tomas-Barberan, and M.E. Saltveit. 1997. Effect of intensity and duration of heat-shock treatments on wound-induced phenolic metabolism in iceberg lettuce. J. Amer. Soc. Hort. Sci. 122:873-877.

López, M.L., M.T. Lavilla, M. Riba, and M. Vendrell. 1998. Comparison of volatile compounds in two seasons in apples: Golden Delicious and Granny Smith. J. Food Qual. 21:155-166.

Luna-Guzmán, I., and D.M. Barrett. 2000. Comparison of calcium chloride and calcium lactate effectiveness in maintaining shelf stability and quality of fresh-cut cantaloupes. Postharv. Biol. Technol. 19:61-72.

Luna-Guzmán, I., M.I. Cantwell, and D.M. Barrett. 1999. Fresh-cut cantaloupe: effects of $CaCl_2$ dips and heat treatments on firmness and metabolic activity. Postharv. Biol. Technol. 17:201-213.

Luo, Y., and G.V. Barbosa-Cánovas. 1996. Preservation of apple slices using ascorbic acid and 4-hexylresorcinol. Food Sci. Technol. Int. 2:315-321.

Luo, Y., and G.V. Barbosa-Cánovas. 1997. Enzymatic browning and its inhibition in new apple cultivar slices using 4-hexylresorcinol in combination with ascorbic acid. Food Sci. Technol. Int. 3:195-201.

Massantini, R., and A.A. Kader. 1995. Conservazione e mantenimento qualitativo delle fette de kiwi [Storability and quality preservation of sliced kiwifruits]. Industrie Alimentari. 34:357-360. Italian.

Mattheis, J.P., D.A. Buchanan, and J.K. Fellman. 1995. Volatile compound production by Bisbee Delicious apples after sequential atmosphere storage. J. Agric. Food Chem. 43:194-199.

Moline, H.E., J.G. Buta, and I.M. Newman. 1999. Prevention of browning of banana slices using natural products and their derivatives. J. Food Qual. 22:499-511.

Molnar-Perl, I., and M. Friedman. 1990. Inhibition of browning by sulfur amino acids. Apples and potatoes. Agric. Food Chem. 38:1652-1656.

Monslave-Gonzalez, A., G.V. Barbosa-Cnovas, R.P. Cavallieri, et al. 1993. Control of browning during storage of apple slices by combed methods. 4-Hexylresorcinol as an anti-browning agent. Food Sci. 58:797-800.

Morris, J.R., W.A. Sistrunk, C.A. Sims, and G.L. Main. 1985. Effects of cultivar, postharvest storage, preprocessing dip treatment and style of pack on the processing quality of strawberries. J. Amer. Soc. Hort. Sci. 110(2):172-177.

Nicoli, M.C., M. Anese, and C. Severini. 1994. Combined effects in preventing enzymatic browning reactions in minimally processed fruit. J. Food Qual. 17:221-229.

O'Connor-Shaw, R.E., R. Roberts, A.L. Ford, and S.M. Nottingham. 1994. Shelf-life of minimally processed honeydew, kiwifruit, papaya, pineapple and cantaloupe. J. Food Sci. 59:1202-1215.

O'Connor-Shaw, R.E., R. Roberts, A.L. Ford, and S.M. Nottingham. 1996. Changes in sensory quality of sterile cantaloupe dice stored in controlled atmospheres. J. Food Sci. 61:847-851.

Ponting, J.D., R. Jackson, and G. Walters. 1971. Refrigerated apple slices: effects of pH, sulfites and calcium on texture. J. Food Sci. 36:449-450.

Ponting, J.D., R. Jackson, and G. Watters. 1972. Refrigerated apple slices: preservative effects of ascorbic acid, calcium and sulfites. J. Food Sci. 37:434-435.

Poovaiah, B.W. 1986. Role of calcium in prolonging the storage-life of fruits and vegetables. Food Technol. 40:86-89.

Portela, S.I., and M.I. Cantwell. 1998. Quality changes of minimally processed honeydew melons stored in air or controlled atmosphere. Postharv. Biol. Technol. 14:351-357.

Pratt, H.K. 1971. Melons. *In* A.C. Hulme, ed., The Biochemistry of Fruits and Their Products, pp. 207-232. Academy Press, New York, NY.

Qi, L., A.E. Watada, and J.R. Gorny. 1998. Quality changes of fresh-cut fruits in CA storage. Fresh-Cut Fruits and Vegetables and MAP. *In* M.E. Saltveit, ed., 7th International Controlled Atmosphere Research Conference, University of California, Davis, July 13-18, 1997, vol. 4, pp. 98-117. University of California, Davis, CA.

Qi, L., T. Wu, and A.E. Watada. 1999. Quality changes of fresh-cut honeydew melons during controlled atmosphere storage. J. Food Qual. 22:513-521.

Rattanapanone, N., and A.E. Watada. 2000. Respiration rate and respiratory quotient of fresh-cut mango (*Mangifera indica* L.) in low oxygen atmosphere, pp. 471-478. *In* S. Subhadrabandhu, and A. Pichakum, Proceedings of the 6th International Symposium on Mango, International Society for Horticultural Science, Working Group on Mango, April 6-9, Leuven, Belgium

Richard, F.C., P.M. Goupy, J.J. Nicolas, et al. 1991. Cysteine as an inhibitor or enzymatic browning. 1. Isolation and characterization of addition compounds formed during oxidation of phenolics by apple polyphenol oxidase. J. Agric. Food Chem. 39:841-847.

Richard-Forget, F.C., P.M. Goupy, and J.J. Nicholas. 1992. Cysteine as an inhibitor of enzymatic browning. 2. Kinetic studies. J. Agric. Food Chem. 40:2108-2114.

Robert, C., F. Richard-Forget, C. Rouch, et al. 1996. A kinetic study of the inhibition of palmito polyphenol oxidase by *L*-cysteine. Int. J. Biochem. Cell Biol. 28:457-463.

Rocha, A.M.C.N., C.M. Brochado, R. Kirby, and A.M.M.B. Morais. 1995. Shelf-life of chilled cut orange determined by sensory quality. Food Control. 6:317-322.

Romig, W.R. 1995. Selection of cultivars for lightly processed fruits and vegetables. HortScience 30:38-40.

Rosen, J.C., and A.A. Kader. 1989. Postharvest physiology and quality maintenance of sliced pear and strawberry fruits. J. Food Sci. 54:656-659.

Saltveit, M.E. 1997. Physical and physiological changes in minimally processed fruits and vegetables. *In* F.A. Tomas-Barberan and R.J. Robins, eds., Phytochemistry of Fruits and Vegetables, pp. 205-220. Claredon Press, Oxford.

Saltveit, M.E., and L.L. Morris. 1990. Overview on chilling injury of horticultural crops. *In* Wang, C.Y., ed., Chilling Injury of Horticultural Crops, pp. 4-15. CRC Press, Boca Raton, FL.

Sapers, G.M. 1993. Browning of foods: control by sulfites, antioxidants, and other means. Scientific status summary. Food Technol. 47:75-84.

Sapers, G.M., P.H. Cooke, A.E. Heidel, et al. 1997. Structural changes related to texture of pre-peeled potatoes. J. Food Sci. 62:797-803.

Sapers, G.M., K.B. Hicks, J.G. Phillips, et al. 1989. Control of enzymatic browning in apple with ascorbic acid derivatives, polyphenol oxidase inhibitors, and complexing agents. J. Food Sci. 54:997-1002,1012.

Sapers, G.M., and R.L. Miller. 1998. Browning inhibition in fresh-cut pears. J. Food Sci. 63:342-346.

Sapers, G.M., and G.F. Simmons. 1998. Hydrogen peroxide disinfection of minimally processed fruits and vegetables. Food Technol. 52:48-52.

Sapers, G.M., and M.A. Ziolkowski. 1987. Comparison of erythorbic and ascorbic acids as inhibitors of enzymatic browning in apple. J. Food Sci. 52:1732-1733.

Schlimme, D.V., and M.L. Rooney. 1994. Packaging of minimally processed fruits and vegetables. *In* R.C. Wiley, ed., Minimally Processed Refrigerated Fruits and Vegetables, pp. 135-182. Chapman and Hall, New York, NY.

Shin, J.K., and Y.R. Pyun. 1997. Inactivation of *Lactobacillus plantarum* by pulsed-microwave irradiation. J. Food Sci. 62:163-166.

Silva, J.L., T. Chanrittisen, C.W. Shannon, and G.R. Ammerman. 1987. Shelf-life of refrigerated cantaloupe and watermelon pieces. Res. Rep. Miss. Agric. Forestry Expt. Stat. 12:1-4.

Solomos, T. 1994. Some biological and physical principles underlying modified atmosphere packaging. *In* R.C. Wiley, ed., Minimally Processed Refrigerated Fruits and Vegetables, pp. 183-225. Chapman and Hall, New York, NY.

Song, J., R. Leepipattanawit, W. Deng, and R.M. Beaudry. 1996. Hexanal vapor is a natural, metabolizable fungicide: inhibition of fungal activity and enhancement of aroma biosynthesis in apple slices. J. Amer. Soc. Hort. Sci. 121:937-942.

Spanier, A.M., M. Flores, C. James, et al. 1998. Fresh-cut pineapple (*Ananas* sp.) flavor. Effect of storage. *In* E.T. Contis et al., eds., Developments in Food Science. Food Flavors: Formation, Analysis, and Packaging Influences, pp. 331-343. Elsevier, Maryland Heights | MO.

Tong, C.B.S., and K.B. Hicks. 1991. Sulfated polysaccharides inhibit browning of apple juice and diced apples. J. Agric. Food Chem. 39:1719-1722.

Vámos-Vigyázó, L. 1981. Polyphenol oxidase and peroxidase in fruits and vegetables. CRC Crit. Rev. Food Sci. Nutr. 15:49-127.

Varoquaux, P., I. Lecendre, F. Varoquaux, and M. Souty. 1990. Changes in firmness of kiwifruit after slicing. Sci. Aliment. 10:127-139.

Walker, J.R.L. and C.E.S. Reddish. 1964. Note on the use of cysteine to prevent browning in apple products. J. Sci. Food Agric. 15:902-904.

Watada, A.E., K. Abe, and N. Yamauchi. 1990. Physiological activities of partially processed fruits and vegetables. Food Technol. 44:116, 118, 120-122.

Watada, A.E., N.P. Ko, and D.A. Minott. 1996. Factors affecting quality of fresh-cut horticultural products. Postharv. Biol. Technol. 9:115-125.

Watada, A.E., and L. Qi. 1999. Quality of fresh-cut produce. Postharv. Biol. Technol. 15:201-205.

Weller, A., C.A. Sims, R.F. Matthews, et al. 1997. Browning susceptibility and changes in composition during storage of carambola slices. J. Food Sci. 62:256.-260.

Wiley, R.C. 1994. Minimally Processed Refrigerated Fruits and Vegetables. Chapman and Hall, London, U.K.

Wong, D.W.S., S.J. Tillin, J.S. Hudson, and A.E. Pavlath. 1994. Gas exchange in cut apples with bilayer coatings. J. Agric. Food Chem. 42:2278-2285.

Wright, K.P., and A.A. Kader. 1997a. Effect of controlled-atmosphere storage on the quality and carotenoid content of sliced persimmons and peaches. Postharv. Biol. Technol. 10:89-97.

Wright, K.P., and A.A. Kader. 1997b. Effect of slicing and controlled-atmosphere storage on the ascorbate content and quality of strawberries and persimmons. Postharv. Biol. Technol. 10:39-48.

Wyllie, S.G., D.N. Leach, and Y. Wang. 1996. Development of flavor attributes in the fruit of *C. melo* during ripening and storage. *In* G.R. Takeoka, R. Teranishi, P.J. Williams, and A. Kobayashi, eds., Biotechnology for Improved Foods and Flavors, pp. 228-239. American Chemical Society, Washington, DC.

Yahia, E.M. 1991. Production of some odor-active volatiles by ‘McIntosh’ apples following low-ethylene controlled-atmosphere storage. HortScience 26:1183-1185.

Yahia, E.M.. 1994. Apple flavor. Hort. Rev. 16:197-234.

Yahia, E.M., T.E. Acree, F.W. Liu. 1990. The evolution of some odor-active volatiles during the maturation and ripening of apples on the tree. Lebensmitt. Wissensch. Technol. 23:488-493.

Fresh-Cut Vegetables

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Introduction

Wounds inflicted during the preparation of fresh-cut vegetables promote many physical and physiological changes that hasten loss of product quality (Brecht 1995, Saltveit 1997). Foremost among these are the removal of the protective epidermal layer and exposure of internal cells. These changes not only facilitate water loss but also provide easy entry for microbial pathogens and chemical contaminants. Packaging or application of edible films can lessen water loss by maintaining a high RH near the cut surface and providing a physical barrier that protects the product from contamination.

Water loss and collapse of injured cells at the cut surface can alter the appearance of the fresh-cut product. As the cut surface loses water, adhering cellular debris may impart a white blush to the surface that masks varietal color; for example, white blush on “baby” carrots decreases the intensity of the underlying orange color. Differential dehydration of exposed cortex and vascular tissue may produce an uneven surface, as with formation of vascular strands projecting a few millimeters from the cut end of celery petioles. Consumers associate both of these surface changes with the loss of freshness.

Physiological processes devoted to wound repair can be beneficial (such as curing potatoes) or detrimental to quality retention. Physiological changes following wounding include increased respiration and ethylene production, promotion of the ripening of climacteric fruit vegetables (such as melons and tomatoes), and enhanced synthesis and accumulation of phenolic compounds that contribute to tissue browning. These changes are managed by the use of low temperatures, creation of reduced O_2 or elevated CO_2 atmospheres, and application of inhibitors of specific chemical reactions or metabolic pathways.

Wound-enhanced respiration and ethylene production can deplete carbohydrate storage reserves and stimulate tissue softening associated with fruit ripening (melons, squash, tomatoes) or chlorophyll loss associated with leaf or tissue senescence (spinach, broccoli). In many tissues, wounding produces a signal that induces the increased synthesis and accumulation of phenolic compounds. Tissue browning can result from the oxidation or polymerization of accumulated phenolic compounds. Lignification and toughening of tissue are others way in which the metabolism of phenolic compounds can reduce quality.

Sanitation, implementation of Good Agricultural Programs (GAPs) in the field, use of Good Manufacturing Programs (GMPs) and Hazard Analysis and Critical Control Point (HACCP) monitoring plans during all steps of processing, and proper temperature control, are all needed to ensure that an initial low microbial load on fresh-cut vegetables is maintained during marketing. The current industry standard washing and disinfection procedures used on whole produce are rather ineffective with fresh-cut vegetables once they have been contaminated with microbial pathogens. Overall microbial load relative to spoilage organisms usually remain below levels of concern as long as visual quality remains acceptable. However, postharvest treatments that maintain visual quality under abusive temperatures may allow microbial loads to reach dangerous levels before quality is reduced below acceptable levels.

Many vegetables are sensitive to nonfreezing temperatures below about 10 °C (50 °F) and suffer physiological damage if held at these chilling temperatures beyond a specific period. These vegetables include jicama, pepper, sweet potato, tomato, and zucchini. In contrast to the whole commodity, which should not be chilled, the increased susceptibility of fresh-cut products to spoilage often means that the product has a longer market life at 0 °C (32 °F) than at higher, nonchilling temperatures. Development of chilling injury symptoms is less pronounced in riper tissue and takes some time to develop. Since most fresh-cut vegetables are consumed soon after purchase and fruit vegetables are fully ripe when processed, chilling injury symptoms usually do not develop to a significant extent because the rate of deterioration due to chilling is slower than the rate of spoilage that is inhibited by low temperatures. The two most important fresh-cut commodities, lettuce and carrots, are not chilling sensitive and should be stored as close to 0 °C (32 °F) as possible without freezing: 1 to 3 °C (34 to 38 °F) in a commercial setting.

The imposed physical damage done to the product during preparation and its increased vulnerability to deleterious internal and external changes requires that fresh-cut vegetables be handled with a greater degree of care than the whole product. Storage requirements for intact produce may be inadequate to handle increased physiological activity and susceptibility to water loss encountered with fresh-cut vegetables.

The highest quality that is available (usually USDA No. 1) and that is compatible with an economic return should be used for processing. Although poor quality pieces of fresh-cut product can be discarded to upgrade quality (an example is culling discolored pieces of cut lettuce leaves or broccoli florets), the associated cost usually adversely affects quality and yields and greatly outweighs the differential cost of using higher quality raw material.

The remainder of this chapter provides information on the commercial packaging and storage of a number of fresh-cut vegetables.

Beets, Red (Grated, Cubed, Whole Peeled)

Fresh-cut beets should be stored at 1 to 3 °C (34 to 38 °F) before and after processing. Respiration is slightly reduced during storage in 5% O_2 and 5% CO_2 at 5 °C (41 °F).

Respiration Rates

Temperature	Whole peeled	Cubed 1 cm cubes	Grated 2 mm
		mg CO_2 kg^{-1} h^{-1}	
2 °C	4	10	12
5 °C	6	12	16
10 °C	19	27	38
23 °C	54	117	162-207

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Broccoli (Florets)

Fresh-cut broccoli florets should be tight, firm, turgid, and dark green without blooming buds. There should be no sulfur odor or discoloration along the stems and cut ends. The core temperature of raw material should be <1.5 °C (35 °F). Raw and processed material should be stored at 1 to 3 °C (34 to 38 °F) to ensure quality and reduce potential for freezing of product during handling, distribution, and storage. Yellowing is a common problem caused by either chlorophyll loss or blooming of the buds. The cut surface and damaged floret stems can turn black during storage. Development of off odors can be a major concern when MAP is used. Temperature abuse promotes soft rot and mold growth.

Whole broccoli heads are hand-cut into florets that are between 2.5 cm (1 in) and 5 cm (2 in) long. They are washed in water containing up to 200 µL L^{-1} total chlorine to wash residual material from the florets as well as reduce aerobic plate counts. Repeated daily washing did not maintain lower microbial counts for >2 days.

The benefit of CA (5% O_2 and 4% CO_2) may be marginal for storage up to 14 days at 0 to 5 °C (32 to 41 °F) compared to air. Lowering O_2 to 0.25% or increasing CO_2 to 10% at 0 to 5 °C (32 to 41 °F) reduces respiration by about 50%. Use of appropriate polymeric film in MAP maintained green color at 0 to 5 °C (32 to 41 °F) for more than 21 days (Cabezas and Richardson 1997). Severe off odors and discoloration at cut ends can develop during MAP storage at 10% CO_2 and 2.5% or less O_2 (Makhlouf et al. 1989). Perforated and microperforated polymeric packages reduce off odor (Izumi et al. 1996a). Reducing ethylene below 1 to 10 µL L^{-1} did not significantly reduce color loss at 1 °C (34 °F), but did have an effect at higher temperatures.

No foodborne disease outbreak has been reported associated with fresh-cut broccoli, although the aerobe population is usually high (>100,000 cfu g^{-1} fresh weight). Florets stored in 5% O_2 and 8% CO_2 at 8 °C (46 °F) have lower aerobic plate counts, total coliform plate counts, and yeast/mold plate counts compared to storage in air.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	26
5 °C	44
10 °C	78

Data from Watada et al. (1996) and Izumi et al. (1996a).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Cabbage, Green and Red (Shredded, Diced)

Fresh-cut green cabbage should be light green with a moderately pungent flavor and no sulfur aroma. Raw and processed material should have typical cabbage flavor with no off notes and should be stored at 1 to 3 °C (34 to 38 °F) to ensure quality and reduce potential for freezing of product during handling, distribution, and storage. Fresh-cut cabbage includes diced and shredded product with cut size varying from 0.63 cm (¼ in) to 0.95 cm (3/8 in). Heads are trimmed to remove wrapper leaves and cored, cut, and washed using chlorinated water (100 µL L^{-1} of total chlorine) for about 1 min before being spun-dried and packaged. For coleslaw, cut cabbage (shredded or diced) can be preblended with carrots or plain-packaged.

A CA of 5 to 7.5% O_2 and 15% CO_2 is recommended (Hiroaki et al. 1993). Lowering O_2 below 5% caused rapid proliferation of fermentative bacteria and off odors within 6 days at 5°C (41 °F). The fermentation induction point of coleslaw mixes in low density polyethylene bags varied with the cabbage to carrot ratio and with temperature. At 5 °C (41 °F), a 70:30 mix went anaerobic at 1.8% O_2, while 3% O_2 was the limit for aerobic respiration at 10°C (50 °F).

Off odors forming in cut cabbage bags with low OTR film (<3,000 mL/m^2 atm^{-1} d^{-1}) and discoloration of cabbage leaf packed in high OTR film (>12,000 mL/m^2 atm^{-1} d^{-1}) bags are the major quality deterioration during storage (Pirovani et al. 1997). At 11 °C (52 °F), *Listeria* spp. grew faster in fresh-cut cabbage packages that had an atmosphere of <1.8% O_2 and >20% CO_2 than in air (Omary et al. 1993).

Respiration Rates

Temperature	3/8 in (9.6 mm)	1/4 in (6.4 mm)
	mg CO_2 kg^{-1} h^{-1}	
2 °C	16-18	18-24
5 °C	22-33	25-39
10 °C	42-48	51-57
23 °C	117-153	153-171

Data from Watada et al. (1996).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production,

multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Cabbage, Chinese (Sliced, Sticks, Shredded)

Fresh-cut Chinese cabbage should be handled like green cabbage and stored at 1 to 3 °C (34 to 38 °F). The recommended CA is 5% O_2 and 5% CO_2; benefits are moderate compared to air storage at 0 °C (32 °F).

Carrots (Diced, Shredded, Sticks, Peeled, Grated, Sliced, Cubed)

Fresh-cut carrots are orange without a white brush or slimy surface. Raw and processed product should be kept at 1 to 3 °C (34 to 38 °F) to ensure quality and reduce potential for freezing of product during handling, distribution, and storage. Most quality loss in cut carrots results from formation of either white blush or off odor and slimy surface generated by bacteria (Carlin et al. 1989).

Fresh-cut carrots include whole peeled (baby), sticks, sliced, shredded, grated, and diced. Whole carrots are washed with water to remove undesirable field material. The stems and tips are excised and the trimmed carrots are peeled, cut, and washed in 100 µL L^{-1} NaOCl for less than 1 min. Washed carrot cuts are centrifuged to remove excess water and packaged in plastic bags.

Dehydration of surface debris on cut and peeled carrots imparts a whitish translucent appearance to the surface (Tatsumi et al. 1991, Cisneros-Zevallo et al. 1995), which is undesirable because consumers associate it with the loss of freshness (Bolin and Huxsoll 1991). Applying an edible coating (Howard and Dewi 1995, 1996, Li and Barth 1998), such as sodium caseinate-stearic acid (Avena-Bustillos et al. 1994), or heating and raising the pH (Bolin and Huxsoll 1991) may be helpful in reducing white blush. Treatments that modify the water-retaining capacity of the cut surface also prevent white blush development (Cisneros-Zevallos et al. 1997).

Fresh-cut carrots derive slight benefit from 2 to 5% O_2 and 15 to 20% CO_2 atmospheres (Izumi et al. 1996b). Lower O_2 or increased CO_2 levels promoted slimy appearance, increased lactic acid bacteria growth, and accelerated microbial decay and excessive alcohol production. Grated carrots retain good quality for up to 10 days at 2 to 10 °C (36 to 52 °F) in MAP with high O_2 permeability films of 10,000 to 20,000 mL m^2 atm^{-1} d^{-1} at 25°C (Carlin et al. 1990). Low permeability films of 950 mL m^2 atm^{-1} day^{-1} resulted in low O_2 damage.

The quality and headspace composition of sliced carrots (0.5 cm) treated with 1% ascorbic acid before packing in MAP was unaffected during 14 days at 4 °C (39 °F) (Galetti et al. 1997). Growth of aerobic mesophilic bacteria on sticks was suppressed by a 0.5% O_2 and 10% CO_2 atmosphere at both 0 and 5 °C (32 and 41 °F); but total microbial count on slices and shreds was unaffected.

The mean microbial population after 9 days storage was much lower (1,300 cfu g^{-1}) for irradiated shredded carrots (0.5 kGy) than for non-irradiated, chlorinated controls (87,000 cfu g^{-1}) (Hagenmaier and Baker 1998). Ethanol and O_2 content of the headspace were not affected.

Respiration Rates

Temperatures	Whole peeled	Sliced	Sticks	Shredded
	mg CO_2 kg^{-1} h^{-1}			
0 °C	—	5	11	15
5 °C	9-12	13	19	24
10 °C	17-21	25	42	46
23 °C	54	72-81	—	108-126

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Celery (Diced, Sliced, Sticks)

Fresh-cut celery petioles have no leaves or brown spots and should not have cracked, flared, or white-blush ends. Raw material should arrive at <7 °C (38 °F) and be stored at 2 to 4 °C (36 to 40 °F) before processing and at 1 to 3 °C (34 to 38 °F) after processing to ensure quality and reduce potential for freezing of product during handling, distribution, and storage. Atmospheres of 5% O_2 and 4% CO_2 were slightly beneficial. Water loss is the main factor affecting eating quality (Gariepy et al. 1986). Small amounts of water loss (2.5 to 5%) can result in litheness, flaccidity, shriveling, and wrinkling. Moisture loss can be reduced 75% by the application of an edible coating (Avena-Bustillos et al. 1997). Differential dehydration of exposed cortex and vascular tissue caused the stronger vascular strands to project a few millimeters from the cut end of celery petioles. Development of pithiness is associated with water stress during growth and wounding during processing (Saltveit and Mangrich 1996). Heat-shock treatments prevented tissue browning without adversely affecting other quality parameters (Loaiza-Velarde et al. 2003).

Sliced celery can only be maintained for 6 days at 4°C (40 °F) without notable quality change (Johnson and von Elbe 1974). Major pathogens are *Pseudomonas fluorescens* and *P. marginalis*, which cause water soaking, soft rot, and discoloration (Robbs et al. 1996). Low-dose irradiation (1.0 kGy) delayed microbial spoilage in fresh, diced celery stored at 4 °C (40 °F) for 3 weeks without affecting sensory attributes. In contrast, blanching and chlorine rinsing had little effect on microbial count. Sensory results indicated the 1 kGy sample was preferred over all other treatments in terms of taste, texture and color.

Garlic (Peeled)

Quality problems with peeled garlic include sprouting and discoloration of areas damaged during peeling. Garlic cloves can be peeled manually or mechanically with compressed air. Acid treatments and edible coatings can improve preservation. Excellent visual quality was maintained for 21, 16, 12, or 8 days of storage in air at 0, 5, 10, or 15 °C (32, 41, 50, or 59 °F), respectively. Decay was not observed at 0 and 5 °C (32 or 41 °F) and was slight at 10 and 15 °C (50 and 59 °F). At 5 and 10 °C (41 and 50 °F), a 1% O_2 and 10% CO_2 CA gave the best quality (lack of decay and least discoloration). Respiration rates in manually peeled garlic were 50% higher than unpeeled cloves. Mechanically peeled garlic has rates of respiration 5 to 10% higher at 5 °C (41 °F) and 20 to 30% higher at 10 °C (50 °F) than hand-peeled cloves.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	35
10 °C	57

Data from Burlo-Carbonell et al. (2000).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Jicama (Sticks, Cubes)

Fresh-cut jicama should be white with a crisp texture. Raw material should be received at <7 °C (44 °F), and processed product should be stored at 1 to 3 °C (34 to 38 °F) to ensure quality and reduce potential for freezing of the product during handling, distribution, and storage. Tuber size does not affect visual quality or color. Browning can be a significant cause of quality loss after 9 days at 5 °C (41 °F). Increased storage temperature results in accelerated discoloration. The best treatment to control browning is a 2-min dip in water at 50 °C (122 °F) and then storage at 2 °C (36 °F).

Quality loss during storage at 0 or 5 °C in air is also attributable to yeast and bacterial growth. A 10% CO_2 atmosphere retards brown discoloration, maintains crisp texture, and delays microbial growth. However, acetaldehyde and ethanol concentrations are higher after 8 days at 5 °C (41 °F) in 10% CO_2 atmospheres and 3% O_2 or air. Atmospheres of 20% CO_2 can damage jicama if stored longer than 8 days.

Kale (Shredded)

Fresh-cut kale should be dark green and crisp without yellow or discolored leaf pieces. Raw material should be received at <7 °C (45 °F) and stored at 1 to 3 °C (34 to 38 °F) after processing to ensure quality and reduce potential for freezing of product during handling, distribution, and storage. Washing shredded kale with 0.1% NaOCl results in a 10-fold reduction in aerobic plate count compared to unwashed products. Fresh-cut kale in perforated (5.96 ± 0.35 mm^2 diameter holes with 6.68 cm^2 total surface area per sack) polyethylene bags (38 µm thick) become unacceptable due to yellowing and microbial spoilage after 3 days at 4 °C (39 °F). Desiccation, yellowing, and spoilage were unacceptable after 1 or 2 days at 20 or 10 °C (68 or 50 °F), respectively (Beaulieu et al. 1997).

Leek (Sliced)

Raw material should be received at, and processed leeks stored at, 1 to 3 °C (34 to 38 °F) to ensure quality and reduce potential for freezing of product during handling, distribution, and storage. A CA of 5% O_2 and 5% CO_2 is moderately beneficial, and slightly reduces respiration at 5 °C (41 °F). A non-perforated film led to unacceptable quality after a few days at 4 °C (39 °F) with high CO_2, ethanol, and acetaldehyde concentrations (Keteleer et al. 1993).

Respiration Rates

Temperature	Whole leaf	Rings 2 mm thick
	—— mg CO_2 kg^{-1} h^{-1} ——	
2 °C	24	32
5 °C	29	49
10 °C	38	57-67
23°C	117	252-288

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Lettuce: Butterhead, Crisphead, Greenleaf, Iceberg, and Romaine (Chopped, Shredded, Whole Leaf)

The quality of the fresh-cut product is very dependent on the initial raw product quality. The raw product should be the best quality available and should be <2 °C (36 °F) when received as whole or cored heads. It should be stored at 1 to 3 °C (34 to 38 °F) before and after processing to ensure quality and reduce potential for freezing of product during handling, distribution, and storage.

Browning (enzymatic) of the cut edges is the main defect of fresh-cut lettuce pieces during storage. The best way to prevent the discoloration is to reduce O_2 to <3%. Antioxidant treatment and heat-shock can inhibit discoloration, but these treatments may result in loss of visual quality. Unless stressed in the field, lettuce has low levels of phenolic compounds and tissue browning occurs after the induction of synthesis and accumulation of phenolics by wounding. A 90-sec heat-shock at 45 °C (104 °F) prevented wound-induced browning of iceberg (Loaiza-Velarde et al. 1997, Loaiza-Velarde and Saltveit 2001) and romaine (Saltveit 2000) lettuce.

Butterhead Lettuce

Browning of the cut edges of butterhead lettuce is reduced by modified atmospheres rapidly created by flushing with N_2 to get 1 to 3% residual O_2 with CO_2 levels of 5 to 10%. Tissue in atmospheres of <1% O_2 and >10% CO_2 develop CO_2 injury or brown stain (Stewart and Ceponis 1968). The incidence of brown stain increased from 16 to 38 to 81% as CO_2 increased from 2.5 to 5 to 10%, respectively, and was enhanced when combined with low O_2 atmospheres (Steward and Uota 1971).

The physiological behavior of butterhead lettuce is modified by cultural practices such as irrigation, climate, and fertilization (Poulsen et al. 1994, 1995, Sorensen et al. 1994). Susceptibility to brown stain varies among cultivars and position of leaves within the head (Krahn 1977). Shelf-life of butterhead lettuce was negatively correlated with respiration rate and susceptibility to CO_2. High O_2 and low CO_2 enhanced enzymatic browning. Off odors and flavors developed (ethanol, acetaldehyde, and ethyl acetate aroma), crispness was lost, and the tissue became translucent when fresh-cut lettuce was stored in <0.5% O_2 or >15% CO_2.

Necrosis of butterhead lettuce may be associated with microbial growth, such as pectolytic *Pseudomonas* (Nguyen-The and Prunier 1989) and other epiphytic bacteria.

Respiration Rates (Chopped)

Temperature	mg CO_2 kg^{-1} h^{-1}
2 °C	12-14
4.5 °C	20-25
10 °C	38-48

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal tonne^{-1} day^{-1}.

Greenleaf Lettuce

A 0.5 to 3% O_2 and 5 to 10% CO_2 CA reduced cut-edge browning of greenleaf lettuce (Lopez-Galvez et al. 1996).

Iceberg Lettuce

The raw product should have <6% pink rib discoloration, while russet spotting, hooked core, and tipburn should be <1%. Moisture content of lettuce is extremely important for maintaining texture and reducing microbial growth. Excess moisture can be removed in a forced-air tunnel or by spinning. Lettuce that was air dried for 10 to 15 min or spin dried for 30 min had less browning during storage than control samples. Consumer sensory panelists indicated that after 4 days of storage, only 15% would purchase control lettuce while 40% would purchase lettuce spin- or air-dried for 15 min. Slicing methods can influence ascorbic acid retention in with the order: manual tearing > manual slicing > machine slicing.

In clamshell trays, market-life of fresh-cut lettuce was <24 h at 23 °C (73 °F), >24 h at 10 °C (50 °F), and >48 h at 2 °C (36 °F) (Zhuang and Barth 1999). Fresh-cut lettuce packages commonly have <1% O_2 to effectively slow browning and >10% CO_2 to inhibit microbial growth (Gorny 1997). An atmosphere of 0.5 to 3% O_2 and 10 to 15% CO_2 reduces cut edge browning, retains visual quality, and reduces psychrophilic bacterial counts. Flushing with 100% N_2 increases retention over MAP. On the basis of ethanol appearance in the headspace, the fermentation induction point was 0.3 to 0.4% O_2 at 5 °C (41 °F) and 0.6 to 0.8% at 10 °C (50 °F). Acetaldehyde and ethyl acetate were detected when O_2 was <0.4% at 5 to 20 °C (41 to 68 °F). The extent of browning increased with O_2 level but not with CO_2 level (Smyth-Anne et al. 1998). Fresh-cut iceberg should be stored at 1 to 3 °C (34 to 38 °F) before and after processing to ensure quality and reduce potential for freezing during handling, distribution, and storage.

Shelf-life of fresh-cut lettuce at 5 °C (41 °F) was 6 days in air, 8 days in 3% O_2, and 12 days in 0.2%

O_2 (Peiser et al. 1997). Increasing CO_2 enhances the beneficial effect of low O_2. A combination of 0.2% O_2 with 7 to 15% CO_2 gave a 16-day shelf-life. A 14-day shelf-life was obtained when shredded iceberg lettuce was stored in 1 to 3% O_2 and 5 to 6% CO_2 at 5 °C (41 °F). However, CO_2 >15% causes brown stain. Reduced O_2 or elevated CO_2 may induce formation of fermentation and off odor (fermentative volatiles, ethanol, and acetaldehyde) in the packages (McDonald et al. 1990, Mateos et al. 1993, Peiser et al. 1997).

Although gram-negative bacteria are numerically dominant, a large yeast population may also be found. Species of *Pseudomonas*, *Erwinia*, and *Serratia* were the most frequently isolated bacteria. *Cryptococcus*, *Pichia*, *Torulaspora*, and *Trichosporon* spp. were the most common yeasts. Beuchat and Brackett (1990) studied the effects of shredding, chlorine treatment, and MAP on survival and growth of *Listeria monocytogenes*, mesophilic aerobes, psychrotrophs, yeasts, and molds. They found that no significant changes in populations of *L. monocytogenes* were detected during the first 8 days of incubation at 41 °F (5 °C); there was a significant increase between 8 and 15 days. Significant increases occurred within 3 days when lettuce was stored at 50 °F (10 °C). Chlorine treatment, MAP of 3% O_2, and shredding did not influence growth of *L. monocytogenes*.

Respiration Rates (Shredded)

Temperature	mg CO_2 kg^{-1} h^{-1}
2.5 °C	12.0-15.0
5 °C	15.6-27.3
7.5 °C	23.1-32.7
10 °C	30.4-39.9

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Lollo Rosso (Red) Lettuce

The beneficial storage atmosphere is 0.5 to 3% O_2 and 5 to 10% CO_2. MAP storage (2 to 3% O_2 and 12 to 14% CO_2) was useful in preventing brown discoloration. However, MAP storage was not beneficial for preserving quality of red tissues and, in fact, their overall visual quality, texture, aroma, and macroscopic breakdown under MAP conditions were worse than those of air-stored tissues (Gil-Maria et al. 1998). Castaner et al. (1997) found that after 14 days of storage at 5 °C (41 °F), the overall visual quality of fresh-cut white and green tissue of Lollo Rosso (red) lettuce is better in MAP than in air. Green tissue had the lowest overall quality after air storage. In addition, there were no significant overall quality differences for red tissue stored under either condition. Texture and aroma were excellent for green tissue held in MAP, while it was unacceptable in air. Both atmospheres maintained texture of red and white tissues. Aroma was excellent for white tissue in both air and MAP. In contrast, aroma was only acceptable for red tissue stored in air.

Romaine Lettuce

Fresh-cut romaine should be stored at 1 to 3 °C (34 to 38 °F) before and after processing to ensure quality and reduce potential for freezing of product during handling, distribution, and storage. MAP exerted a beneficial effect on sensory quality by preventing pink discoloration. Compared to air, 3% O_2 and 6, 10, or 14% CO_2 MAP delayed development of tissue discoloration and increased shelf-life by about 50%. Of the three CO_2 levels, 10% was slightly more effective than 6 and 14% (Hamza et al. 1996, Lopez-Galvez et al. 1996, Segall and Scanlon 1996).

The aerobic plate counts of fresh-cut Romaine lettuce in MAP were decreased by 0.15 and 0.35 kGy gamma irradiation (Prakash et al. 2000). The 0.35 kGy treatment decreased aerobic plate counts by 1.5 logs and yeast and mold counts by 1 log. A combination of MAP and 0.35 kGy resulted in a 2-log reduction in microbial counts. These differences were maintained through 22 days of storage. Irradiation at 0.15 kGy caused smaller reductions in microbial counts. A 10% loss in firmness was observed at 0.35 kGy, while other sensory attributes such as color, generation of off flavor, and appearance of visual defects were not affected. The control sample reached microbial counts of 10^7 in 14 days compared to the MAP samples, which reached the same level in 17 days, and the combination samples (0.35 kGy and MAP), which took 28 days. Color, flavor, and odor were unaffected by irradiation, although an off odor was obvious in MAP samples after 21 days (17% CO_2 and <1% O_2). Low-dose irradiation increased shelf-life of cut romaine lettuce by 2 to 5 days (Prakash et al. 2000)

Mushrooms (Sliced)

Fresh-cut mushroom slices are white with no darkening and wrinkling. Mushroom slices should be stored at 1 to 3 °C (34 to 38 °F). Wrinkling and brown surface patches are caused by excessive moisture loss (Roy et al. 1996). A CA of 10% CO_2 and 3% O_2 maintains quality, while 5% O_2 and 5% CO_2 at 5 °C slightly reduces respiration. More than 20% CO_2 accelerates tissue darkening, while <3% O_2 may result in potential *botulinum* toxin production. Inoculation studies have demonstrated that *C. botulinum* type A will sporulate and produce endotoxin in 0.9 to 2% O_2 after 6 days at 75 to 79 °F (24 to 26 °C) (Sugiyama and Yang 1975, Sugiyama and Rutledge 1978). It is not recommended to use low O_2 MAP due to the inherent food safety risk.

Respiration Rates (Sliced)

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	20-60
5 °C	39-88
10 °C	86-124

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Onions (Diced, Slivered, Rings, Chunks)

Fresh-cut onions should have no discoloration, skin and core. Bulbs should be dry, free of decay, firm, and 7.5 to 10 cm (3 to 4 in) in diameter. The core of whole onions should be 1.5 °C (35 °F) at receiving and 1 to 3 °C (34 to 38 °F) before and after processing to ensure quality and reduce potential for freezing of product during handling, distribution, and storage. The seed stems and new internal growth should be less than 10%; double centers and translucent scale should be less than 5%.

Whole onions are peeled and trimmed by machine or hand. Washing with chlorinated water can be done before or after processing. Bulbs for onion rings are washed with cold water at 0 °C (32 °F) before processing. However, diced and slivered onions are washed using chlorinated water after processing.

Browning, yellowing, and development of translucence are major factors affecting the visual quality of diced onion (Blanchard et al. 1996). Cutting causes important biochemical changes in tissues, including development of sulfur aromatic volatiles. These compounds are produced enzymatically by hydrolysis of alliins (odorless derivatives of amino acids) by alliinase (Schwimmer and Weston 1961, MacLoed 1970). Among the volatiles present in the aromatic profile of onion are oxides of disulfide, thiosulfinates, and propene disulfide, known bacteriostats (Davidson et al. 1983). Their action on microorganisms may be due to the inhibition of respiratory enzymes containing thiol groups (Augusti 1990). Thiopropanal-S-oxide, a lacrimogenous factor, has antifungal properties (Sharmon et la. 1979) and may be involved in development of bitterness and browning of onion puree (Howard et al. 1994).

CA of 2 to 5% O_2 and 10 to 15% CO_2 decreases respiration and microbial proliferation and retains sucrose and pungency of cut onions. Lowering the O_2 level can be beneficial for visual quality but has no effect on aroma. Enrichment in CO_2 improves both qualities. Rapid reduction of O_2 in the package reduces discoloration. Browning can be slowed slightly by lowering O_2, and more so by CO_2 enrichment. Langerak (1975) reported that freshly cut onion became brown and unacceptable after cooking when wrapped in perforated film, in comparison with onion wrapped in film that achieved MAP conditions more rapidly. Atmospheres containing 1 to 2% O_2 prevent the loss of pyruvic acid, an indicator of onion flavor intensity, and reduce the rate of respiration of the fresh-cut tissue (Mencarelli et al. 1990).

The inclusion of potassium permanganate (as an ethylene scrubber) and sulfur volatiles in packages of diced onions improves sensory quality. A storage life of 10 days is possible for fresh-cut onions packaged in polymeric bags without a gas flush and stored at 2 °C (36 °F). Addition of absorbents, potassium permanganate and clay, in packages increased shelf-life up to 18 days at 1 °C (34 °F) (Howard et al. 1994, Toivonen 1997).

Yeasts and molds were virtually absent on diced onion. When present, their count did not increase beyond 100 cfu g^{-1} (Garg et al. 1990, Blanchard et al. 1996). Psychrotrophic and mesophilic flora increased throughout storage under all treatments. Their growth in diced onion was slowed under CA as compared to air (Blanchard et al. 1996).

Respiration rates vary significantly depending on how long whole onions were in cold storage prior to processing. CA (5% O_2 and 5% CO_2) at 5 °C (41 °F) reduces respiration rate by 25%.

Respiration Rates

Temperature	Sliced 2 mm thick rings	Diced 1 cm cubes
	mg CO_2 kg^{-1} h^{-1}	
2 °C	14.0	12.0
5 °C	23.4	15.6
10 °C	38.0	22.8
23 °C	126-131	90-99

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Pepper, Bell (Diced, Sliced)

Fresh-cut bell pepper should have no discoloration (darkening) or water soaking. Raw material should be received at <7 °C (45 °F) and stored at 7 to 10 °C (45 to 50 °F), but stored at 1 and 4 °C (34 to 40 °F) after processing to ensure quality and reduce potential for freezing of product during handling, distribution, and storage. Defects that reduce overall visual quality include darkening of the green or red pulp, brown discoloration of the cut surfaces, and decay. Whole peppers should be spray-washed before processing and washed after being cored and cut to reduce microbial population. Alternatively, cut pepper can be washed using a combination of open-flume and close-flume systems.

Although intact peppers are chilling sensitive, it is necessary to store fresh-cut red and green pepper at 0 to 5 °C (32 to 41 °F) to maintain visual quality (El-Bassuoni and Cantwell 1994). Visual quality was maintained and few compositional changes occurred during 15 days of storage at 1 °C (34 °F) (Abe et al. 1991, Zhou et al. 1992). Full ripe or red peppers are less chilling sensitive than mature-green fruits of the same cultivar.

The recommended CA is 3% O_2 and 5 to 10% CO_2. Levels of CO_2 >10% can result in tissue darkening and softening. Shelf-life and sensitivity to CO_2 injury vary significantly among cultivars. CA using air with 10% CO_2 maintains quality at both 5 and 10 °C (41 and 50 °F). Aroma and texture decrease after 6 days in 10% CO_2 but were maintained in air at 0°C. Storage in high CO_2 at 5 °C (41 °F) and air at 0 °C (32 °F) retard decay development. Atmospheres with 5% CO_2 help maintain quality but are not as effective as 10% CO_2. Fresh-cut pepper pieces that were ripening or were already fully red ripe had better shelf-life than pieces from mature-green fruit (Lopez-Galvez et al. 1997). They also found that visual quality was best maintained in air or CA at 0 °C (32 °F), with important quality loss observed by day 9 at 5 °C (41 °F) and by day 3 at 10 °C (50 °F). Decay is caused by both fungi (*Alternaria* and *Botrytis* spp.) and soft-rot-causing bacteria. Diced tissue was more susceptible to decay than slices (Lopez-Galvez et al. 1997).

Respiration Rates

Temperature	Sliced 5 cm	Diced 1 cm cubes
	—— mg CO_2 kg^{-1} h^{-1} ——	
0 °C	2-6	2-9
5 °C	4-7	6-12
10 °C	6-13	11-18

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal tonne^{-1} day^{-1}.

Potato (Sticks, Diced, Sliced, Peeled)

Fresh-cut potatoes should be firm and without brown discoloration. Enzymatic browning is a major problem in the discoloration of peeled or fresh-cut potatoes. Hand-peeling and lye-peeling result in good quality, while abrasion-peeling is undesirable for fresh potatoes. Anti-browning dips such as 0.5% L-cysteine and 2% citrate, in combination with MAP, are needed to prevent browning of whole peeled potatoes. Pretreatment with heated ascorbate and citrate solutions, prior to a browning inhibitor dip containing 4% ascorbate, 1% citrate, and 1% sodium pyrophosphate, has greatly extended storage life over that after the dip alone (Sapers and Miller 1995, Sapers et al. 1997). However, under some conditions, such pretreatment-induced changes in the cooked product that result in surface firming (case hardening) and partial separation of the case-hardened superficial layer from underlying tissue during slicing. Furthermore, case-hardened potatoes form large lumps during mashing (Martin et al. 1999). The recommended storage temperature is 0 °C (32 °F). Shelf-life of minimally processed products can be extended to 3 weeks under CA and refrigeration.

Dipping potato strips in chlorine solutions (100 and 300 µL L^{-1}) result in higher microbial populations during storage, while potatoes treated with antibrowning solutions combined with MAP showed only a slight increase. MAP had no significant effect on microbial populations compared to nonpackaged samples. The predominant organism was *Pseudomonas fluorescens* (Gunes et al. 1997).

The recommended CA is 1 to 3% O_2 and 6 to 9% CO_2. Reducing O_2 level to 10% or 3%, with 10% CO_2, at 2 °C (36 °F) reduces respiration of potato sticks by 50 to 75%. However, 5% O_2 and 5% CO_2 at 5°C (41 °F) increases respiration of sticks during storage.

Active modification of package atmospheres is necessary to prevent browning and achieve extended shelf-life. MAP alone will not prevent browning (Gunes and Lee 1997). Vacuum packaging of fresh-cut potatoes may create anaerobic conditions that allow growth of *Clostridium botulinum*.

Respiration Rates

Temperature	Whole peeled	Halves	Slices 2 mm	Sticks 0.95 cm cross-section
	mg CO_2 kg^{-1} h^{-1}			
2 °C	6.0-8.0	8.0	10.0-12.0	12.2
5 °C	7.8	7.8-9.8	11.7-15.6	-
10 °C	17.1-19.0	21-22.8	38.0	-
23 °C	54-63	81	-	117-126

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Rutabaga (Cubed, Shredded, Peeled)

Fresh-cut rutabaga should have uniform yellow flesh without decay, bruises, or discoloration. Raw material should arrive at <7 °C (45 °F), while raw and fresh-cut product should be stored at 1 to 3 °C (34 to 38 °F) before and after processing to ensure quality and reduce potential for freezing during handling, distribution, and storage. A CA of 5% CO_2 and 5% O_2 is slightly beneficial and reduces respiration at 5 °C (41 °F).

Respiration Rates

Temperature	Quarters peeled	Shredded 2 mm	Diced 1 cm cubes
	mg CO_2 kg^{-1} h^{-1}		
2 °C	8	16	18
5 °C	12	20	25
10 °C	15	42	42-48
23 °C	45	72-81	153-162

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Spinach (Whole Leaves, Cut Leaves)

Fresh-cut spinach should be green without any decay or bruise. Raw material should arrive at 1.5 °C (35 °F). Fresh and processed products should be stored at 1 to 3 °C (34 to 38 °F) before and after processing to ensure quality and reduce potential for freezing of product during handling, distribution, and storage.

Storage in 0.8 to 3% O_2 and 8 to 10% CO_2 is beneficial. Spinach stored in 0.8% O_2 at 20°C (68 °F) had a lower respiration rate, superior appearance, and better taste than spinach leaves stored in air (Izumi et al. 1997). Atmospheres of 0.8% O_2 or 0.8% O_2 and 10% CO_2 reduced the number of aerobic mesophilic and psychrotrophic microorganisms on fresh-cut spinach leaves by 10- to 100-fold, compared to air-stored leaves at 5 °C (41 °F); however, there was no effect at 10 °C (50 °F). These atmospheres had no effect on texture changes during storage at 5 °C (41 °F) for 9 days or at 10 °C (50 °F) for 7 days (Babic and Watada 1996).

An atmosphere of 4% O_2 and 9% CO_2 reduced the loss of ascorbic acid by 50% compared to air (Burgheimer et al. 1967). Increasing CO_2 concentrations up to 13% caused a rapid decrease in ascorbic acid and development of off odors that were not acceptable after 1 week storage at 7 °C (45 °F) (McGill et al. 1966). Chlorophyll loss can be reduced by 50% with ethylene scrubbing. Low O_2 (0.8%) results in a slightly reduced respiration rate of cleaned spinach leaves.

Microbiological and sensory changes occur in all packaged spinach samples, being more pronounced at 10 °C (50 °F) than at 4 °C (40 °F). Spinach leaves harbor high numbers of mesophilic, psychrotrophic, and Pseudomonadaceae bacteria (Babic and Watada 1996). The pectinolytic species *Pseudomonas fluorescens* is probably the major spoilage agent of fresh-cut spinach. Microbial populations on fresh-cut spinach leaves increase during storage in air and CA at 5 and 10 °C (41 and 50 °F). Populations of Enterobacteriaceae and Micrococcaceae are not greatly affected by storage atmosphere.

Respiration Rates (Whole Leaves)

Temperature	mg CO_2 kg^{-1} h^{-1}
0 °C	6.0-14.0
5 °C	11.7-23.4

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Sweet Potato (Shredded, Sliced)

Fresh-cut sweet potatoes should be firm and without discoloration. Whole sweet potatoes are washed with water before peeling and shredding. Cut sweet potatoes are then washed with 100 µL L^{-1} sodium hypochlorite, rinsed, and centrifuged to remove excess water. Product quality remains acceptable during 2 weeks storage at 0 to 4 °C (32 to 40 °F) in polymeric bags. Color of shredded sweet potato darkens and firmness declines during storage. β-Carotene remains stable at 7.8 mg per 100 g at 4 °C (40 °F). Vitamin C remains stable at 7 mg per 100 g for 1 week and then decreases. A 6.5% CO_2 and 12% O_2 atmosphere is slightly beneficial.

Tomato (Sliced, Diced)

Fresh-cut tomatoes should have consistent red color and firm texture. Sliced tomatoes have no gel loss from the seed cavities. Diced tomatoes have no seeds or stem pieces. ‘Roma’ tomatoes are often used for diced tomatoes; the ripening stage should be 5 or higher (USDA standard). The ripening stage of round tomatoes for slicing should be 5.5 or higher. Fruit should be firm and have small seed cavities. For diced tomato products, ‘Roma’ tomatoes should be spray-washed with chlorinated water before cutting. After cutting, an open fluming system with 0.25% $CaCl_2$ and 100 µL L^{-1} chlorine is used to wash and remove seeds. For sliced tomato products, whole tomatoes are dipped in 200 µL L^{-1} chlorinated water for more than 1 min before slicing. Various automated slicing machines have been developed for tomatoes. Sliced tomatoes can be packed in stacking, shingling, or soldier style.

Although tomatoes are chilling sensitive, they can be stored at 0 to 5 °C (32 to 41 °F) for a few days before processing to retard softening. A CA of 3% O_2 and 3% CO_2 will delay ripening as well as SSC and TA losses (Mencarelli and Saltveit 1988). Water soaking that produces translucent tissue, textural changes, and softening reduces the quality of diced tomatoes during storage. In addition to these deleterious changes, quality of tomato slices can be reduced by seed germination and loss of locular gel. The high acidity of tomato products suppresses microbial growth, but growth of yeasts and molds can reduce quality in storage.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
20 °C	57.6-93.6

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production,

multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Zucchini (Slices)

Fresh-cut zucchini should have a dark green peel, white tissue, and a crisp texture. Raw material should be received at <13 °C (55 °F) and stored at 5 to 10 °C (41 to 50 °F). Storage should be at 0 to 5 °C (32 to 41 °F) after processing. A CA of 0.25 to 1% O_2 is beneficial. Lowering O_2 to <0.5% at 5 °C (41 °F) reduces respiration by 50%; respiration is reduced by 80% at 10 °C (50 °F). Sliced zucchini develops water-soaked areas (chilling injury) at 0 °C (32 °F) and brown discoloration at 5 to 10 °C (41 to 50 °F), which increases with storage duration. Zucchini slices can be dipped in solutions of $CaCl_2$ alone or with NaOCl. Calcium treatments reduce development of decay, total microbial growth, and ascorbate loss.

Respiration Rates

Temperature	mg CO_2 kg^{-1} h^{-1}
5 °C	21.1
10 °C	19.4-49.4

Data from Gorny (1997).

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

References

Abe, K., K. Yoshimura, Y.-F. Zhou, and T. Iwata. 1991. Studies on physiological and chemical changes of partially processed sweet pepper fruit. II. Changes of chemical compounds in cut surface of sweet pepper in relation to difference of storability by shredding direction. J. Jap. Soc. Cold Preserv. Food 17:146-151.

Augusti, K.T. 1990. Therapeutic and medicinal values of onions and garlic. *In* J.L. Brewser and H.D. Rabinowitch, eds., Onions and Allied Crops, vol. III, Biochemistry, Food Science, and Minor Crops, pp. 93-108. CRC Press, Boca Raton, FL.

Avena-Bustillos, R.D.J., J.M. Krochta, and M.E. Saltveit. 1997. Water vapor resistance of red delicious apples and celery sticks coated with edible caseinate-acetylated monoglyceride films. J. Food Sci. 62:351-354.

Avena-Bustillos, R.J., L.A. Cisneros-Zevallos, J.M. Krochta, and M.E. Saltveit. 1994. Application of casein-lipid edible film emulsions to reduce white blush on minimally processed carrots. Postharv. Biol. Technol. 4:319-329.

Babic, I., and A.E. Watada. 1996. Microbial populations of fresh-cut spinach leaves affected by CAs. Postharv. Biol. Technol. 9:187-193.

Beaulieu, J.C., F.A.R. Oliveira, T.D. Fernandes, et al. 1997. Fresh-cut kale: quality assessment of Portuguese store-supplied product for development of a MAP system. *In* J. Gorny, ed., vol. 5, Fresh-Cut Fruits and Vegetables and MAP, pp. 145-151. Proceedings of the 7th International Controlled Atmosphere Conference, University of California, Davis CA.

Beuchat, L.R., and R.E. Brackett. 1990. Survival and growth of *Listeria monocytogenes* on lettuce as influenced by shredding, chlorine treatment, modified atmosphere packaging and temperature. J. Food. Sci. 55: 755-758.

Blanchard, M., F. Caistaingne, C. Willemot, and J. Makhlouf. 1996. Modified atmosphere preservation of freshly prepared diced yellow onions. Postharv. Biol. Technol. 9:173-185.

Bolin, H.R., and C.C. Huxsoll. 1991. Control of minimally processed carrot *(Daucus carota)* surface discoloration caused by abrasion peeling. J. Food Sci. 56:416-418.

Brecht, J.K. 1995. Physiology of lightly processed fruits and vegetables. HortScience 30:18-21.

Burgheiner, F., J.N. Macgill, A.I. Nelson, and M.P. Steinberg. 1967. Chemical changes in spinach stored in air and CA. Food Technol. 21:109-111.

Burlo-Carbonell, F.M., A.A. Carbonell-Barrachina, D. Valero, et al. 2000. Acid treatment and edible coatings can improve preservation of fresh garlic. Institute of Food Technologists, Annual Meeting 2000, Technical Program and Book of Abstracts, pp. 133. Institute of Food Technologists, Chicago, IL.

Cabezas, A., and D.G. Richardson. 1997. Modified atmosphere packaging of broccoli florets of temperature and package type. *In* J. Gorny, ed., vol. 5, Fresh-Cut Fruits and Vegetables and MAP, pp. 8-15. Proceedings of the 7th International Controlled Atmosphere Conference, University of California, Davis CA.

Carlin, F., C. Nguyen-The, Y. Cudennec, and M. Reich. 1989. Microbial spoilage of fresh, "ready-to-use" grated carrots. Sciences des Alinents. 9:371-386.

Carlin, F., C. Nguyen-The, G. Hilbert, and Y. Chambroy. 1990. Modified atmosphere packaging of fresh, "ready-to-use" grated carrots in polymeric films. J. Food. Sci. 55:1033-1038.

Castaner, M., M.I. Gil, F. Ferreres, et al. 1997. Effect of modified atmospheres on anthocyanin stability and other phenolic metabolites during storage of minimally processed red lettuce. *In* J. Gorny, ed., vol. 5, Fresh-Cut Fruits and Vegetables and MAP, pp. 134-138. Proceedings of the 7th International Controlled Atmosphere Conference, University of California, Davis CA.

Cisneros-Zevallos, L., M.E. Saltveit, and J.M. Krochta. 1995. Mechanism of surface white discoloration of peeled (minimally processed) carrots during storage. J. Food Sci. 60:320-323,333.

Cisneros-Zevallos, L.A., M.E. Saltveit, and J.M. Krochta. 1997. Hygroscopic coatings control surface white discoloration of peeled (minimally processed) carrots during storage. J. Food Sci. 62:363-366.

Davidson, P.M., L.S. Post, A.L. Branen, and A.R. McCordy. 1983. Naturally occurring and miscellaneous food antimicrobials. *In* A.L. Bradeo and P.M. Davidson, eds., Antimicrobials in Foods, pp. 275-276. Marcel Dekker, New York, NY.

El-Bassuoni, R., and M. Cantwell. 1994. Low temperatures and CAs maintain quality of fresh cut bell pepper. HortScience 29:448.

Galetti, L., H. Berger, V. Escalona, et al. 1997. Modified atmospheres and ascorbic acid for minimum process of carrot slices. *In* J. Gorny, ed., vol. 5, Fresh-Cut Fruits and Vegetables and MAP, pp. 139-144. Proceedings of the 7th International Controlled Atmosphere Conference, University of California, Davis CA.

Garg, N., J.I. Churey, and D.F. Splinsioester. 1990. Effect of processing conditions on the microflora of fresh-cut vegetables J. Food Prot. 53:701-703.

Gariepy, Y., G.S.V. Raghavan, and R. Theriault. 1986. CA storage of celery with the silicone membrane system. Int. J. Refrig. 9:234-239.

Gil-Maria. I., M. Castaner, F. Ferreres, et al. 1998. Modified-atmosphere packaging of minimally processed "Lollo Rosso" *(Lactuca sativa):* phenolic metabolites and quality changes. Zeitschrift Lebensmittel Untersuchung Forschung. 206:350-354.

Gorny, J.R., ed. 1997. A summary of CA and MA requirements and recommendations for fresh-cut (minimally processed) fruits and vegetables. *In* J. Gorny, ed., vol. 5, Fresh-Cut Fruits and Vegetables and MAP, pp. 30-67. Proceedings of the 7th International Controlled Atmosphere Conference, University of California, Davis CA.

Gunes, G., and C.Y. Lee. 1997. Color of minimally processed potatoes as affected by modified atmosphere packaging and anti-browning agents. J. Food Sci. 62:572-575.

Gunes, G., D.F. Splittstoesser, and C.Y. Lee. 1997. Microbial quality of fresh potatoes: effect of minimal processing. J. Food Prot. 60:863-866.

Hagenmaier, R.D., and R.A. Baker. 1998. Microbial population of shredded carrot in modified atmosphere packaging as related to irradiation treatment. J. Food Sci. 63:162-164.

Hamza, F., F. Castaigne, C. Willemot, et al. 1996. Storage of minimally processed romaine lettuce under CA. J. Food Qual. 19:177-188.

Hiroaki, K., U. Masayuki, and O. Yutaka. 1993. Storage of shredded cabbage under dynamically CA of high O_2 and high CO_2. Biosci. Biotech. Biochem. 57:1049-1052.

Howard, L.R., and T. Dewi. 1995. Sensory, microbiological and chemical quality of mini-peeled carrots as affected by edible coating treatment. J. Food Sci. 60:142-144.

Howard, L.R., and T. Dewi. 1996. Minimal processing and edible coating effects on composition and sensory quality of mini-peeled carrots. J. Food Sci. 61:643-646,651.

Howard, L.R., K.S. Yoo, L.M. Park, and G.H. Miller Jr. 1994. Quality changes in diced onions stored in film packages. J. Food Sci. 59:110-112.

Izumi, H., T. Nonaka, and T. Muraoka. 1997. Physiology and quality of fresh-cut spinach stored in low O_2 CAs at various temperature. *In* J. Gorny, ed., vol. 5, Fresh-Cut Fruits and Vegetables and MAP, pp. 130-133. Proceedings of the 7th International Controlled Atmosphere Conference, University of California, Davis CA.

Izumi H., A.E. Watada, and W. Douglas. 1996a. Optimum O_2 or CO_2 atmosphere for storing broccoli florets at various temperatures. J. Amer. Soc. Hort. Sci. 121:127-131.

Izumi, H., A.E. Watada, N.P. Ko, and W. Douglas. 1996b. CA storage of carrot slices, sticks and shreds. Postharvest Biol. Technol. 9:165-172.

Johnson, C.E., and J.H. von Elbe. 1974. Extension of postharvest storage-life of sliced celery. J. Food Sci. 39:678-680.

Keteleer, A., C. De Mulder, A. Hermans, and P. Tobback. 1993. Biplot presentation of the physiological-biochemical characterization and the sensorial quality of minimally processed leek stored under modified atmosphere. Acta Hort. 343:345-346.

Krahn, T.R. 1977. Improving the keeping quality of cut head lettuce. Acta Hort. 62:79-92.

Langerak, D.I. 1975. The influence of irradiation and packaging on the keeping quality of prepared cut endive, chicory and onions. Acta Alim. 4:123-138.

Li, P., and M.M. Barth. 1998. Impact of edible coatings on nutritional and physiological changes in lightly-processed carrots. Postharvest. Biol. Technol. 14:51-60.

Loaiza-Velarde, J.G., M.E. Mangrich, R. Campos-Vargas, and M.E. Saltveit. 2003. Heat-shock reduces browning of fresh-cut celery petioles. Postharv. Biol. Technol. 27:305-311.

Loaiza-Velarde, J.G., and M.E Saltveit. 2001. Heat shocks applied either before or after wounding reduce browning of lettuce leaf tissue. J. Amer. Soc. Hort. Sci. 126:227-234.

Loaiza-Velarde, J.G., F.A. Tomás-Barberá, and M.E. Saltveit. 1997. Effect of intensity and duration of heat-shock treatments on wound-induced phenolic metabolism in iceberg lettuce. J. Amer. Soc. Hort. Sci. 122:873-877.

Lopez-Galvez, G., R. El-Bassuoni, X. Nie, and N. Cantwell. 1997. Quality of red and green fresh-cut peppers stored in CAs. *In* J. Gorny, ed., vol. 5, Fresh-Cut Fruits and Vegetables and MAP, pp. 152-157. Proceedings of the 7th International Controlled Atmosphere Conference, University of California, Davis CA.

Lopez-Galvez, G., M. Saltveit, and M. Cantwell. 1996. The visual quality of minimally processed lettuces stored in air or CA with emphasis on romaine and iceberg types. Postharv. Biol. Technol. 8:179-190.

MacLoed, A.L. 1970. The chemistry of vegetable flavor. Flav. Ind., October, pp. 665-672.

Makhlouf, J., F. Castaign, J. Arul, et al. 1989. Long-term storage of broccoli under CA. HortScience 24:637-639.

Martin, S.T., G.M. Sampers, and R.L. Miller. 1999. Process for inhibiting enzymatic browning and maintaining textural quality of fresh peeled potatoes. U.S. Patent No. 5912034.

Mateos, M., D. Ke, M. Cantwell, and A.A. Kader. 1993. Phenolic metabolism and ethanolic fermentation of intact and cut lettuce exposed to CO_2-enriched atmospheres. Postharv. Biol. Technol. 3:225-233.

McDonald, R.E., L.A. Risse, and C.R. Barmore. 1990. Bagging chopped lettuce in permeability films. HortScience 25:671-673.

McGill, J.N., A.I. Nelson, and M.P. Steinberg. 1966. Effects of modified storage atmospheres on ascorbic acid and other quality characteristics of spinach. J. Food Sci. 31:510-517.

Mencarelli, F., D. De Santic, R. Massantini, and M. Contini. 1990. Low O_2 concentrations use for the short-term onion slice storage. Industrie Alinentari. 29:982-984.

Mencarelli, F., and M.E. Saltveit Jr. 1988. Ripening of mature-green tomato fruit slices. J. Amer. Soc. Hort. Sci. 113:742-745.

Nguyen-The, C., and J. Prunier. 1989. Involvement of *Pseudomonas* in 'ready-to-use' salad deterioration. Int. J. Food Sci. Technol. 24:47-56.

Omary, M., R. Testin, S. Barefoot, and J. Rushing. 1993. Packaging effects on growth of *Listeria* innocula in shredded cabbage. J. Food Sci. 58:623-626.

Peiser, G., G. Lopez-Galvez, and M. Cantwell. 1997. Changes in aromatic volatiles during storage of packed salad products. *In* J. Gorny, ed., vol. 5, Fresh-Cut Fruits and Vegetables and MAP, pp. 23-28. Proceedings of the 7th International Controlled Atmosphere Conference, University of California, Davis CA.

Pirovani, M.E., D.R. Guenes, A.M. Piagentini, and J.H.D. Pentima. 1997. Storage quality of minimally processed cabbage packaged in plastic films. J. Food Qual. 20:381-389.

Poulsen, N., A.S. Johnson, and J.N. Sorensen. 1995. Influence of growth conditions on the value of crisphead lettuce, 4: Quality changes during storage. Plant Foods Hum. Nutr. 47:157-162.

Poulsen, N., J.N. Sorensen, and A.S. Johnson. 1994. Influence of growth conditions on the value of crisphead lettuce, 2: weight losses during storage as affected by nitrogen, plant age and cooling system. Plant Foods Hum. Nutr. 46:13-18.

Prakash, A. A.R. Guner, F. Caporaso, and D.M. Foley. 2000. Effects of low-dose gamma irradiation on the shelf-life and quality characteristics of cut romaine lettuce packaged under modified atmosphere. J. Food Sci. 65:549-553.

Robbs, P.G., J.A. Bartz, G. McFie, and N.C. Hodge. 1996. Causes of decay of fresh-cut celery. J. Food Sci. 61:444-448.

Roy, S., R.C. Anantheswaran, and R.B. Beelman. 1996. Modified atmosphere and modified humidity packaging of fresh mushrooms. J. Food Sci. 61:391-397.

Saltveit, M.E. 1997. Physical and physiological changes in minimally processed fruits and vegetables. *In* F.A. Tomas-Barberan and R.J. Robins, eds., Phytochemistry of Fruit and Vegetables, pp. 205-220. Clarendon Press, Oxford, U.K.

Saltveit M.E. 2000. Wound induced changes in phenolic metabolism and tissue browning are altered by heat shock. Postharv. Biol. Technol. 21:61-69.

Saltveit, M.E., and M.E. Mangrich. 1996. Use of density measurements to study the effect of excision, storage, abscisic acid and ethylene on the development of pithiness in celery (*Apium graveolens* L.) petioles. J. Amer. Soc. Hort. Sci. 121:137-141.

Sapers, G.M., P.H. Cooke, A.E. Heidel, et al. 1997. Structural changes related to texture of pre-peeled potatoes. J. Food Sci. 62:797-803.

Sapers, G.M., and R.L. Miller. 1995. Heated ascorbic citric acid solution as browning inhibitor treatment for pre-peeled potatoes. J. Food Sci. 60:762-766.

Schwimmer, S., and W.J. Weston. 1961. Enzymatic development of pyruvic in onion as a measure of pungency. Ag. Food Chem. 9:301-304.

Segall, K.I., and M.G. Scanlon. 1996. Design and analysis of a modified-atmosphere package for minimally processed romaine lettuce. J. Amer. Soc. Hort. Sci. 121:722-729.

Sharmon, A., G.M. Tewari, A.J. Shrikhande, et al. 1979. Inhibition of aflatoxin-producing fungi by onion extract. J. Food Sci. 44:1545-1547.

Smyth-Anne, B., J. Song, and C. Cameron-Authur. 1998. Modified atmosphere packaged cut iceberg lettuce: effect of temperature and O_2 partial pressure on respiration and quality. J. Ag. Food. Chem. 46:4556-4562.

Sorensen, J.N., A.S. Johnnsen, and N. Poulsen. 1994. Influence of growth conditions on the value of crisphead lettuce, 1: marketable and nutritional quality as affected by nitrogen supply, cultivar and plant age. Plant Foods Human Nutr. 46:1-12.

Stewart, J.K., and M.J. Ceponis. 1968. Effect of transit temperatures and modified atmospheres on market quality of lettuce shipped in nitrogen-refrigerated trailers. Agricultural Marketing Research Report 832, U.S. Department of Agriculture, Washington, DC.

Stewart, J.K., and M. Uota. 1971. Carbon dioxide injury and market quality of lettuce held in CAs. J. Amer. Soc. Hort. Sci. 96:27-30.

Sugiyama, H., and K.S. Rutledge. 1978. Failure of *Clostridium botulinum* to grow in fresh mushrooms packaged in plastic film overwraps with holes. J. Food Prot. 41:348-350.

Sugiyama, H., and K.H. Yang. 1975. Growth potential of *Clostridium botulinum* in fresh mushrooms packaged in semi-permeable plastic film. App. Microbiol. 30:964-969.

Tatsumi, Y., A.E. Watada, and W.P. Wergin. 1991. Scanning electron microscopy of carrot stick surface determines cause of white translucent appearance. J. Food Sci. 56:1357-1359.

Toivonen, P.M.A. 1997. Quality changes in packaged, diced onions (*Alliumcepa* L.). *In* J. Gorny, ed., vol. 5, Fresh-Cut Fruits and Vegetables and MAP, pp. 1-6. Proceedings of the 7th International Controlled Atmosphere Conference, University of California, Davis CA.

Watada, A.E., N.P. Ko, and D.A. Minott. 1996. Factors affecting quality of fresh-cut horticultural products. Postharv. Biol. Technol. 9:115-125.

Zhou, Y.F., K. Abe, and T. Iwata. 1992. Effect of shredding modes on the deterioration of the quality of partially processed pepper fruits. Nippon Shokuhin Kogyo Gakkaishi 39:161-166.

Zhuang, H., and M.M. Barth. 1999. Control of browning discoloration in tray-packed fresh-cut iceberg lettuce. *In* 1999 Institute of Food Technologists Annual Meeting, Technical Program and Book of Abstracts, pp. 226. Institute of Food Technologists, Chicago, IL.

Bedding Plants and Seedlings

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Introduction

Storage of vegetable and flower bedding plants may be necessary if adverse weather conditions, seasonal availability, or extension of the time of availability makes it essential. There are two stages of plants in bedding plant production and storage: plugs and finished plants. Generally, finished bedding plants are hardier and can withstand greater environmental changes than the plug stage of the same plant. However, storage is easier when the plant is in the more compact plug stage.

Plug Storage

Most bedding plants are produced as plugs. Research on plug storage is mainly limited to that published in recent years. Heins et al. (1995) found that the duration a species could be stored without plant death or flowering delay was influenced by storage temperature and irradiance. Plant quality improved with the addition of light compared to that of plants in dark storage, especially as the duration of storage and storage temperature increased (Heins and Lange 1992a,c,d, Heins and Wallace 1993a,d). The effect of storage on plugs may vary depending on the specific storage conditions, age, species, cultivar, and physiological state of the plugs. The optimum storage temperatures and maximum storage durations for selected species are shown in table 1.

Shipping plugs in boxes or trucks is in fact a form of short-term storage. As the duration of shipping increases, cooling plugs prior to shipping becomes more important and will improve their postharvest condition when they reach their final destination (Lange et al. 1991b, Heins et al. 1994b, Kaczperski et al. 1996).

Growers who only have one or two coolers may need to store plugs of several species at one time. Researchers in Michigan (Heins and Lange 1992d, Heins et al. 1992) showed how to identify a compromise temperature—one that is collectively acceptable, although maybe not individually optimal. If only short-term storage is necessary, a temperature warmer than the optimum may be more economical (Heins et al. 1994b). Also, the environmental conditions before and after storage can influence the growth of the plugs following storage (Heins et al. 1991, 1994b, Heins and Lange 1992c, Kaczperski et al. 1996).

A major disease problem associated with plug storage is botrytis (Lange et al. 1991a,b, Heins et al. 1992, 1994b, 1995). Maintaining a high RH in a cooler decreases the frequency of watering but favors the growth of botrytis. The disease is generally not a problem on pansies but does affect many species including impatiens, geraniums, and petunias. Those crops should be stored under low RH conditions and irrigated if plugs are stored longer than 1 week (Heins et al. 1991).

Low RH in coolers with significant air velocity causes plugs to dry out quickly. The frequency of irrigations will vary, depending on the temperature and RH of the cooler. Contact between the foliage and water should be minimized to avoid fungal infection. Plugs can be subirrigated with clear water as needed during storage because the plants' nutritional needs are minimal under low temperatures (Heins and Lange 1992c, Heins et al. 1994b). Heins et al. (1994b) recommend applications of certain fungicide tank mixtures for controlling botrytis blight and sporulation during plug storage.

Table 1. Optimal storage temperatures and maximum storage durations for plugs of selected bedding plant species and cultivars either in the dark or under a minimum of 5 footcandles of light

Species	Cultivars evaluated	Optimal storage temperature		Maximum weeks storage		References
		°C	°F	In the dark	In the light	
Ageratum	'Blue Danube'	7.5	45.0	6	6	Heins et al. 1992 Heins et al. 1994a Heins et al. 1995 Heins and Lange 1992a
Alyssum	'New Carpet of Snow'	2.5	36.0	5	6	Heins et al. 1994a Heins et al. 1995
Begonia, fibrous	'Vodka'	5.0	41.0	6	6	Heins et al. 1994a Heins et al. 1995
		5.0-7.5	41.0-45.0			Heins et al. 1992 Heins and Lange 1992c
Begonia, tuberous	'Nonstop Scarlet'	5.0	41.0	3	6	Heins et al. 1994a Heins et al. 1995
		5.0-7.5	41.0-45.0			Heins & Wallace 1993d
Celosia	'Cherry Red'	10.0	50.0	2	3	Heins et al. 1994a Heins et al. 1995
Dahlia	'Amore / Figaro'	5.0	41.0	2	5	Heins et al. 1994a Heins et al. 1995
		5.0-7.5	41.0-45.0	—	—	Heins and Wallace 1993c

Table 1. Optimal storage temperatures and maximum storage durations for plugs of selected bedding plant species and cultivars either in the dark or under a minimum of 5 footcandles of light—*continued*

Species	Cultivars evaluated	Optimal storage temperature		Maximum weeks storage		References
		°C	°F	In the dark	In the light	
Geranium	'Pinto Red'	3.0	37.5	—	—	Heins et al. 1991 Lange et al. 1991b
		2.5	36.0	4	4	Heins et al. 1994a Heins et al. 1995
Impatiens	'Accent Orange'	7.5	45.0	6	6	Heins et al. 1991 Heins et al. 1994a Heins et al. 1995 Lange et al. 1991a
Lobelia	'Blue Moon'	5.0	41.0	6	6	Heins et al. 1994a Heins et al. 1995 Heins and Wallace 1993e
Marigold, French	'Hero Yellow'	5.0	41.0	3	6	Heins et al. 1992 Heins et al. 1994a, Heins and Lange 1992c Heins et al. 1995
New Guniea impatiens	'Kientzler Agua' 'Kientzler Anaea' 'Kientzler Apollon' 'Kientzler Celerio' 'Kientzler Celsia' 'Kientzler Eurema' 'Kientzler Marpesia' 'Kientzler Melissa' 'Kientzler Octavia' 'Kientzler Saturnia' 'Kientzler Sesia'	12.5	55.0	2	3	Heins et al. 1994a Heins et al. 1995

Table 1. Optimal storage temperatures and maximum storage durations for plugs of selected bedding plant species and cultivars either in the dark or under a minimum of 5 footcandles of light—*continued*

Species	Cultivars evaluated	Optimal storage temperature		Maximum weeks storage		References
		°C	°F	In the dark	In the light	
	'Paradise Antigua' 'Paradise Aruba' 'Paradise Barbados' 'Paradise Bora-Bora' 'Paradise Lanai' 'Paradise Maui' 'Paradise Papete' 'Paradise Samoa' 'Paradise Tahiti' 'Paradise Tobago' 'Paradise Tonga' 'Paradise Trinidad'					
Pansy	'Majestic Yellow'	2.5	36.0	6	6	Heins et al. 1991 Heins et al. 1994a Heins et al. 1995
		0-2.5	32.0-36.5	—	—	Heins and Lange 1992d Lange et al. 1991a
Petunia	'Ultra Red'	3.0	37.5	—	—	Heins et al. 1991 Lange et al. 1991b
		2.5	36.0	6	6	Heins et al. 1994a Heins et al. 1995
Portulaca	'Fuchsia'	7.5	45.0	5	5	Heins et al. 1994a Heins et al. 1995
		5.0-7.5	41.0-45.0	—	—	Heins & Wallace 1993e

Table 1. Optimal storage temperatures and maximum storage durations for plugs of selected bedding plant species and cultivars either in the dark or under a minimum of 5 footcandles of light—*continued*

Species	Cultivars evaluated	Optimal storage temperature		Maximum weeks storage		References
		°C	°F	In the dark	In the light	
Salvia	'Red Hot Sally'	5.0	41.0	6	6	Heins et al. 1994a Heins et al. 1995
		7.5	45.0	—	—	Heins et al. 1992 Heins and Lange 1992a
Tomato	'Rutgers'	7.5	45.0	3	3	Heins et al. 1994a Heins et al. 1995 Heins and Wallace 1992
Verbena	'Romance Mix'	7.5	45.0	1	1	Heins et al. 1994a Heins et al. 1995
Vinca	'Peppermint Cooler'	10.0	50.0	5	6	Heins et al. 1994a Heins et al. 1995

because of reductions in fertility prior to storage are more resistant to botrytis (Heins et al. 1995). In addition, hardening of these plugs will aid in resistance to drought stress. A hardened plug will resist drought damage better than a plug grown with high levels of phosphorus (Borch et al. 1999).

Plug storage has the potential to become a viable grower management tool (Heins and Lange 1992a) if cooler space is available. However, as with any new technique, growers should experiment with just a few plug trays before they commit a large volume to storage (Heins et al. 1991, Lange et al. 1991a,b, Heins and Lange 1992c, Heins and Wallace 1993b). See table 1 for specific species storage temperatures and light levels.

Finished Plant Storage

Finished bedding plants are those that are in a state ready for sale to the general public. Generally, finished plants are not stored in coolers because of the difficulty in moving large quantities of plants from greenhouse to cooler. To reduce plant growth, greenhouse temperatures are dropped while waiting for the crop to sell. Finished plants should be held at temperatures low enough to reduce growth but not to cause damage or impair future growth. Table 2 lists certain cultivars of popular bedding plants and suggested holding temperatures.

According to Nelson (1983), a general greenhouse holding temperature of 13 °C (55 °F) is applicable for many of the common types of bedding plants. Alyssum, begonia, geranium, impatiens, marigold, petunia, and salvia all keep well at this temperature. Impatiens plants were still marketable after 36 days at this temperature. Bedding plants hold better at a higher light level (7,500 lux) than at a lower light level (500 to 2,700 lux).

Table 2. Short-term greenhouse-holding temperatures for finished bedding plants[1]

Hold at or above	Reference
15 °C (60 °F)	
Balsam	Ross and Aldrich 1976
Begonia (fibrous)	Ross and Aldrich 1976
Celosia	Ross and Aldrich 1976
Coleus	Ross and Aldrich 1976
Kochia	Ross and Aldrich 1976
Vinca rosea	Ross and Aldrich 1976
Zinnia (dwarf & tall)	Ross and Aldrich 1976
10-13 °C (50-55 °F)	
Ageratum	Ross and Aldrich 1976
Aster	Ross and Aldrich 1976
Browallia	Ross and Aldrich 1976
Centaurea cyanus	Ross and Aldrich 1976
Dahlia	Ross and Aldrich 1976
Dianthus	Ross and Aldrich 1976
Dusty Miller	Ross and Aldrich 1976
Geranium	Ross and Aldrich 1976
Impatiens	Ross and Aldrich 1976
Marigold	Ross and Aldrich 1976
Nierembergia	Ross and Aldrich 1976
Petunia	Ross and Aldrich 1976
Phlox	Ross and Aldrich 1976
Portulaca	Ross and Aldrich 1976
Salvia	Ross and Aldrich 1976
Verbena	Ross and Aldrich 1976
7-10 °C (45-50 °F)	
Alyssum	Ross and Aldrich 1976
Calendula	Ross and Aldrich 1976
Carnation	Ross and Aldrich 1976
Larkspur	Ross and Aldrich 1976
Lobelia	Ross and Aldrich 1976
Pansy	Ross and Aldrich 1976
Snapdragon (tall & dwarf)	Ross and Aldrich 1976

[1]Temperatures are the lowest recommended growth temperatures after transplant. At lower temperatures, plant quality may be adversely affected by chilling injury. Refer to the plug storage table for temperatures and lengths of time the plants may be stored without damage.

Conifer and Hardwood Seedling Storage

Storage of conifer and hardwood forest seedlings is possible at a low temperature and high RH (Duffield and Eide 1959, Aldhous 1964, Camm et al. 1994). Loosely tied bundles of seedlings, as well as containerized seedlings, may be stored in conditions that lower the metabolic activity of the plants. For most species, however, temperatures should be kept above freezing to avoid injury (Lantz et al. 1989, Camm et al. 1994). Top and root growth capacity of certain seedlings are affected by the cold storage, and these are dependent on seed source and lifting date of the seedlings (Jenkinson et al. 1993). A cold-hardened seedling will store more successfully and for longer time than a nonhardened seedling. Maximum stress resistance occurs in late fall to early winter. Therefore, lifting dates for seedlings being put into cold storage should be delayed as long as possible (Camm et al. 1994).

Warehouses or sheds can be used for storage of seedlings at a variety of temperatures. Refrigerated storage rooms or coolers are also used for storing seedlings at cooler temperatures (1 to 4 °C, 34 to 40 °F). High RH and good air circulation, as well as daily photoperiod control if possible, are important factors that influence the success of seedling storage (Lantz et al. 1989, Camm et al. 1994).

Storage of seedlings may be done in polyethylene bags to facilitate high RH, but spacing between the bags must be enough to allow for adequate air movement in order to prevent fungal pathogens. Loosely tied bundles of seedlings may be packed with slightly wet peat surrounding the roots and then wrapped in film-coated paper with the tops exposed and placed in a container for storage. With prolonged storage (>6 mo), root growth capacity can decline, as well as lead to a disruption of naturally occurring seasonal progression events.

The following species may be stored for up to 3 mo at 1 to 4 °C (34 to 40 °F):

Norway spruce	Sycamore
Sitka spruce	Sweetgum
Douglas-fir	Green ash
Lodgepole pine	Oak
Scotch pine	Birch
Loblolly pine	Yellow poplar
Ponderosa pine	Hybrid poplar*
Western hemlock	Eastern cottonwood*
Lawson cypress	

* hardwood cuttings

References

Aldhous, J.R. 1964. Cold storage of forest nursery plants: an account of experiments and trials, 1958-1963. Forestry (Great Britain) 37:47-63.

Ross, D.S., and R.A. Aldrich. 1976. Production Operations Analysis. In J.W. Mastalerz, ed., Bedding Plants, 2 edition, pp. 386-397. Pennsylvania Flower Growers. University Park, PA.

Barrett, J., et al. 1999. Tips on Growing Bedding Plants. OFA Serv., Inc., Columbus, OH.

Borch, K., T. Bouma, J.P. Lynch, and K.M. Brown. 1999. Interactions of ethylene and phosphorus nutrition on root growth. Plant Cell Environ. 22:425-431.

Camm, E.L., D.C. Goetze, S.N. Silim, and D.P. Lavender. 1994. Cold storage of conifer seedlings: an update from the British Columbia perspective. Forestry Chronicle 70:311-316.

Duffield, J.W., and R.P. Eide. 1959. Polyethylene bag packaging of conifer planting stock in the Pacific Northwest. J. Forestry, 57:578-579.

Heins, R.D., W. Carlson, and N. Lange. 1991. Plug into storage. Greenhouse Grower’s Plug Guide, Fall, pp. 72-73.

Heins, R.D., M.P. Kaczperski, T.F. Wallace Jr., et al. 1995. Low-temperature storage of bedding plant plugs. Acta Hort. 396:285-296.

Heins, R.D., and N. Lange. 1992a. Development of systems for storage of bedding-plant plugs. Bedding Plants Foundation, no. F-056, February, pp. 1-8.

Heins, R.D., and N. Lange. 1992b. How to store begonia and marigold plugs. Greenhouse Grower, March, pp. 34-38.

Heins, R.D., and N. Lange. 1992c. How to store salvia and ageratum plugs. Greenhouse Grower, February, pp. 76-82.

Heins, R.D., and N. Lange. 1992d. One temp can fit all. Greenhouse Grower, April, pp. 30-36.

Heins, R.D., N. Lange, and T.F. Wallace Jr. 1992. Low-temperature storage of bedding-plant plugs. *In* K. Kurata and T. Kozai, eds., Transplant Production Systems, pp. 45-64. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Heins, R.D., N. Lange, T.F. Wallace Jr., and W. Carlson. 1994a. Plug Storage. Greenhouse Grower.

Heins, R.D., Y. Si, and M. Hausbeck. 1994b. Control of *Botrytis* during storage of bedding-plant plugs. Bedding Plants Foundation, no. F-9406, November, pp. 1-8.

Heins, R.D., and T.F. Wallace Jr. 1993a. How to store alyssum plugs. Greenhouse Grower, March, pp. 32-33.

Heins, R.D., and T. Wallace Jr. 1993b. How to store New Guinea impatiens. Greenhouse Grower, Fall, pp. 55-58.

Heins, R.D., and T.F. Wallace Jr. 1993d. How to store vinca plugs. Greenhouse Grower, April, pp. 44-45.

Jenkinson, J. L., J. A. Nelson, and M. E. Huddleston. 1993. Improving planting stock quality—The Humboldt experience. General Technical Report PSW-GTR-143. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.

Kaczperski, M.P., A.M. Armitage, and P. M. Lewis. 1996. Performance of plug-grown geranium seedlings preconditioned with nitrogen fertilizer or low-temperature storage. HortScience 31:361-363.

Lange, N., R. Heins, and W. Carlson. 1991a. Another look at storing plugs. Greenhouse Grower, February, pp. 18-24.

Lange, N., R. Heins, and W. Carlson. 1991b. Store plugs at low temperatures. Greenhouse Grower, January, pp. 22-28.

Lantz, C.W., 1989. A guide to the care and planting of southern pine seedlings. Management Bull. R8-MB39, U.S. Department of Agriculture, Forest Service, Atlanta, GA.

Nelson, L.J. 1983. Correct conditions extend bedding plant marketability. The Great Lakes Vegetable Growers News, October, pp. 8-9.

Christmas Trees

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Introduction

Approximately 33 million natural Christmas trees were used in the U.S. in 1998. Given a conservative wholesale value of $10.00 per tree, the value of the trees alone approaches $330 million. When associated products are added to the picture, total value is well above $500 million. The National Christmas Tree Association estimated the average retail price for Christmas trees in 1998 at $3.45 to $6.30 per ft. Based on a standard 6- to 7-ft tall (2 m) tree, the retail value of natural Christmas trees approaches $1.5 billion.

About 25% of the live Christmas trees consumed in the U.S. are sold on choose-and-cut farms. This means that 75% of the trees experience some form of storage and shipment after harvest. Storage and shipment times can be several weeks for trees shipped between countries or less than one day for trees sold in local markets.

Natural Christmas trees quickly lose quality if handled improperly. People who grow, sell, handle or use Christmas trees should know something about tree keepability. This is true of the consumer who may use only one tree each year, as well as brokers or growers who handle thousands of trees.

Many publications have been written concerning postharvest physiology, handling, and keepability of Christmas trees. Despite this, there is often ignorance of the subject, resulting in wasted trees, reduced tree quality, erroneous information, or dissatisfied consumers. In this chapter, we provide a summary of information concerning Christmas tree keepability.

Moisture Status of Cut Trees

A Christmas tree is a perishable product that contains a finite amount of water when cut. Postharvest quality and fire safety are closely tied to moisture status. When a tree is cut, it begins to dry. Rate of drying is affected by species as well as environmental conditions (vapor pressure deficit, temperature, wind) and cold hardiness.

The two most common methods for determining moisture status are twig moisture content (MC) and water potential (ψ). The second method uses a pressurized chamber to extrude water from the cut end of a twig encased in a heavy-walled metal chamber. The drier the twig, the greater the pressure required to force water out of the end of the twig. Freshly harvested trees normally have ψ = -0.2 to -0.8 MPa. (1 MPa = 10 atmospheres or about 10 bars.)

The temporal change in moisture content has several inflection points. Initially, the tree dries quickly to an inflection point, V_1, which varies considerably by species. For example, V_1 is about -1.8 MPa (-18 bar) in eastern red cedar, -2.2 MPa (-22 bar) in eastern white pine, and -2.8 MPa (-28 bar) in Fraser fir. At that point, the rate of drying slows noticeably, presumably because stomata close to reduce water loss under increasing stress. Eventually, another value is reached, V_2, at which the drying rate accelerates again, presumably when increasing drying stress exceeds the capacity of guard cells to limit water loss. V_2 probably corresponds to the “damage threshold,” a term first used by Montano and Proebsting (1986). Further drying results in irreversible damage (needle abscission, discoloration, failure to rehydrate when placed in water) to the tree. The damage threshold for Douglas-fir and Fraser fir is between -3.5 and -4.0 MPa (-35 to -40 bar), compared to -3.0 to -3.2 MPa (-30 to -32 bar) for eastern white pine. Spruces typically experience very heavy needle loss when they dry to a certain MC, making it important to handle these species in a way that minimizes moisture loss after harvest and to display them in water before they reach that threshold.

The values of V_1 and V_2 vary by species. In addition, a pressure potential of -3.0 MPa (-30 bar) does not correspond to the same value of MC in various species. The time required to reach a particular MC also varies by species. For example, eastern red cedar and Atlantic white cedar dry very fast when displayed under room conditions, whereas Fraser fir and noble fir dry much slower. The latter species are regarded as long-lasting trees, whereas the former have a short shelf-life.

The moisture status of the tree determines its ability to rehydrate when recut and displayed in water. Fresh-cut trees typically have an MC in excess of 100%. When a fresh tree is recut and displayed in water, it typically gains weight, reaching a MC 5 to 10% above the initial value. Trees without water gradually lose moisture and can readily rehydrate at moisture levels approaching V_2. Beyond that, the degree of rehydration may decrease; or if rehydration occurs, there may be adverse changes in quality (needle abscission, discoloration). For example, eastern red cedar rehydrates when V_2 = -4.5 to -5.0 MPa (-45 to -50 bar), but not without subsequent abscission of foliage.

The moisture status during display also varies among species. Species that endure for a long time during the display period, such as noble fir and Fraser fir, tend to maintain MC and ψ close to the initial value for at least 4 weeks. Species that have a short shelf-life, such as eastern red cedar and Atlantic white cedar, maintain a high water level for about 1 wk and then begin to slowly dry even while displayed in water. This process is reflected by a decrease in ψ (more negative), a decrease in twig MC, and a reduction in water consumption.

Water Use

When supplied with water, cut Christmas trees generally consume about 1 qt (about 1 L) of water per day per inch (2.54 cm) of stem diameter. Thus, a tree with a 4-in diameter trunk would use about 4 qt (about 4 L) of water per day. The biggest mistake by consumers is using a stand with too little capacity, resulting in trees drying up between waterings. If this happens, the tree might not rehydrate when rewatered.

Water use changes during the display period and also varies among species. Compared to other species, true firs tend to use large quantities of water over extended display periods. For example, a 6-ft (about 2 m) Fraser fir can easily use 4 qt of water per day during the first 5 to 7 days and 2 to 3 qt (about 2 to 3 L) per day thereafter for the next 3 to 4 weeks. In contrast, water use by an eastern red cedar might decrease noticeably after a week. In general, if the tree continues to use a relatively constant amount of water, it indicates that the tree is maintaining its initial water status. On the other hand, if there is a marked reduction in water consumption, it probably indicates that the tree is beginning to dry.

Additives

Many chemicals and home concoctions have been tested in hopes of prolonging the life of cut Christmas trees. Additives are of little benefit and sometimes produce adverse effects. Additives can undesirably increase water consumption by displayed trees. Because people often use stands that are too small, increased water consumption would increase the likelihood of a tree “going dry” in the stand. Some additives can induce heavy needle loss. The best tree preservative is plain water, without additives.

Cold Hardiness

Cold-hardened Christmas trees keep better after harvest and better withstand exposure to low temperatures. Induction of cold hardiness requires photosynthesis, reduced temperatures, and shorter days. In this context, it will not occur in darkness, as in a refrigerator. When trees are harvested too early, heavy needle loss is possible, even with proper care. It is not known why cold-hardened trees keep better than nonhardened trees. Foliar raffinose increases during fall, although the absolute amount is small compared to sucrose. The increase in raffinose is mostly a response to lower temperatures. The role of raffinose is not clear, although in other plants it can reduce the ice crystallization temperature in cell sap. Nonhardened trees also transpire more and thus dry faster than hardened trees.

Tree species and seed sources also differ in their ability to tolerate exposure to cold temperatures. Coastal types of Douglas-fir are genetically not as cold-hardy as intermountain types. If coastal types of Douglas-fir are shipped into cold-weather market areas and not protected from exposure to cold temperatures, they can exhibit severe needle loss due to cold injury. The level of damage depends on the level of cold hardiness of the trees, the rate of temperature drop, and the lowest temperatures the trees are exposed to. People should be aware that tree species, the environmental conditions prior to harvest, and the environmental conditions that trees are exposed to during transit and on retail lots can have a bearing on postharvest quality.

Diseases and Pests

Christmas trees can be damaged by a variety of diseases and pests. Although trees and branches can be killed, most of the damage results in cosmetic needle discoloration or loss of needles prior to harvest. Little information is available concerning the direst impact of various diseases and pests on the postharvest keepability of trees. Swiss needle cast on Douglas-fir Christmas trees can accelerate moisture loss and needle loss when trees are displayed indoors.

Quarantine Issues

Live Christmas trees sometimes harbor plant pathogens, insects, and other arthropods. Most are only an annoyance; but some, if exported to places that have no natural enemies, could potentially cause serious problems. States and countries impose various quarantines in an effort to prevent the introduction or further spread of potentially harmful pests. For example, trees grown in areas infested with the gypsy moth, European pine shoot moth, or pine shoot beetle are frequently prevented from being shipped out of these areas unless they have been certified to be free of these pests. Many quarantine problems can be avoided by appropriate scouting, trapping, management practices, and certification programs. Mechanical shakers can be used to remove old dead needles and certain types of insects. The failure to meet quarantine requirements can result in entire shipments being rejected, causing great loss and inconvenience to producers and importers.

Fumigation. In some instances trees are required to be treated prior to entry, especially in some foreign countries. Fumigation is a common method used to meet quarantine requirements for a number of horticultural products. Although methyl bromide is one of the most common materials used to fumigate horticultural products, information on the tolerance of various types of Christmas trees to methyl bromide is limited. Chastagner (1990) fumigated several species typically grown in the Pacific Northwest with methyl bromide at rates up to 6 lb per 1,000 ft^3 for 2 h at 10 °C (50 °F). Douglas-fir and noble fir were not damaged, Fraser fir and grand fir experienced only slight damage, Scotch pine showed moderate damage, and Shasta fir was severely damaged. Use of methyl bromide will diminish in the future, and alternatives are needed. Increasing development of international markets will increase the demand for procedures to ensure that exported trees are pest-free.

Irradiation. Gamma radiation can be used to sterilize or kill insects at all stages of the life cycle, including larvae and pupae within the wood. Little information is available for Christmas trees, but balsam fir is sensitive to chronic, low-level doses of gamma radiation. The cumulative lethal dose (LD_{50}) is about 0.1 kGy over a period of years. Dormant branches of Fraser fir, when subjected to single doses of gamma radiation, experienced significant needle loss at 0.10 kGy. Massive needle loss occurred within 2 days for branches that receive higher doses of radiation. In addition, there was great intertree variation; for example, for the 0.1 kGy treatment, needle loss ranged from 5 to 100% for branches displayed for 2 weeks in water (average 42%). Irradiation discolored foliage and accelerated drying.

If Fraser fir is representative of other Christmas tree species, irradiation does not appear to be a viable way to meet insect quarantine requirements. Sterilizing insect pests would probably require irradiation doses of 0.5 to 1.0 kGy, and levels needed to outright kill insects would be higher. These levels of radiation would result in virtually complete defoliation of Fraser fir within a few days after exposure.

Controlled Atmosphere (CA) and Modified Atmosphere (MA) Storage

Information is limited, but short-term CA or MA storage at low temperature (5 °C, 41 °F) appears to be of little benefit with Fraser fir. CO_2 >5%, as well as O_2 <3%, can lead to increased needle loss. The respiration rate at 21 °C (70 °F) is about four times that at 5 °C (41 °F).

Fire Safety

Fresh Christmas trees, if properly watered and maintained, are not a fire hazard and are very difficult to ignite with a point source of flame. But problems can arise when trees become too dry. Several factors are important in assessment of fire risk, including ignition time, peak heat release rate (PHRR), total heat released, peak smoke release rate, and total smoke released**.** Dry trees produce extremely high PHRR in short periods. A PHRR of 500 kW is enough to cause flashover. Although limited PHRR data is limited, very dry Douglas-fir can produce PHRR up to 3,000 kW within 1 min of exposure to an open flame.

Experiments (Chastagner 2002, unpublished) tested 21 conifer species to determine the MC at which branches initially begin to fail an ignition test and the MC for consistent failure. Branches were exposed to a flame from a small alcohol lamp for 5 sec. If the sample failed to burn or self-extinguished without any additional spread when removed from the flame, it passed the test. If there was any spread of the flame after the sample was removed from the flame, it failed the test. There is considerable interspecific variation in the MC for ignition. In addition, there is often a large transition zone of MC from the point of initially failing the flammability test to the point of flash ignition. For example, Douglas-fir begins to fail the flammability test at about 68% MC, but is totally consumed only when dried to about 30% MC.

There is a close relationship between twig MC and water potential (ψ), which also varies among species. With noble fir, twig MC must reach about 37% before it begins to fail the flammability test. This corresponds to a pressure potential below -6 MPa (-60 bars), well beyond its damage threshold. Based on this and other postharvest display data, one can estimate how long it would take for trees to dry to moisture levels at which they would fail the test. With proper care, winter-hardened noble fir and Fraser fir can easily be displayed in water for 6 to 8 wk without becoming a fire hazard.

The use of flame retardants on trees is not recommended unless required by law. Flame retardants can damage needles and increase moisture loss from trees. The best way to minimize any potential fire hazard associated with cut Christmas trees is to display them in water-holding stands.

Colorants, Stickers, and Antitranspirants

Many conifers naturally fade to a yellow-green color in fall. Colorants, similar to latex paint, mask this effect if applied prior to the change, increasing consumer acceptability. Needle stickers, which dry to a clear, shiny film on the surface of foliage, supposedly cause better needle retention, but this has not been confirmed by research.

Antitranspirants form a thin film on the surface of foliage. Although it would seem that such products should greatly reduce the drying process, this is usually not the case. Under moderate to strong drying conditions, they do little to retard drying

Table 1. Postharvest quality ratings for Christmas trees, displayed dry or in water (Trees are assumed to be cold-hardened.)

Species	Scientific name	Rating Displayed— Dry†	Wet
Arizona corkbark fir	*Abies lasciocarpa* (Hook.) Nutt. ssp. *arizonica* (Merriam) E. Murray	F	E
Arizona cypress	*Cupressus arizonica* Green var. *glabra* (Sudw.) Little 'Carolina sapphire'	P/F	F/G
Atlantic white cedar	*Chamaecyparis thyoides* (L.) BSP.	P	P/F
Balsam fir	*Abies balsamea* L.	F	G/E
California red fir	*Abies magnifica* A. Murray	G	E
Canaan fir	*Abies balsamea* (L.) Mill. var. *phanerolepis* Fern.	F	G/E
Colorado blue spruce	*Picea pungens* Engelm.	F	G/E
Concolor fir	*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.	P/G*	P/E*
Douglas-fir (coastal)	*Pseudotsuga menziesii* ssp. *glauca* (Beissn.) E. Murray	P/F	G
Douglas-fir (intermountain)	*Pseudotsuga menziesii* (Mirb.) Franco ssp. *menziesii*	F/G*	G/E
Eastern red cedar	*Juniperus virginiana* L.	P	F
Eastern white pine	*Pinus strobus* L.	G	G/E
European silver fir	*Abies alba* Mill.	P	G/E
Fraser fir	*Abies fraseri* (Pursh) Poir.	G	E
Grand fir	*Abies grandis* (Douglas ex D. Don) Lindl.	P	G/E
Greek fir	*Abies cephalonica* Loud.	P	G/E
Korean fir	*Abies koreana* Wils.	G	G/E
Leyland cypress	× *Cupressocyparis leylandii* (Dallim. & A. B. Jackson) Dallim.	F	G/E
Monterey pine	*Pinus radiata*	F	G
Noble fir	*Abies procera* Rehd.	G	E
Nordmann fir	*Abies nordmanniana* (Steven) Spach.	P/G*	E
Norway spruce	*Picea abies* (L.) Karst.	P	G
Pacific silver fir	*Abies amabilis* Douglas ex Forbes	F	G/E
Scotch pine	*Pinus sylvestris* L.	F/G	G
Shasta fir	*Abies magnifica* A. Murray var. *shastensis* Lemmon	P/F	F/G
Turkish fir	*Abies nordmanniana* ssp. *equitrojani* (Asch. & Sint. Ex Boiss.) Coode & Cullen (syn. *Abies x bornmuelleriana* Mattf.)	P/G*	E
Veitch fir	*Abies veitchii* Lindl.	G	E
Virginia pine	*Pinus virginiana* Mill.	F	F
Western white pine	*Pinus monticola* Douglas ex D. Don	G	G/E
White spruce	*Picea glauca* (Moench) Voss	P	G

Scientific names from Griffiths (1994).

Ratings: Excellent (E) has potential to last 4-6 wk under typical household conditions. Good (G) can last 3-4 wk. Fair (F) can last 10 d to 3 wk. Poor (P) lasts only 7-10 d.

* Results vary greatly among seed sources.

† It is never a good practice to display Christmas trees dry.

unless applied at levels sufficiently high to render trees qualitatively less acceptable to consumers by making them sticky. However, minor differences sometimes occur. For example, drying of eastern red cedar was slowed by latex colorant, but the overall drying rate of trees was so fast that the difference was of little practical significance.

Species Comparisons

Some Christmas tree species maintain postharvest quality better than others. Based on various experiments and observations by the authors, a rating of the postharvest quality of 30 species of Christmas trees is given in table 1. Ratings in this table should be used as a guide, given that the postharvest quality of cut Chrismas trees can be affected by preharvest and postharvest environmental factors and can vary between different seed sources within a species.

The postharvest period has two phases: the period between cutting and placement back in water and the period after placement in water. Some trees endure well in both phases, such as noble fir and Fraser fir. Others do poorly when displayed dry but endure well in water, such as white spruce and grand fir. Some species have a short shelf-life whether displayed wet or dry, such as eastern red cedar, and are not suited for wholesale marketing or long-term display in the home. Many of the true firs have excellent quality when displayed in water but tend to shed needles when displayed dry, such as Nordmann fir.

Tree Handling Recommendations for Growers and Retailers

Cut Christmas trees can deteriorate under the effects of heat, wind, sunlight, and extreme changes in temperature. Thus, reducing exposure to these elements should be the goal of every grower and retailer. Below is a series of recommendations that should ensure consumers get the freshest tree possible:

- In warm climates, harvest trees as late in the season as possible to allow for cold hardening, which will improve keepability after harvest.
- Bale trees soon after cutting, especially if the weather is sunny and warm. Drying can be very rapid in the first 24 h.
- Temporarily store trees in areas that are shaded and cool. Trees can be stored either vertically (standing on the end of the trunk) or horizontally (piles or pallets). It is not clear if one method is better than the other; however, under some conditions horizontal stacking can lead to increased mold problems and damage to foliage and branches. Limiting the height of storage piles and thus reducing the compaction of trees helps minimize these problems.
- Avoid baling wet trees under warm temperatures because doing so can lead to premature needle loss.
- Ship or sell trees on a “first in, first out” basis.
- Avoid piling baled trees on hot parking lots or against south-facing brick or concrete walls.
- The best storage condition is low temperature of 33 °F to 50 °F (1 °C to 10 °C), high RH of 85 to 95%, and darkness.
- Use refrigerated trucks, if possible, especially on hauls exceeding 400 miles or when moving trees into warm regions. For long-distance shipment and storage in refrigerated trucks and containers, trees should be loaded and baffled to allow for air circulation on top, bottom and sides and refrigeration systems should be run on wet cycles so they do not dehydrate the trees.
- Never allow closed vans or flatbeds to sit idle in the sun for extended periods because it quickly leads to overheating.
- In warm marketing areas, trees should be displayed under shade, protected from the wind, and standing in water.
- On retail lots, store trees upright or in shallow piles in a shady, cool place out of high traffic areas. If permanent shade is unavailable, use a tarp or shade cloth

suspended above the trees and down the sides with at least a 2-ft (61 cm) air-space for ventilation.

- Minimize or eliminate walking on baled trees because it breaks limbs and leaders and crushes foliage. Be especially careful handling frozen trees: They are very brittle.
- Trees on display in retail lots in warm market areas can be misted or sprayed with water at night to reduce the moisture lost during daylight hours. Misting trees on the surface of storage piles may also be beneficial, but soaking trees can result in severe mold and deterioration problems.
- Trees hauled long distances on open trucks should be smoke-tarped on the front and covered with shade cloth on the top and sides to prevent windburn and damage from diesel smoke.
- Avoid temperatures above 10 °C (50 °F) in closed storage.
- In cold-weather market areas, protect trees from drying winds. Do not attempt to sell trees such as coastal Douglas-fir in these types of markets unless they can be protected from exposure to potentially damaging temperatures.

References

Chastagner, G.A. 1990. Insect contaminants—a problem that is limiting the market for Pacific Northwest trees. Pacific Northwest Christmas Tree Association., Northwest Lookout 23(3):72-74.

Montano, J.M., and W.M. Proebsting. 1986. Storage of cut Douglas-fir: relationship to the damage threshold. HortScience 21:1174-1175.

Further Reading

AMS [U.S. Department of Agriculture, Agricultural Marketing Service]. 1989. United States standards for grades of Christmas trees. U.S. Department of Agriculture, Washington, DC.

Ahrens, J.F., and G.R. Stephens. 1975. Effect of harvest date or dry storage on moisture content and flammability of white spruce. Amer. Christmas Tree J. 19(4):13-16.

Ahrens, J.F., and G.R. Stephens. 1975. The effects of additives on freshness and flammability of Christmas trees. Connecticut Agricultural Experiment Station Bull. no. 760, New Haven, CT.

Blankenship, S.M., and L.E. Hinesley. 1990. Tolerance of controlled atmosphere storage of cut Fraser fir and its respiration rate in air. HortScience 25:941-943.

Chastagner, G.A. 1984. Moisture levels in Douglas-fir Christmas trees on retail lots in Washington and California. Pacific Northwest Christmas Tree Assoc., Northwest Lookout 17(3):10-14.

Chastagner, G.A. 1985. Research on Christmas tree keepability. Amer. Christmas Tree J. 29(4):31-35.

Chastagner, G.A. 1986. Effect of postharvest moisture stress on the keeping qualities of Douglas-fir Christmas trees. HortScience 21:485-486.

Chastagner, G.A. 1987. Trees of the future: tree keepability research needs. Amer. Christmas Tree J. 31(2):30-34.

Chastagner, G.A. 1989. Maximizing your sales by keeping cut trees fresh. California Christmas Tree Assoc. Bull. 35:12-19.

Chastagner, G.A. 1991. How were these superior trees developed? Pacific Northwest Christmas Tree Assoc., Northwest Lookout 24(2):36.

Chastagner, G.A., and R.S. Byther. 1984. Postharvest moisture stress and the keeping qualities of Douglas-fir Christmas trees. Pacific Northwest Christmas Tree Assoc., Northwest Lookout 17(3):29-34.

Chastagner, G.A., and R.S. Byther. 1984. Impact of Swiss needle cast on postharvest hydration and needle retention of Douglas-fir Christmas trees. Plant Dis. 68:192-195.

Chastagner, G.A., and K. Riley. 1990. Effect of water additives on the postharvest quality of Douglas-fir Christmas trees. California Christmas Tree Assoc. Bull. 141(Oct):6-11.

Chastagner, G.A., and K. Riley. 1991. Effect of foliar sprays of antitranspirants on the postharvest quality of Douglas-fir Christmas trees. California Christmas Tree Assoc. Bull. 143:36-40.

Davis, T.S., and T.A. Fretz. 1972. The anti-transpirant effect on harvested Christmas trees. Amer. Christmas Tree J. 16(1):3-5.

Dugle, J.R. 1986. Growth and morphology in balsam fir: effects of gamma radiation. Can. J. Bot. 64:1484-1492.

Griffiths, M. 1994. Index of Garden Plants: The New Royal Horticultural Society Dictionary. Timber Press, Portland, OR.

Hinesley, L.E. 1984. Measuring freshness of cut Fraser fir Christmas trees. HortScience 19:860-862.

Hinesley, L.E. 1988. Water relations of cut eastern redcedar Christmas trees. HortScience 23:589-591.

Hinesley, L.E. 1990. Grower postharvest handling of Christmas trees. Christmas Tree Notes, CTN-015, North Carolina Cooperative Extension Service, Raleigh, NC.

Hinesley, L.E. 1990b. Latex colorant slows drying of redcedar Christmas trees. HortScience 25:673-674.

Hinesley, L.E., and S.M. Blankenship. 1991. Attributes of water additives affect postharvest needle retention of Fraser fir. HortScience 26: 569-570.

Hinesley, L.E., and S.M. Blankenship. 1991. Effect of water additives on Fraser fir needle retention. HortTechnology 1:90-91.

Hinesley, E., and G. Chastagner. 1993. Common myths and questions: the handling and care of cut Christmas trees. Amer. Christmas Tree J. 37(4):16-19.

Hinesley, L.E., and W.T. Huxster Jr. 1991. Retail merchandising of North Carolina Fraser fir. Christmas Tree Notes, CTN-017, North Carolina Cooperative Extension Service, Raleigh, NC.

Hinesley, L.E., and L.K. Snelling. 1991. Vapor pressure deficit, temperature and light affect postharvest drying of Fraser fir and eastern white pine. HortScience 26:402-405.

Hinesley, L.E., and L.K. Snelling. 1993. “Crop-Life” does not slow postharvest drying of Fraser fir and eastern redcedar. HortScience 28:1054.

Hinesley, L.E., and L.K. Snelling. 1993. Gamma radiation unpromising as insect quarantine treatment for Fraser fir branches. HortScience 28:1109-1110.

Hinesley, L.E., and L.K. Snelling. 1994. Postharvest drying of Leyland cypress, eastern red cedar, and Fraser fir Christmas trees. HortScience 30:1427-1428.

Hinesley, L.E., and L.K. Snelling. 1997. Postharvest drying and rehydration of Leyland cypress, Atlantic white cedar, Virginia pine, Arizona cypress and eastern white pine Christmas trees. HortScience 32:1252-1254.

Hinesley, L.E., L.K. Snelling, and S. Goodman. 1992. Rehydration of Fraser fir Christmas trees: effect of time since cutting. HortScience 27:930.

Hummel, R.L. 1996. Cold hardiness and dormancy. Amer. Christmas Tree J. 40(2):24-26.

Koelling, M. 1998. Christmas trees do not cause fires: some facts! Amer. Christmas Tree J. 42(4):4,6,8,10,12,14,16,18-21.

Kubiske, M.E., M.E. Abrams, and J.C. Finley. 1990. Keepability of Pennsylvania versus West Coast grown Douglas-fir Christmas trees: genotypic variation in relation to subfreezing temperatures. Northern J. Appl. For. 7:86-89.

McKinley, C.R., and L.E. Hinesley. 1995. Handling Christmas trees on retail lots. Christmas Tree Notes, CTN-026, North Carolina Cooperative Extension Service, Raleigh, NC.

Miller, D.R., and W.T. Bagley. 1970. Christmas tree flammability. Amer. Christmas Tree J. 14(4):9-12.

Mitcham-Butler, E.J., L.E. Hinesley, and D.M. Pharr. 1988. Effects of harvest date and storage temperature on the postharvest needle retention of Fraser fir branches. J. Environ. Hort. 6(1):1-4.

Seiler, J.R., T.J. Nichols, and D.J. Paganelli. 1988. Rehydration characteristics of cut white pine and Norway spruce Christmas trees. HortScience 23:164-166.

Tilton, E.W., and A.K. Burditt Jr. 1983. Insect disinfestation of grain and fruit. *In* E.S. Josephson and M.S. Peterson, eds., Preservation of Foods by Ionizing Radiation, vol. 3, pp. 215-229. CRC Press, Boca Raton, FL.

Cut Flowers and Greens

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Botany and Introduction

Plant materials from a wide range of taxa are grown and harvested as cut flowers or florist greens; these include ferns and lycopods, gymnosperms, and angiosperms. Because of this diversity, these guidelines include a general review of postharvest requirements for cut ornamentals, followed by brief summaries of the requirements of a selection of the most common materials used in commercial floriculture. The references cited are usually the most recent report on a particular crop and therefore provide an entree to the literature that is the basis for the recommendations.

Quality Characteristics and Criteria

Cut ornamentals are complex plant organs, in which loss of quality of stems, leaves, or flower parts may result in rejection in the marketplace. In some ornamentals, loss of quality may result from one of several causes, including wilting or abscission of leaves or petals, yellowing of leaves, and geotropic or phototropic bending of scapes and stems. In evaluating factors that affect the life of ornamentals and how to maximize their market life, it is important first to understand the diverse causes of quality loss.

Growth, Development, and Aging

The whole plant and its individual organs are an integral part of the plant's life cycle. Even when there is no senescence of floral organs or leaves, continued growth can result in quality loss; for example, in spike-type flowers that bend in response to gravity.

Flower Senescence

The early death of flowers and greens is a common cause of quality loss and reduced vase life for many ornamentals. Flowers can be divided into several categories on the basis of their senescence. Some flowers are extremely long-lived, especially in the Asteraceae and Orchidaceae families, while others are short-lived, including many of the bulb crops such as tulip, iris, and narcissus.

Wilting

Extended life for cut ornamentals depends absolutely on a continuing and adequate supply of water. Rapid wilting of shoot tips, leaves, and petals results from an obstruction of the water supply through the cut stems.

Leaf Yellowing and Senescence

Yellowing of leaves and other organs (buds, stems) is commonly associated with the end of display life in some flowers; alstroemeria being an important example (Hicklenton 1991). Leaf yellowing is a complex process that may be caused by a range of different environmental factors.

Shattering

Abscission and loss of leaves, buds, petals, flowers, or even branchlets is a process called "shattering," and it is a common problem in cut flowers and potted plants (van Doorn and Stead 1997). Very often, this problem is associated with the presence of ethylene in the air, but other environmental factors may also be involved.

Factors Affecting Postharvest Quality

Maintaining the freshness of cut flowers and other ornamentals requires an understanding of the factors that lead to their deterioration. A number of these factors are different from those that apply to the edible crops covered in this handbook. Nevertheless, understanding these factors allows us to develop and implement optimum postharvest handling technologies.

Variety

Many commercial cut flowers and cut greens are patented cultivars, characterized by specific attributes such as color, form, disease resistance, and size. Sometimes, breeders fail to consider other commercially important attributes. For example, some of the modern alstroemeria cultivars have wonderful flowers, but their display life is short because of rapid leaf yellowing under commercial conditions. There is relatively little published information comparing the postharvest life of different ornamental cultivars (Van Der Meulen-Muisers et al. 1999).

Preharvest Factors

What goes on in the greenhouse or field is an important determinant of the quality and life of cut flowers and foliage (Celikel and Karaaly 1995). Disease-free plants that were properly irrigated and fertilized will produce flowers that look better and perform better in the vase. However, the large leaves on roses grown under supplementary light with CO_2 fertilization make them more susceptible to postharvest wilting.

Food Supply

Starch and sugars stored in the stem, leaves, and petals provide much of the food needed for cut-flower opening and maintenance. The levels of these carbohydrates are highest when plants are grown in high light with proper cultural management. Carbohydrate levels are, in fact, generally highest in the late afternoon—after a full day of sunlight. However, flowers are preferably harvested in the early morning, because temperatures are lower, plant water content is higher, and a whole day is available for processing the cut flowers.

The quality and vase life of many cut flowers can be improved by pulsing them immediately after harvest with a sugar solution. Pulsing is done by standing the cut flowers in the solution for a short period, usually less than 24 h, and often at low temperature. Typical examples include tuberose, for which storage life and opening are dramatically improved; gladiolus, for which flowers open further up the spike, are bigger, and have a longer vase life; and sweet peas, for which vase life was improved (Ichimura and Suto 1999). Sugar is also an important part of the bud-opening solution used to open bud-cut flowers before distribution (Kuiper et al. 1995) and as part of the vase solution used at the retail and domestic level. Potted plants are able to provide their own food supply through photosynthesis if they are held in adequate light conditions.

Light

The presence or absence of light during storage is generally not a concern except in cases where yellowing of foliage is a problem. The leaves of certain cultivars of chrysanthemum, alstroemeria, marguerite daisy, and other crops can yellow if stored in darkness at warm temperatures. The blackening of leaves of cut *Protea nerifolia* flowers can be prevented by maintaining them in high light or by giving them a sugar pulse. This suggests that the problem is induced by low carbohydrate status in the harvested inflorescence (Bieleski et al. 1992).

Water Supply

Cut flowers, especially those with large leaf areas, lose water and wilt very rapidly. They should be stored above 95% RH to minimize water loss, particularly during long-term storage. Water loss is dramatically reduced at low temperatures, another reason for prompt and efficient cooling of cut flowers and potted plants. Even after flowers have lost considerable water (for example, during transportation or storage) they can be fully rehydrated using proper techniques. Cut flowers will absorb solutions without difficulty providing there is no obstruction to water flow in the stems. Air embolism, plugging with bacteria, plant debris or dirt, and poor water quality reduce solution uptake (van Doorn 1999).

Air embolism. Air embolisms occur when small bubbles of air (emboli) are drawn into the stem at the time of cutting. These bubbles cannot move far up the stem, so the upward movement of solution to the flower may be restricted. Emboli may be removed in many ways; for instance, recutting the stems under water (removing about 2 cm), ensuring that the solution is acid (pH 3 or 4), placing the stems in a vase solution heated to 40 °C (104 °F; warm, but not hot) or in an ice-cold solution (0 °C), placing the stems in deep (>20cm) water, or treating the flowers with a detergent "pulse."

Bacterial plugging. The cut surface of a flower stem releases the contents of the cut cells (proteins, amino acids, sugars, and minerals) into the vase water. These are ideal food for bacteria, yeasts, and fungi, which grow rapidly in the anaerobic environment of the vase. Slime produced by the bacteria, and the bacteria themselves, can obstruct the water-conducting system. This problem must be addressed at every step of the postharvest chain by—

- Using clean water to make postharvest solutions
- Cleaning and disinfecting buckets
- Using white buckets—dirt is easier to see in a white bucket.

Include a biocide in all bucket and vase solutions. $Ca(OCl)_2$, NaOCl, $Al_2(SO_4)_3$, and salts of 8-hydroxyquinoline are commonly used bactericides. An acidic solution also inhibits bacterial growth.

Hard water. Hard water frequently contains minerals that make the water alkaline (high pH). Water movement in flower stems is drastically reduced when the water is of high pH. This problem can be overcome either by removing minerals from the water (by using a deionizer, still, or reverse osmosis system) or by making the water acid (pH ~3.5). Citric acid is commonly used as a safe acidulant.

Water Quality

Chemicals commonly found in tap water are toxic to some ornamentals. Sodium, present in high concentrations in soft water, is toxic to carnations and roses and will cause salt burn (burning of the leaf tips and margins) in potted plants. Fluoride is very toxic to gaillardia (Rajitha et al. 1999), gerbera, gladiolus, roses, and freesia. Fluoridated drinking water contains enough flouride (about 1 $\mu L\ L^{-1}$) to damage these flowers.

Growth Tropisms

Certain responses of cut flowers to environmental stimuli (tropisms) can result in quality loss. Most important is geotropism (bending away from gravity) and phototropism (bending towards light). Geotropism often reduces quality in spike-flower crops like gladiolus, snapdragon, lisianthus, and gerbera because the flowers and spike bend upward when stored horizontally (Philosoph et al. 1995). These flowers should be handled upright whenever possible.

Mechanical Damage

Physical abuse of cut flowers and foliage results in torn petals, damaged leaves, and broken stems. Obvious injuries are undesirable for aesthetic reasons, and disease organisms can more easily infect plants through injured areas. Additionally, respiration and ethylene evolution are generally higher in injured tissues, further reducing storage and vase life.

Horticultural Maturity Indices

Minimum harvest maturity for most cut flowers is the stage at which harvested buds can be opened fully and have satisfactory display life after distribution. Many flowers are best cut in the bud stage and opened after storage, transport, or distribution. This technique has many advantages, including reduced growing time for single-harvest crops, increased product packing density, simplified temperature management, reduced susceptibility to mechanical damage, and reduced desiccation. Many flowers are presently harvested when the buds are starting to open (rose, gladiolus), although others are normally fully open or nearly so (chrysanthemum, carnation). Flowers for local markets are generally harvested much more open than those intended for storage or long-distance transport. Cut foliage is harvested when the uppermost leaves are fully expanded to avoid postharvest wilting of the shoot tips.

Grades, Sizes, and Packaging

The designation of grade standards for cut flowers is one of the most controversial areas in their care and handling. Objective standards such as stem length, which is still the major quality standard for many flowers, may bear little relationship to flower quality, vase life, or usefulness. Weight of the bunch for a given length is a method that has been shown to strongly reflect flower quality. Straightness of stems, stem strength, flower size, vase life, freedom from defects, maturity, uniformity, and foliage quality are among the factors that should also be used in cut flower grading. If used, mechanical grading systems should be carefully designed to ensure efficiency and to avoid damaging the flowers.

Flowers are normally bunched, except for anthuriums, orchids, and some other specialty flowers. The number of flowers in the bunch varies according to growing area, market, and flower species. Groups of 10, 12, and 25 are common for single-stemmed flowers. Spray-type flowers are bunched by the number of open flowers, by weight, or by bunch size. Bunches are held together by string, paper-covered wire, or elastic bands and are frequently sleeved soon after harvest to unitize the bunch, protect the flower heads, prevent tangling, and identify the grower or shipper. Materials used for sleeving include paper (waxed or unwaxed), corrugated card (smooth side towards the flowers), and polyethylene (perforated, unperforated, and blister). Sleeves can be preformed (although variable bunch size can be a problem), or they can be formed around each bunch using tape, heat-sealing (polyethylene), or staples.

There are many shapes of packing containers for cut flowers, but most are long and flat. This design restricts the depth to which the flowers can be packed in the box, and this may reduce physical damage. In addition, flower heads can be placed at both ends of the container for better use of space. With this kind of flower placement, whole layers of newspaper are often used to prevent the layers of flowers from injuring each other. The use of small pieces of newspaper to protect only the flower heads, however, is probably the better practice, since it allows for more efficient cooling of flowers after packing. It is critically important that containers be packed in such a way that transport damage is minimized. Some packers anchor the product by using enough flowers and foliage in the box so that flowers in the package, after banding, are immobilized by the surrounding material. To avoid longitudinal slip, packers in many flower-producing countries use one or more “cleats.” These are normally foam- or newspaper-covered wood pieces that are placed over the product, pushed down, and stapled into each side of the box. Padded metal straps, elastic bands, high density polyethylene blocks, and cardboard tubes can also be used as cleats. The heads of the flowers should be placed 6 to 10 cm (2.4 to 4 in) from the end of the box to allow effective precooling and to eliminate the danger of petal bruising should the contents of the box shift.

Gladioli, snapdragons, and some other species are often packed in vertical hampers to prevent geotropic curvature that reduces their acceptability. Cubic hampers are used for upright storage of daisies and other flowers. A new packaging system uses “proconas”—plastic bases and a cardboard sleeve—to allow transport of flowers upright in water. This system is more expensive than traditional boxes, and less can be packed in it. However, the presence of water may improve flower quality when they are not transported under proper temperature conditions.

Specialty flowers such as anthurium, orchid, ginger, and bird of paradise are packed in various ways to minimize friction damage during transport. Frequently, flower heads are individually protected by paper or polyethylene sleeves. Cushioning materials such as shredded paper and paper or wood wool may be placed between packed flowers to further reduce damage.

Precooling Conditions

By far the most important part of maintaining the quality of harvested flowers is ensuring that they are cooled as soon as possible after harvest and that optimum temperatures are maintained during distribution. Most flowers should be held at 0 to 1 °C (32 to 34 °F). Chilling-sensitive flowers (anthurium, bird of paradise, ginger, tropical orchids) should be held at temperatures above 10 °C (50 °F).

Once packed, cut flowers are difficult to cool. Their high rate of respiration and the high temperatures of most greenhouses and packing areas result in heat build-up in packed flower containers unless measures are taken to ensure temperature reduction. It is therefore necessary to cool the flowers as soon as possible after packing. Individually, flowers change temperature rather rapidly, with half-cooling times of a few minutes. However, individual flowers brought out of cool storage into a warmer packing area will warm quickly and water will condense on the flower. The simplest method of ensuring that packed flowers are adequately cooled and dry is to pack them in the cool room. Although this method is not always popular with packers, and may increase labor cost and slow down packing somewhat, it will ensure a cooled, dry product.

Forced-air cooling of boxes with end holes or closeable flaps is the most common and effective method for precooling cut flowers. Cool air is sucked or blown through the boxes. Care must be taken to pack them so that air can flow through the box and not be blocked by the packing material or flowers. In general, packers use less paper when packing flowers for precooling. The half-cooling time for forced-air cooling ranges from 10 to 40 min, depending on product and packaging. Flowers should be cooled for three half-cooling times, by which time they are 7/8 cool.

If the packages are to remain in a cool environment after precooling, vents may be left open to assist removal of the heat of respiration. Flowers that are to be transported at ambient temperatures can be packed in polyethylene caskets, foam-sprayed boxes, or boxes with the vents resealed. Ice that is used after precooling is only effective if placed to intercept heat entering the carton (that is, it must surround the product), and care must be taken to ensure that the ice does not melt onto flowers or cause chilling damage. Precooling of vertical hampers or proconas presents a particular challenge, but can be achieved using a “tunnel” forced-air cooling system.

Chilling Sensitivity

Some tropical crops such as anthurium, bird of paradise, some orchids, ginger, and many foliage plants are injured at temperatures below 10 °C (50 °F). Symptoms of chilling injury include darkening of the leaves and petals, water soaking of the petals, and in severe cases collapse and drying of leaves and petals. Special care needs to be taken with tropical flowers shipped in a mixed load. The flowers should be packed in plenty of insulating material (an insulated box packed with shredded newsprint, for example). These flowers should not be precooled. If they are to be shipped by refrigerated truck, they should be placed in the middle of the load, away from direct exposure to cooling air.

Ethylene Production and Sensitivity

A number of flowers, especially carnations, gypsophila, and some rose cultivars, senesce rapidly if exposed to minute concentrations of ethylene gas. A number of flowers (such as carnations and sweet peas) produce ethylene as they age, and this endogenous ethylene is involved in the death of the flower. Other flowers, such as snapdragon and delphinium, produce little ethylene themselves, but exogenous ethylene causes flower abscission (or shattering). Concentrations of ethylene above 100 ppb (nL L^{-1}) in the vicinity of sensitive ornamentals can cause damage and therefore should be avoided. Storage and handling areas should be designed not only to minimize contamination of the atmosphere with ethylene, but should also have adequate ventilation to remove any ethylene contamination that may occur. Treatment with the anionic thiosulfate complex of silver (STS) or with 1-methylcyclopropene (1-MCP) inhibits the deleterious effects of ethylene whether a product of atmospheric contaminant (exogenous) or produced by the flower (endogenous) (Macnish et al. 2000). Finally, refrigerated storage is beneficial in that both ethylene production and sensitivity are reduced greatly when temperatures are low.

Optimum Storage Conditions

The vase life of flowers that are stored even for a few days is closely correlated with their respiration during storage. Rapid cooling and proper refrigeration are thus essential to maintaining quality and satisfactory vase life of cut flowers and foliage. The recommended conditions for commercial storage of most cut flowers are 0 to 1 °C (32 to 34 °F) at 95 to 99% RH. Although flowers are commonly held in water for short-term storage, better vase life after longer storage is achieved by storing the flowers dry. Under these conditions, stable temperatures (to reduce condensation and *Botrytis* infection) and high RH are essential. Flowers for longer-term storage are typically wrapped in newsprint (to absorb any condensation) and perforated polyethylene (to reduce water loss). Storage life varies by species but is typically less than 3 weeks.

Controlled Atmosphere (CA) Considerations

There have been relatively few reported benefits of CA storage for cut flowers. Any consideration of the use of CA must follow achievement of proper temperature control and elimination of the effects of *Botrytis* during storage. Recommended atmospheres vary from pure nitrogen (daffodils) to more conventional atmospheres (carnations).

Retail Outlet Display Considerations

The simple way to ensure rapid rehydration of all but the most difficult or desiccated flowers is to recut the stems and place them in a clean bucket of water containing a quality flower preservative solution *in the cooler*. The pH of the preservative solution should be below 5. For badly wilted flowers a rehydration solution may be helpful, since the sugar in vase preservatives reduces the flow of water in stems. Flowers with woody branches respond particularly well to low pH (3.5 is optimal), and some flowers (sunflowers, astilbe) respond well to a 10-min “pulse” with a 0.02% detergent solution. Flower coolers should be <5 °C (41 °F); flowers should be placed in the coolers when not on display or being used for preparing arrangements.

Respiration Rates

Cut flowers have extremely high rates of respiration that increases exponentially with temperature (Cevallos 1998). Various cultivars of the same species may have quite different respiration rates and may respond differently to temperature.

Physiological Disorders

There are relatively few recognized physiological disorders in the postharvest life of cut flowers and foliage. "Topple" of tulips, a collapse of the scape, is a disorder associated with low calcium status of the flowers. Petal blackening in some red roses has been suggested also to be associated with inadequate calcium and perhaps boron nutrition.

Postharvest Pathology

Flowers are very susceptible to disease, not only because their petals are fragile but also because the secretions of their nectaries often provide an excellent nutrient supply for even mild pathogens. Transfer from cold storage to warmer handling areas often results in condensation of water on the harvested flowers. The most commonly encountered disease organism, gray mold *(Botrytis cinerea)*, can germinate wherever free moisture is present. In the humid environment of the flower head, it can even grow, albeit more slowly, at near freezing. Proper greenhouse hygiene management (Hammer and Evensen 1996), temperature control, and minimized condensation on harvested flowers reduce losses caused by this disease.

Quarantine Issues

Export of cut flowers to other markets requires phytosanitary certification. A number of pests on cut flowers are the subject of quarantine regulations in a number of overseas markets. Disinfestation of quarantine insects in cut flowers is the subject of active research.

Suitability as Fresh-Cut Product

There is a small market for edible flowers, and some high-value fresh-cut salads include petals in the mix. Obviously chemicals not registered for food use may not be used in postharvest handling of flowers intended as food.

Special Considerations

Many special considerations that arise from the unique physiology, handling, and marketing of cut flowers and foliage are addressed in the following section for individual crops.

Guidelines for Individual Crops

The following section contains guidelines for individual crops. The content is organized by scientific name and introduction, quality characteristics and criteria, grading and bunching, ethylene sensitivity, pretreatments, storage conditions, packing, and special considerations.

The following individual crops are discussed:

Alstroemeria
Anemone, windflower
Anthurium, flamingo flower
Asparagus fern, lace fern, Sprengeri
Aster, Michaelmas daisy
Baby's breath, gypsophila
Bird of paradise
Bouvardia
Calla lily
Carnation, miniature carnation
Chrysanthemum, florist mum
Daffodil
Delphinium, larkspur
Emerald palm
Eucalyptus, silver dollar tree
Fir, spruce, pine
Freesia
Gerbera, Transvaal daisy
Ginger, shell ginger, torch ginger
Gladiolus, glad
Heliconia, parrot flower
Holly, ilex
Huckleberry
Iris, fleur-de-lis
Leatherleaf fern
Lemonleaf, salal
Liatris, gay feather
Lily of the Nile, agapanthus

Lily, Asiatic lily, Oriental lily
Lisianthus, prairie gentian
Marguerite daisy, Boston daisy
Orchids
Protea, pincushion
Rose, spray rose, sweetheart rose
Snapdragon
Statice, German statice
Stock
Sunflower
Sweet pea
Sweet William
Tuberose
Tulip
Waxflower, Geraldton waxflower
Yellow aster

Alstroemeria

Scientific Name and Introduction

Alstroemeria cvs., hybrids. In the last 30 yr, flowers of various hybrids of species of the genus *Alstroemeria,* variously called alstroemeria, Peruvian lily, or lily of the Incas, have become an increasingly important part of commercial cut flower trade. Flowers come in a variety of types and colors. All have a long postharvest life, typically terminated by petal wilting or drop and yellowing of the leaves. The Swedish Consul in Spain, Klas Alstroemer, had seeds of this species brought to Europe in 1754. The famous plant taxonomist Carl Linnaeus, a friend of Alstroemer, subsequently named the species after him.

Quality Characteristics and Criteria

For long-distance markets, flowers are harvested when the buds are about to open and start to color. For local market, harvest is delayed until the first three flowers have opened. Flowers are pulled off or cut, depending on the variety. Where pulling may damage the underground parts of the plant (as in young plants of ‘Regina’), the stem should be cut. If flowers are cut, the remaining stem should be removed later. At least one flower per stem should be open at time of purchase. Purchase only by cultivar name.

Grading and Bunching

There are no grade standards for alstroemeria, but in addition to the common characters of freedom from damage, stem length, strength, and straightness, it is suggested that the flowers in a bunch should be uniform. The flower head should be symmetrical, and leaves should be bright green. The minimum acceptable number of florets per stem varies with cultivar, but is typically 7 to 10.

Ethylene Sensitivity

Alstroemeria flowers are ethylene sensitive.

Pretreatments

Although untreated alstroemeria flowers have a long vase life, petal drop (particularly a problem if there is ethylene in the environment) can be delayed by pretreatment with 1-MCP or STS. In some cultivars, leaf yellowing occurs before flower senescence; it can be delayed by a pulse treatment with preservative containing growth regulators (gibberellins [Kappers et al. 1998] or cytokinins).

Storage Conditions

Alstroemeria should be stored at 0 to 1 °C (32 to 34 °F). Present information suggests that alstroemeria can readily be stored for up to 1 week at 1 °C (34 °F).

Packing

Alstroemeria are normally bunched in groups of 10, sleeved, and packed in horizontal boxes. Flower pedicels are affected by gravity and will bend upwards if temperature control during storage is poor.

Special Considerations

When recutting, remove the whitish or blanched bottom portion of the stem, if present, for maximum solution uptake and life. Leaf removal will reduce vase life if enough flowers are not present for solution uptake. Since *Alstroemeria* is a member of the Amaryllidaceae, a botanical family from which many pharmaceutical products are derived, it's not surprising that some humans get allergic dermatitis from this species.

Anemone, Windflower

Scientific Name and Introduction

Anemone spp. Brightly colored in deep reds, blues, purples, and white, anemones have rather short stems and are typically a spring flower. New, improved tetraploid varieties have been introduced into commerce (Jacob et al. 1997). Anemone is an ancient Greek name meaning windflower, from *anemos* for wind.

Quality Characteristics and Criteria

Flowers should be harvested when the buds are fully colored and 25 to 50% open, but before the petals have expanded and the pollen is shed. Purchase when true colors are showing.

Grading and Bunching

Anemones are normally sold in bunches of 10 stems.

Ethylene Sensitivity

Ethylene exposure causes petal shatter and reduced vase life.

Pretreatments

Pretreatment with STS or MCP prevents the deleterious effects of ethylene.

Storage Conditions

Anemones should be stored in a vertical position at 0 to 1 °C (32 to 34 °F), and may be dry-stored for at least 1 week.

Packing

Flowers are usually packed in standard horizontal fiberboard boxes.

Special Considerations

The anemone's prominence and beauty in arrangements is a double-edged sword because of the flower's relatively short vase life. It is preferable not to use anemones as focal points. Keep stems wrapped during rehydration to help keep them straight. There is no scientific basis for the practice of piercing a hole through the flower base to extend life. Placing anemones in vases with freshly cut daffodils can reduce their life because of the harmful juices exuded from the daffodils.

Anthurium, Flamingo Flower

Scientific Name and Introduction

Anthurium andraeanum. With their brilliant glossy spathes (the brightly colored ornamental part of the flower) and slender spadices, anthuriums are classic tropical flowers. New cultivars provide a wide range of colors and forms, and their vase life can be very long. The elegant blooms of this tropical aroid are produced and sold throughout the world. The true flowers are found on the spadix, the upright organ in the center of the spathe, which is the decorative petallike organ surrounding the spadix. Although anthuriums are sensitive to low temperatures, they have a long vase life when properly handled. The end of their vase life is usually the result of inability to draw water from the vase solution and is associated with loss of glossiness and then blueing of the spathe. Most of the water lost by the flower evaporates from the spadix. Application of wax to prevent this water loss or pulsing with silver nitrate to improve water relations of the flower can extend their vase life considerably. Anthurium is also known as "tailflower."

Quality Characteristics and Criteria

Maturity of anthurium flowers is determined by the proportion of open flowers on the spadix. In immature anthuriums, the spadix is smooth. Flower opening starts at the base of the spadix and proceeds upwards. Spadices with open flowers are noticeably rough. Although producers in some countries harvest anthuriums when as little as 20% of the spadix is rough, Hawaiian growers harvest flowers when only 25% of the spadix is still smooth (75% of the flowers are therefore open). Harvesting anthuriums when more mature increases overall vase life. Avoid flowers that show any signs of chilling injury (purpling of the spathe, browning or wilting of the spadix). For maximum life, flowers should be purchased when the spadix, the slender "tail" of the flower, is 50 to 75% rough. The spadix is the true inflorescence of the anthurium, and the rough mature flowers are easily distinguished from the smooth, immature flowers.

Grading and Bunching

Although there are no formal grade standards for anthuriums, top quality implies long stems, uniformity of color and size, proper maturity, glossiness of the spathe, and freedom from any damage or disease. Anthuriums are normally packed individually.

Ethylene Sensitivity

Anthuriums are not affected by exposure to ethylene, and anti-ethylene treatments provide no benefit.

Pretreatments

Some researchers recommend pretreatment to increase the vase life of anthuriums, but some cultivars (such as 'Osaki') achieve maximum vase life with DI alone. It seems probable that vase-life problems are associated with bacterial contamination of the cut stem bases. If anthuriums are placed in water after harvest, a biocide such as 50 µL L^{-1} hypochlorite should be added. One of the following methods should be used:

- Pulse the recut stems for 10 to 20 min in 1,000 µL L^{-1} silver nitrate. Rinse stems with fresh water after treatment.
- Dip the whole flower in an emulsion of carnuba wax. Use a 3% dilution of the wax. After dipping, place flower stems in water while the wax dries.

Storage Conditions

Anthuriums should be stored at 12.5 to 20 °C (55 to 68 °F) because they are very sensitive to chilling injury (Pritchard et al. 1991). Holding the flowers for any length of time at temperatures below 10 °C (50 °F) will induce purpling, then browning, and then death of the flowers. Anthuriums should therefore never be precooled with other flowers nor held in low-temperature cool-rooms. Anthuriums shipped in mixed loads at low temperatures should be protected from chilling exposure by appropriate insulation (for example, wrapping the flowers in newsprint and packing them in an insulated box). Anthurium flowers can be stored for at least 1 week if packed in moist shredded newsprint and held at 15 °C (59 °F). They also respond favorably to storage in controlled atmosphere. Vase life after storage was increased by 50% when flowers were stored at 12.5 °C (55 °F) in 2% O_2 for up to 2 weeks.

Packing

Anthuriums are commonly packed in moist shredded newsprint or other shredded paper. Major damage during transportation is the result of spadices puncturing the spathe of neighboring flowers in the pack. Many producers now sheathe the flowers in small plastic bags and pack the anthuriums more densely in the box.

Special Considerations

Anthuriums can have a vase life of up to 3 weeks if properly treated. Even after storage, vase life can be adequate if proper techniques are used to handle the flowers. They are very susceptible to stem blockage and easily bruised because of mechanically induced injuries, especially during packing and unpacking. Keep holding solutions clean by using an effective preservative solution.

Asparagus Fern, Lace Fern, Sprengeri

Scientific Name and Introduction

Asparagus spp. Asparagus fern *(A. setaceus* and other species in the genus *Asparagus)* is probably better known in the floral trade as *A. plumosus* or plumosus fern. It provides an interesting foliage and filler for arrangements. These species are not true ferns but are members of the lily family, in the same genus as edible asparagus. The *Asparagus densiflorus* "Sprengeri" group is another common foliage used as a filler.

Quality Characteristics and Criteria

As with other foliage, asparagus fern should be harvested when the fronds are fully mature; immature tips are very likely to wilt after harvest. Make sure that the fronds are mature and uniformly green, that there are no yellow leaves, and that leaves do not fall from the fronds when they are shaken.

Grading and Bunching

There are no formal grade standards for asparagus fern, but fronds should be intact and of uniform length, maturity, and color. Fronds are frequently bunched in groups of 20 and not normally placed in sleeves.

Ethylene Sensitivity

Exposure to ethylene will cause leaf-fall in some species of asparagus fern, and therefore pretreatment with 1-MCP or STS is beneficial.

Pretreatments

Because ethylene exposure will cause accelerated leaf fall, treatment with 1-MCP or STS is recommended.

Storage Conditions

Store asparagus ferns at 0 to 1 °C (32 to 34 °F), wrapped in polyethylene to reduce drying during storage. The fern should be cooled before being wrapped in polythene.

Packing

Because of their relatively low value, asparagus and other ferns are packed densely in boxes—usually horizontal boxes that are filled as full as possible. This places an additional emphasis on the importance of precooling; but no paper or plastic is used, which permits reasonably effective forced air cooling.

Special Considerations

Asparagus fern suffers from premature leaf fall. Induced primarily by water stress, this can be a serious problem. To avoid yellowing and leaf fall, avoid prolonged storage. Certain preservative solutions aggravate premature leaf yellowing.

However, preservative should be used in all arrangements containing this fern, as other items in the arrangement will benefit.

Aster, Michaelmas Daisy

Scientific Name and Introduction

Aster spp. The family Asteraceae and the genus *Aster* include numerous species and cultivars used in horticulture. *A. ericoides* 'Monte Casino' is particularly important in the florist trade. Another important aster for florists is the China aster, *Callistephus chinensis*.

Quality Characteristics and Criteria

As with most members of the Asteraceae, immature flowers (ones harvested too early) will generally not open properly. Purchase as you would purchase chrysanthemums, more open (at least 75% open) than in a bud stage. Avoid specimens with yellowing leaves as this is an indication of improper storage and/or growing conditions.

Grading and Bunching

There are no grade standards as such, apart from the standard quality attributes of stem length, foliage quality, uniformity, and freedom from defects. Depending on species and cultivar, bunches may be prepared by stem number (China aster, for example) or by bunch size ('Monte Casino' aster, for example).

Ethylene Sensitivity

Members of the Asteraceae are generally unaffected by exposure to moderate concentrations of ethylene.

Pretreatments

The vase life of asters is often limited by poor water relations, demonstrated by wilting of the flower or buds. Their vase life has been shown experimentally to be extended by a 10-sec pretreatment with a high concentration (1,000 $\mu L\ L^{-1}$) of silver nitrate, which is a very effective germicide.

Storage Conditions

Store asters at 0 to 1 °C (32 to 34 °F).

Packing

Asters are packed in traditional flower boxes, hampers, or proconas.

Special Considerations

It is very difficult to make broad flower care recommendations for asters because of the large number of species and cultivars. Keep stems and vase solution clean. It is especially important with asters to remove leaves that might be in the water since bacteria grow quickly on leaves that are underwater, contaminating the vase solution and leading to early wilting. Treat with a hydrating solution, and prepare the preservative solution properly to minimize contamination by debris and microorganisms.

Baby's Breath, Gypsophila

Scientific Name and Introduction

Gypsophila paniculata. A favorite for use in bouquets and dried flower arrangements, gypsophila is most often field-grown. The flowers are sensitive to water deficit and intense sunlight and will brown and shrivel easily if subjected to these stress conditions. On the other hand, damp or rainy conditions increase the risk of gray mold *(Botrytis)* and *Phytophthora* root rot. *Gypsophila* is Greek for “gypsum-loving,” in reference to this species’ good growth performance in high-calcium soils.

Quality Characteristics and Criteria

Gypsophila plants produce flowers on large panicles whose individual flowers open over a considerable time period. Flowering stems are usually cut 20 to 40 cm (8 to 16 in) long. The degree of maturity at harvest is determined by whether the flowers are intended for the fresh market or for dried arrangements. Stems are cut when 50% of the flowers are open if they are to be placed in a drying solution immediately or marketed within 24 h. Stems are cut when 20 to 30% of the flowers are open if they are to be dried later or held longer than 24 h. Purchase gypsophila that has plenty of unopened buds and shows no signs of water stress, wilting, or disease (brown florets).

Grading and Bunching

Stems are gathered into field bunches using rubber bands or ties to secure the cut ends. Bunches from California are sold as growers’ bunches with 5 to 25 stems, whereas gypsophila from South America comes in bunches weighing 300 g.

Ethylene Sensitivity

Exposure to ethylene causes wilting of open flowers and sleepiness of opening buds.

Pretreatments

Gypsophila responds best to pretreatment with STS, which protects not only open florets but also the developing buds (Newman et al. 1998). Gypsophila flowers treated with STS and held in a solution containing Physan will maintain excellent display life for several weeks as new buds open on the panicle. However, STS sometimes is of little benefit because stem blockage prevents uptake. Be sure stems are rinsed and recut underwater before placement in STS.

Storage Conditions

Store at 0 to 1 °C (32 to 34 °F) in high (90%) RH to reduce flower and stem desiccation. Because botrytis can be a serious problem, florists should ask suppliers (or be prepared themselves) to treat with appropriate fungicides. Stems with about 50% of their flowers open can be kept in a preservative solution (200 µL L^{-1} Physan) at 1 °C (34 °F) for up to 3 weeks.

Packing

Gypsophila may be packed in horizontal boxes or hampers. Thirty bunches are packed in a standard box.

Special Considerations

Gypsophila harvested in the bud stage (5% of flowers open) can be opened to excellent quality in a bud-opening solution containing 200 µL L^{-1} Physan-20 and 5 to 10% sucrose. Flowers should be held at about 20 °C (68 °F) and 50% RH and with light levels of about 15 mmol m^{-2} sec^{-1} PAR (use cool-white fluorescent lamps). For drying gypsophila, a solution containing 1 part glycerine to 2 parts water should be used. Cut stems are then dried by hanging bunches upside down in a warm dry environment.

Bird of Paradise

Scientific Name and Introduction

Strelitzia reginae. The bird of paradise inflorescence consists of a boat-shaped bract containing a series of four or five flowers, so when an exposed flower withers, another one can be pulled out. Few cut flowers have this capability. Traditionally, Southern California growers bag the inflorescence a few weeks before harvest. Slender, elongated waxed paper bags are placed over the expanding bracts a week or more before the orange flowers are ready to emerge. The bags protect the brittle flowers by holding them inside or next to the bracts. The bag also helps prevent *Botrytis* mold, rain and hail damage, aphid attacks, and sunburn of the flowers. The specific epithet "reginae" means "queen."

Quality Characteristics and Criteria

Inflorescences bend as they reach maturity, assuming a 90° angle to the stem. The first emerging orange flowers can barely be seen through the paper bags. The stems are pulled at this point. Stems can also be harvested in the tight bud stage before the first flowers emerge. At this stage the inflorescence is swollen, and there is a slight orange crack on the upper surface. The inflorescence is mature at the tight bud stage, and this is the optimum stage for harvest from the point of view of ease of handling and flower longevity. Flower stems are generally pulled off rather than cut. A side to side pulling motion is often necessary to loosen the stem at the base of the plant, although the inflorescences can break off if jerked too vigorously. Make sure flower heads are dry at time of purchase. If flowers are wet or have excessive nectar exudation upon unpacking, then the possibility of subsequent disease problems is increased.

Grading and Bunching

Strelitzia stems are sorted into at least three grades according to stem length and inflorescence size. For premium grade flowers, the field bags are replaced with new bags. Five stems are firmly tied together at two points, with the inflorescences facing in the same direction. The stem ends are evenly trimmed. A paper wrapper is placed around the bunched inflorescences to further protect the flowers.

Ethylene Sensitivity

Strelitzia flowers are insensitive to ethylene and their life is not improved by treatment with STS or 1-MCP.

Pretreatments

Flower longevity can be substantially increased by pulsing buds or flowers for 24 h (48 h is even better) with a solution containing 10% sucrose, 250 µL L^{-1} 8-hydroxyquinoline citrate (8-HQC), and 150 µL L^{-1} citrate (Halevy et al. 1978).

Storage Conditions

The optimum long-term storage temperature range for this species is 6 to 7 °C (43 to 45 °F), which is different from most other flowers. Storage below this recommended range can result in chilling disorders, the appearance of brown lesions on the flowers and bracts, and the failure of the flower to open properly. For short-term storage, hold the flowers at room temperature or in a tropical storage room at 12.5 °C (55 °F). *Strelitzia* flowers harvested in the tight bud stage will open and have satisfactory vase life after 4 weeks in storage if pretreated with a fungicide, wrapped to prevent desiccation, and stored at 7 °C (45 °F) and 85 to 90% RH.

Packing

Waxed paper bags on each inflorescence and the paper wrapper on each bunch give ample protection from handling injury and desiccation. Because they are very heavy, *Strelitzia* stems should be packed in shallow cartons.

Special Considerations

If flowers do not emerge from the spathe (modified leaf below the flower), the first flower can be gently eased out by hand and will normally provide good display life.

Bouvardia

Scientific Name and Introduction

Bouvardia spp. Bouvardia flowers are a relatively recent addition to the florist's palette. Their bright salmon, red, and white color range and interesting flower form offer interesting design possibilities. The genus is named after Charles Bouvard (1572-1658) who was physician to Louis XIII and superintendent of the Royal Gardens in Paris.

Quality Characteristics and Criteria

Bouvardia flowers are normally harvested with two to three outer flowers open. Purchase when one or two flowers are open on each stem. Avoid flowers that have yellowed foliage or are showing signs of wilting. If the flowers have been pretreated to prevent the effects of ethylene, there should be little shattering when the flower bunch is shaken.

Grading and Bunching

There are no formal grade standards for bouvardia, but top quality flowers will be uniform in maturity and color, free of defects, and have good quality foliage and long stems. Flowers are normally bunched; bunches contain 10 stems and are sleeved prior to packing.

Ethylene Sensitivity

Accelerated wilting and abscission result from exposure of flowers to ethylene.

Pretreatments

Because of their ethylene sensitivity, bouvardia flowers should be pretreated with 1-MCP or STS. Research has shown STS to be the superior pretreatment because it protects not only open flowers but also the developing buds from the effects of ethylene. Treatment for 4 to 24 h with water containing detergents such as Agral LN or Nonoxynol-8.5 prior to dry storage prevents early wilting of the flowers (van Doorn et al. 1993).

Storage Conditions

Although previous recommendations have been to store bouvardia at 7 to 10 °C (45 to 50 °F), this species is not chilling sensitive and therefore should be stored, like most temperate cut flowers, at 0 to 1 °C (32 to 34 °F).

Packing

Bouvardia may be packed in horizontal boxes or proconas.

Special Considerations

Bouvardia exhibits leaf yellowing and is wilt sensitive. In some markets a special preservative formulation is sold that can reduce leaf yellowing. Recut stems underwater and use good sanitation procedures to reduce the frequency of wilted flowers. Postharvest performance differs greatly among the many cultivars marketed.

Calla Lily

Scientific Name and Introduction

Zantedeschia spp. The striking white blooms of *Zantedeschia aethiopica* have long been an important cut flower, and new green-tinged and differently shaped variants are increasingly important. The hybrid "minicallas," with their elegant shape and wide range of colors, continue to increase in importance as cut flowers and potted plants. The showy spathe is a leaflike organ that surrounds the true flowers—the thick, fleshy spadix. The genus is named for Francesco Zantedeschia, who wrote about Italian plants around 1825. Although often called calla lilies, these flowers are not related to the true lily.

Quality Characteristics and Criteria

Callas should be harvested when the spathe has opened enough that the spadix can be seen. Flowers harvested more mature will be more susceptible to damage and may have reduced vase life. The flowers are normally pulled from the rhizome and recut to ensure adequate water uptake. The spadix (the thick fleshy inflorescence inside the showy spathe) should be visible at the time of purchase. Watch for bruising of the fleshy stems due to packaging. If cut too tight, flowers will usually not open properly.

Grading and Bunching

Quality callas have long stems, are uniform in maturity and color, and have no defects such as damage to the spathe or spadix. Both large and mini callas are normally bunched in groups of 10. Minicallas are sometimes sleeved to provide additional protection.

Ethylene Sensitivity

Calla flowers are not ethylene sensitive, although some researchers have shown positive effects of STS pretreatment. Contrary to popular belief, callas do not produce significant quantities of ethylene.

Pretreatments

Callas do not require any pretreatments.

Storage Conditions

Callas should be stored at 0 to 1 °C (32 to 34 °F).

Packing

The flowers may be packed horizontally or in upright hampers or water packs. If they are packed horizontally, avoid direct contact with cleats, which may damage the fleshy stems. Standard callas may bend in response to gravity unless held at the proper storage temperature.

Special Considerations

The minicallas have fewer postharvest problems and are generally easier to handle and use because of their smaller size.

Carnation, Miniature Carnation

Scientific Name and Introduction

Dianthus caryophyllus. Long one of the most important of the commercial cut flowers, the carnation has benefited enormously from the use of STS, which can increase its vase life 2- to 3-fold. The wide range of colors and forms, especially for miniatures, allows florists and consumers to use and enjoy them in many ways. The genus name, *Dianthus,* derives from the Greek for “flower of love.” Carnations used to be called “clove gilly-flowers” in reference to their intense clovelike aroma. Some modern cultivars are very fragrant and are used to make perfumes. Carnations can be stored longer than any other flower and can be opened to high quality flowers from very tight buds. Miniature carnations are also referred to as spray carnations.

Quality Characteristics and Criteria

The maturity at which carnations are harvested depends on the proposed marketing procedure. Star-stage buds are too immature for most purposes except long-term storage. Buds at the “paint-brush” stage, with petals straight up, will open quickly. Flowers for immediate use are normally harvested with the outer petals between vertical and horizontal. To minimize spread of disease, avoid harvesting from plants with obvious disease symptoms. Many pickers place cut flowers on top of wires for later collection into bunches. Flowers collected into canvas slings can be taken to the shed by mechanical devices ranging from overhead cables to tractor-hauled trailers designed to hold slings. Standard carnations ship better and last longer if purchased in the bud stage, while miniature carnations should be purchased when at least one flower per stem is open. Fragrant cultivars have more consumer appeal.

Grading and Bunching

Both standard and miniature carnations are graded by stem strength, stem length, bloom diameter, and freedom from defects. Stem strength is determined by holding the stem horizontally at a point one inch above the minimum length for the grade. If the deviation of the flower head is more than 30° from horizontal (with the natural curvature down), the flower is considered defective. Other defects include slabsides, bullheads, blown heads, singles, sleepy appearance, splits, discoloration, and damage from insects and diseases. Standard carnations are bunched and tied at the base and at least one other place below the flower heads. Instead of different colored labels, some growers indicate different grades by color or number of rubber bands on the bunches. Standards for miniature carnation bunches vary; a bunch normally contains a minimum of 30 buds total, at least 7 of which are open. With standard carnations, flower heads may be alternated (five high and five low) at the top of the bunch to produce a neat and compact bunch and reduce the risk of the neck breaking.

Ethylene Sensitivity

Carnations are ethylene sensitive, and exposure to ethylene causes premature petal wilting referred to as “sleepiness.” Some newer cultivars are less sensitive to ethylene than the standard ‘Sim’ types, and carnations have now been genetically modified by the addition of a mutation of the ethylene-binding site that makes them insensitive to ethylene (Bovy et al. 1999).

Pretreatments

Carnation flowers must be pretreated with 1-MCP or STS. Research shows that the effectiveness of 1-MCP is lost within a week at room temperature but is retained for extended periods when carnations are held at low temperatures. Pulsing the treated flowers overnight with a preservative containing 10% sucrose improves flower opening, and quality carnation buds can be opened at room temperature and under normal room lighting in a solution containing 7% sucrose and 200 µL L^{-1} Physan. The buds should have been treated first with 1-MCP or STS.

Storage Conditions

Carnations should be stored at 0 to 1 °C (32 to 34 °F). Bud-harvested flowers perform best in storage because they are less sensitive to ethylene than mature flowers. Flowers or buds for storage should be of the highest quality and absolutely free of pests and diseases. They should be treated with 1-MCP or STS and a fungicide for botrytis control then packed in a box lined with polyethylene and newspaper. Open flowers can be stored 2 to 4 weeks, while bud-cut flowers can be safely stored up to 4 to 5 weeks. There are methods available for storing buds for up to 4 mo.

Packing

Carnations are usually packed in standard horizontal fiberboard boxes.

Special Considerations

Spray carnations do not always respond well to STS because the different flower maturities do not take up the STS solution equally. It is difficult to recognize water-stressed carnations, but severe reduction in vase life is the result; so keep them hydrated when held above 0 to 1 °C (32 to 34 °F).

Chrysanthemum, Florist Mum

Scientific Name and Introduction

Dendranthema × grandiflorum. Less important than formerly, but still an important cut flower, chrysanthemums (which come in a wide range of colors and forms, including standard and spray, or pompon) have a long postharvest life when properly handled. The chief postharvest problems in these flowers are failure to draw water (which results in premature leaf wilting) and leaf yellowing. Chrysanthemum is Greek for "golden flower."

Quality Characteristics and Criteria

Standard chrysanthemums are normally harvested fully open, or nearly so, and pompons are harvested with the most mature flowers fully open. Harvesting too early may result in failure of the flowers to open. However, chysanthemums can be harvested as quite tight buds and opened satisfactorily with simple bud-opening solutions. Bud-cut standards can be harvested when the inflorescence is about 5 cm (2 in) across or greater and opened into full-sized flowers. Spray varieties can be harvested when most of the petals on the most mature flower are still upright. The flowers can be opened after storage or transportation.

Stems should be cut (with a knife or shears) at least 10 cm (4 in) above the soil line to avoid taking woody plant tissue. Pinched spray chrysanthemums can be pulled from the soil and then cut to correct length. Leaves are removed from the lower third of the stems. Proper rehydration is vital for good vase life of chrysanthemums that have been stored or shipped long distances. Remove chrysanthemum bunches from the boxes, recut stems to remove about 2.5 cm (1 in), and place in a good rehydration solution. Educate workers and customers to accept flowers that are from two-thirds to three-quarters open, as these flowers will last longer than ones harvested when tighter.

Grading and Bunching

Standard chrysanthemums are graded by length and packed individually. Spray types are graded by length and bunched. Standards or disbuds of equal sizes are graded into groups of 10 or 12. Each bunch of 5 to 8 spray chrysanthemums should be sleeved with plastic to prevent flowers from becoming entangled. Standards and spider mums can be wrapped individually with thin wax paper to avoid bruising and entangling florets. Some growers place nets over spider mums in the greenhouse before the buds open.

Ethylene Sensitivity

Chrysanthemums are not sensitive to ethylene.

Pretreatments

Stems should be placed in a rehydration solution or in water containing a germicide soon after harvest if they are not to be packed immediately (van Meeteren and van Gelder 1999). Immersion in solutions of the cytokinin 6-benzyl adenine has been shown to be effective in preventing premature leaf yellowing in some spray cultivars that are prone to this problem. This treatment is not yet used commercially. Bud-harvested flowers can be opened in fresh-flower solutions containing 2 to 3% sugar (higher concentrations damage leaves) at 15 to 20 °C (59 to 68 °F) with 16 h per day of normal room-intensity light. Physan is a common, effective germicide, but it discolors the stem portion in the solution; therefore, only 3 to 8 cm (1.2 to 3.2 in) of solution should be used. After the buds are open, the injured portion of the stem can be removed. Silver nitrate at 25 $\mu L\ L^{-1}$ plus citric acid at 75 $\mu L\ L^{-1}$ is very effective but more expensive to use than Physan. Silver nitrate is, however, absorbed into the stem and becomes a lasting germicide throughout the life of the flower.

Storage Conditions

Chrysanthemums should normally be stored at 0 to 1 °C (32 to 34 °F). Bud-cut standard chrysanthemums harvested when the bud is 1.2 cm (3 in) across can be stored up to 2 weeks, and 1.6-cm (4-in) buds for up to 3 weeks, at 0 to 1 °C (32 to 34 °F). Bud-cut stems that are held in cold storage beyond the recommended time can develop flat-topped flowers. Fully mature blooms can be stored dry (wrapped in polyethylene) for 3 to 4 weeks at 0 °C (32 °F). Storage at 0 to 1 °C (32 to 34 °F) should not exceed 2 weeks. Yellowing of leaves can occur at 5 °C (41 °F) in the dark, but is less likely at 1 °C (34 °F).

Packing

Chrysanthemums are normally packed in standard horizontal fiberboard boxes. Standards are packed individually, and a layer of wax paper often separates each row of flowers.

Special Considerations

The main postharvest problems for chrysanthemums are premature foliage yellowing, wilting, and the failure of the flowers to fully open. Yellow foliage is cultivar specific and is caused by poor production, excessive or improper storage, and preservative solutions used at higher than recommended concentrations. The bottom portion of some mum stems can be woody; make sure these stems are cut above this woody tissue in order to facilitate water uptake, delay wilting, and extend end-user life.

Daffodil

Scientific Name and Introduction

Narcissus cvs. daffodils—symbol of spring and known for their bright yellow, orange, red, pink, and white colors—are garden favorites world wide. Unfortunately, these flowers have relatively short vase life that cannot as yet be increased substantially with standard postharvest treatments. Narcissus is a classical Latin name, from the Greek; perhaps, as the origin suggests, an allusion to narcotic properties. It is not clear whether it was named after the youth Narcissus in mythology.

Quality Characteristics and Criteria

Daffodils are normally harvested at the "goose-neck" stage. Jonquils are often harvested at the "one-bell" stage, when only one flower is open on the spike. Harvesting is normally done by cutting the flower from the foliage and bulb, although the whole plant may be removed and the bulb and leaves then cut from the flower spike. Flowers should be purchased in the pencil to goose-neck stages. These terms refer to flower position relative to the stem; pencil being straight up and gooseneck bent downwards to about a 45° angle.

Grading and Bunching

As with a number of other spike-type flowers, narcissus will bend upwards away from gravity if laid down flat. For this reason, flowers should be kept vertical when they are not cooled to the proper storage temperature. Although there are no formal grade standards for these flowers, the most important quality attributes are maturity, uniformity of color, and freedom from damage or disease. Flowers are normally bunched in groups of 10 or 25, tied with twist-ties, and sleeved in paper or plastic.

Ethylene Sensitivity

Senescence of these flowers is accelerated by exposure to ethylene, although their natural senescence does not involve ethylene. Pretreatment with 1-MCP or STS may extend flower life where flowers are handled in ethylene-polluted environments such as mass market outlets.

Pretreatments

Pretreatment with 1-MCP or STS can help extend vase life of flowers that are likely to be exposed to ethylene.

Storage Conditions

Daffodils and jonquils should be stored at 0 to 1 °C (32 to 34 °F). Store upright as these flowers will bend upwards from gravity. Narcissus can be stored at 1 °C (34 °F) and 90% RH for up to 2 weeks with only slight reduction in vase life. They may also be stored for several weeks in an atmosphere of 100% N_2. Narcissus stored in this way have as long a vase life as fresh-cut flowers and nearly double the vase life of air-stored flowers. Flowers are best stored upright and dry in containers that permit rapid cooling of the flowers, such as fiberboard boxes.

Packing

Because of their sensitivity to gravity, daffodils are often packed in hampers; although they may be packed in horizontal fiberboard boxes if they are properly precooled and maintained at the correct storage temperature.

Special Considerations

Daffodils exude a gelatinous (slimy) substance that, when transferred through a common holding solution to other flowers like tulips and anemone, can result in premature death for the other species (van Doorn 1998). Therefore, place freshly cut or recut flowers into a separate holding bucket for a few hours. Later they can be placed with other flowers and used (even recut if required) in arrangements without affecting the life of the other flowers.

Delphinium, Larkspur

Scientific Name and Introduction

Delphinium, Consolida spp. The tall spikes of delphinium and the smaller spikes of larkspur are important accent flowers with colors ranging from white through pink, purple, and blue.

Quality Characteristics and Criteria

Delphiniums and larkspur are normally harvested with one or two open flowers on the spike. Avoid flowers with mildew-infected leaves. At least one or two flowers per stem should be fully opened at the time of purchase with no sign of flower fall. Make sure stems are rinsed prior to recutting and arranging to remove dirt and debris.

Grading and Bunching

There are no formal grade standards for larkspur and delphinium. Flower number per spike, stem length, stem straightness, and foliage quality are important quality attributes in these flowers. Larkspur are normally bunched by size with an average of 10 stems per bunch.

Ethylene Sensitivity

Delphiniums are very sensitive to ethylene, which causes rapid loss of all of the flowers on the spike.

Pretreatments

Flower spikes should be pretreated with 1-MCP or STS to extend their vase life and protect them from exposure to ethylene. Because flowers are on spikes and are therefore at different maturity stages at the time of anti-ethylene treatment, STS may be more effective than 1-MCP.

Storage Conditions

Delphinium and larkspur should be stored at 0 to 1 °C (32 to 34 °F). For longer term storage, they should be wrapped in perforated polyethylene to reduce water loss.

Packing

These flowers are often packed in hampers with or without water, but they may also be packed in standard horizontal boxes. They are somewhat sensitive to gravity, so horizontally packed flowers should be precooled and maintained at proper holding temperatures.

Special Considerations

Flowers called larkspur or delphinium often are named incorrectly.

Emerald Palm

Scientific Name and Introduction

Chamaedorea spp. *Chamaedorea* is a small-leaved member of the palm family with leaves that perform well in the vase. Three other members of the palm family (coconut, date-palm, and oil-palm) make up the commercially important species for food consumption in North America.

Quality Characteristics and Criteria

Chamaedorea palms are harvested in the wild as well as being produced in plantations. Fronds are harvested when fully expanded, mature, and dark green. Fronds of *Chamaedorea* should be dark green, clean, and uniform. Avoid fronds whose leaf tips show marginal necrosis or dead areas and fronds that are beginning to turn yellow.

Grading and Bunching

There are no formal grade standards for *Chamaedorea,* but uniformity, size, color, and absence of defects are important criteria of quality. Bunches of emerald palm contain 25 stems.

Ethylene Sensitivity

Exposure to ethylene has no deleterious effects on *Chamaedorea* fronds.

Pretreatments

No pretreatments are recommended for *Chamaedorea* fronds.

Storage Conditions

Because *Chamaedorea* is a tropical foliage, it is sensitive to chilling damage if stored at low temperatures for extended periods. Fronds may be stored for 1 to 2 weeks at 12.5 °C (55 °F) and high RH.

Packing

Fronds are packed densely, usually without sleeves of paper, in standard horizontal fiberboard boxes.

Special Considerations

Early death of the fronds, drying, and inrolling of individual leaves (pinnae) result from water stress. Make sure that stems are recut before arranging them as this can quadruple their life. The species is chill sensitive, so hold at proper temperatures.

Eucalyptus, Silver Dollar Tree

Scientific Name and Introduction

Eucalyptus spp. The silvery-green leaves of the juvenile form of *Eucalyptus pulverulenta* are a very popular foliage item, used in fresh and dried form. A number of other species of *Eucalyptus* also are used as cut foliage. Eucalyptus is Greek for well and lid, referring to the sepals and petals, which are united to form a cap that is shed when the flower opens, revealing the showy, colored stamens.

Quality Characteristics and Criteria

As with other foliage, eucalyptus performs better in the vase if leaves are mature. Branches are harvested to provide long stems but leave growing points behind for development of new branches. Stem tips should not be wilted when purchased.

Grading and Bunching

Quality foliage is bright blue-green in color, has undamaged leaves, and is uniform in length. Eucalyptus branches are sold in grower bunches by weight, usually as 454 g (1 lb) bunches.

Ethylene Sensitivity

Eucalyptus branches are not sensitive to ethylene, but if the foliage is poorly handled, warm, and water-stressed, it can produce concentrations of ethylene that could damage ethylene-sensitive flowers that have not been treated with 1-MCP or STS.

Pretreatments

No pretreatments are required.

Storage Conditions

Eucalyptus foliage should be stored at 0 to 1 °C (32 to 34 °F).

Packing

Eucalyptus is normally packed in horizontal fiberboard boxes without additional packing materials.

Special Considerations

Handle this species with gloves to prevent hands from becoming sticky. Eucalyptus is native to areas like Australia and Tasmania, but over 200 species have been introduced elsewhere. As a result, this species predominates in certain woodlands in California. Many florists believe eucalyptus gives off a lot of ethylene because of its strong fragrance. In fact, most species and cultivars do not produce excessive amounts of ethylene gas, although some will produce potentially detrimental quantities of ethylene if they become water-stressed. Hence, make sure this species is properly hydrated. Eucalyptus can be treated with various colored glycerin-based solutions, which result in preserved specimens. Australian and Israeli researchers are investigating the possible use of eucalyptus as flowering branches, and we may expect to see this interesting item increasing in the trade in the future.

Fir, Spruce, Pine

Scientific Name and Introduction

Abies, *Picea*, and *Pinus* spp. Fir, spruce, and pine are all members of the pine family (Pinaceae). The 200+ species are noted for producing resins, lumber, and numerous ornamental landscape species. As foliage, mature branches are long lasting, provide a piney fragrance, and are often used in arrangements during the Christmas season.

Quality Characteristics and Criteria

Branches should be harvested when tips and needles are mature. Soft green growth is more likely to wilt in the vase. Branches should be mature, with uniform dark green foliage. Avoid bunches with fungal growth or whose needles are falling off.

Grading and Bunching

There are no grade standards for conifer branches and Christmas greens. Quality foliage is dark green and well hydrated and shows no abscission or fungal infection.

Ethylene Sensitivity

Conifer branches are not usually affected by exposure to ethylene and contrary to what is commonly suggested, do not produce any ethylene.

Pretreatments

No pretreatments are required for conifer branches.

Storage Conditions

Store at 0 to 1 °C (32 to 34 °F). These foliages store very well when held around 0 °C (32 °F), wrapped in plastic to reduce water loss. Make sure the branches are cooled prior to wrapping in plastic to avoid condensation and rots.

Packing

Because of the low value and relative hardiness of these materials they are usually packed loose in horizontal fiberboard boxes without any protection.

Special Considerations

Antitranspirant dips have not been shown to reduce water stress or to extend user life. Despite their strong aroma, these foliage materials have not been demonstrated to produce ethylene. If they are infected by fungi, it is possible that they may produce ethylene, but otherwise they are safe to store with ethylene-sensitive flowers.

Freesia

Scientific Name and Introduction

Freesia × cvs. Native to South Africa, the single or double flowers range in color from yellow, orange, red, and bronze to purple. Some cultivars retain the delightful fragrances that are common in garden freesias. The genus was named for Dr. Freese (1785-1876), a native of Kiel, Germany, and a student of South African plants.

Quality Characteristics and Criteria

Stems are harvested when the first flower colors and opens. Several flowering stems may be harvested from one plant. In that case, the uppermost flower stem should be cut just above the junction of the desired lateral flowering stem. When the lateral stem reaches maturity, it too is harvested. The upper flowering stem will have more flowers per stem and better postharvest life than lateral flowering stems. One or two florets per stem should be just beginning to open at the time of harvest and hence, at the time of purchase. If harvested too tight, many florets may not open unless preservative solutions are used properly. Learn cultivar names and market those that have good postharvest characteristics.

Grading and Bunching

There are no standard grades for freesias, but they may be graded according to maturity, number of flowers per stem, and the length of stem. Quality freesias have at least seven florets per spike and have long, straight stems. Flowers are sold in bunches of 10 stems, usually of the same color.

Ethylene Sensitivity

The open florets on freesia inflorescences are not affected by exposure to ethylene, but the effects of this gas are seen in young buds, which fail to develop.

Pretreatments

A 1-MCP or STS pulse pretreatment is effective in preventing abortion of small buds on the inflorescence. Freesias can be pulsed for 18 h in the dark with a preservative solution containing 25% sucrose. Pulsing should be carried out at about 20 °C (68 °F) with 85% RH. This treatment will increase flower size, percentage of flowers that open, and vase life (van Meeteren et al. 1995).

Storage Conditions

Freesia should be stored at 0 to 1 °C (32 to 34 °F).

Packing

Freesias are packed in horizontal boxes or upright hampers.

Special Considerations

The species is ethylene sensitive, but it responds well to STS, which inhibits premature flower fading and the appearance of translucent petals. STS helps open more flowers per stem, and more open flowers absorb more STS, protecting against ethylene-induced disorders. Water stress can cause significant ethylene production and reduce life.

Gerbera, Transvaal Daisy

Scientific Name and Introduction

Gerbera jamesonii and hybrids. Cut gerbera flowers, known for their remarkable variety in coloration and form, are an increasingly important part of the florists' palette. Their postharvest life can be substantial if they are given proper postharvest conditions, but they are sensitive to gravity, to light, and to bacterial contamination of the vase solution. Originally spelled "Gerberia," the genus was named after Traug Gerber, a German naturalist.

Quality Characteristics and Criteria

Most gerbera varieties should be harvested when the two outer rows of disk florets have begun to open; but some cultivars can be harvested later, particularly those types that close at night. Flowers are harvested by twisting the stems off near the point of attachment to the rhizome; this is thought to encourage subsequent flower production. If flower stems are pulled from the ground, immediately cut 10 cm (4 in) from the bottom to remove the "woody" base of the stem, which does not draw water readily. Place soon after harvest in a solution containing 40 µL L^{-1} hypochlorite. Make sure that at least one or two rows of disk flowers (tubular flowers in the center of the head) are showing pollen. With well over 300 cultivars in commerce that vary greatly in vase life (Wernett et al. 1996), it is important that florists order gerberas by cultivar name. Unfortunately, the large number of cultivars makes it difficult to learn the names of better ones.

Grading and Bunching

Maturity; freedom from defects; and stem length, strength, and straightness are important quality criteria for gerberas. Some producers bunch the flowers, but most pack them individually. Some producers place each flower into a firm plastic sleeve and may insert the stem into a plastic tube to reduce stem-bending.

Ethylene Sensitivity

Gerberas are unaffected by exposure to ethylene.

Pretreatments

Present industry practice is to place cut gerbera stems in a 40 µL L^{-1} sodium hypochlorite solution immediately after harvest to improve vase life. A rapid pulse treatment with 100 µL L^{-1} silver nitrate is sufficient to greatly alleviate postharvest problems with gerbera cultivars that are relatively short-lived. The silver nitrate presumably guards against bacterial contamination of the stem and vase water. After the dip, rinse the flowers in good-quality water. This treatment causes only minimum phytotoxicity (brown damage to the stem). The use of 6% sugar plus 200 µL L^{-1} 8-HQC as a preservative has shown to be of some benefit but can cause stem elongation during storage and may reduce overall flower quality.

Storage Conditions

Gerberas should be stored at 0 to 1 °C (32 to 34 °F); the widely-held opinion that gerberas are sensitive to chilling injury has not been scientifically substantiated. Generally, gerberas should not be stored longer than 1 week; even this short storage period can reduce subsequent vase life.

Packing

Most commonly, producers pack individual flowers horizontally in shallow cardboard containers especially designed to support gerberas. Flower stems are passed through slits in the bottom of a cardboard tray so that the flower heads face up showing their colors while the stems pass under the box. Several rows of flowers can be arranged in each box. The boxes are then hung so that the stems dangle downward and can be placed in a rehydration solution (hypochlorite is most commonly used). Afterward, two trays of flowers are packed horizontally into a fiberboard box in such a way that the flowers are facing upward and easily seen while the stems are underneath the flower cards.

Special Considerations

Stem bending is primarily in response to gravity and is greatly reduced if flowers are held at the proper storage temperature. One of the major problems in postharvest handling of these flowers is their tendency to “conk”: the stem folds 10 to 15 cm (4 to 6 in) below the flower head, resulting in an unmarketable flower. This bending has been variously attributed to harvesting of the flower before the stem has hardened sufficiently and to microbial plugging of the stem and subsequent water stress. The tendency to conk varies with variety and also varies throughout the year for any given variety. Be sure to enhance water uptake by keeping holding solutions and buckets clean and including hypochlorite in the water. Since more water is lost through the flower stem (scape) than through the flower petals, the scapes should be handled with as much care as the flowers themselves. Hang flower heads through a meshed support or shipping tray when first hydrating to keep stems straight.

Ginger, Shell Ginger, Torch Ginger

Scientific Name and Introduction

Alpinia zerumbet, A. purpurata. The ginger flowers represent a range of species and genera from the tropics that include the plants producing the edible ginger rhizome. One of the common lei flowers used in Hawaii is white ginger. Torch ginger flowers are spectacular spikes of red flowers that give an especially tropical effect in arrangements. The genus is named after the Italian botanist Prosper Alpinus.

Quality Characteristics and Criteria

No specific maturity standards have been developed for these flowers. They are normally harvested when all of the flowers on the spike are open. Make sure flowers do not exhibit chill damage symptoms such as off-colored (grayish/bluish) blooms.

Grading and Bunching

There are no specific grade standards for gingers. Proper maturity and freedom from flower and foliage defects would be important indicators of quality. Gingers are large flowers and are therefore normally packed individually. Some species may be individually sleeved to protect the delicate petals.

Ethylene Sensitivity

These flowers do not appear to be particularly sensitive to ethylene.

Pretreatments

There is no evidence that pretreatments provide any benefit to ginger flowers.

Storage Conditions

Store at 12.5 to 15 °C (55 to 59 °F). Gingers are chilling sensitive, so they must be held at warmer temperatures.

Packing

Gingers are packed flat in standard or insulated fiberboard boxes.

Special Considerations

Their large size makes gingers difficult to manage. Since insects sometimes make the trip from grower to wholesaler to retailer, make sure flowers are inspected and any insects removed.

Gladiolus, Glad

Scientific Name and Introduction

Gladiolus cvs., hybrids. Still an important commercial cut flower despite a substantial decline in production in recent years, gladiolus responds well to proper postharvest management. The smaller flowered and “butterfly” cultivars, as well as modern standards in a variety of colors and forms, have helped transform this often stereotypic funeral flower into a contemporary favorite that can be an important accent flower in arrangements. *Gladiolus* is Latin for “small sword,” in reference to the sword-shaped leaves. Modern day gladioli are the results of hybridization programs that commenced in Belgium around 1841 using South African species.

Quality Characteristics and Criteria

Normal harvest is at the stage when the bottom two or three florets on the spike are showing color. For long-distance transportation, an even earlier harvest stage can be recommended if it is combined with sugar pulsing to ensure proper opening of the flowers at their destination. Local market flowers are cut when the first floret is open. Harvesting is carried out so as to leave as many leaves on the plant as possible. A knife is run down between the leaves with the back of the knife down. When the knife blade is as low as the cutter believes it should go, it is pulled upward and out, severing the stem, which can then be pulled out of the leaves. It is possible to open almost all florets on flower spikes if they are harvested in the green bud stage and handled properly. However, it is recommended that color be visible in one to three florets at time of purchase to help ensure that most florets will open.

Grading and Bunching

Gladioli, like most spike-type flowers, are very sensitive to gravity and will always tend to grow away from the ground, particularly at warm temperatures. This can result in permanent deformation of the upper part of the spike and consequent reduction of flower quality. To avoid deformation, gladioli should be held upright throughout postharvest procedures. This rule may be relaxed only while the flowers are held at low temperature during storage and transportation. Quality factors for gladiolus include stem straightness and strength, freedom from damage and disease, and maturity. The flowers are bunched by color and maturity in groups of 10.

Ethylene Sensitivity

Although exposure to ethylene does not affect the life of open florets, it can reduce the flower life by causing abortion of unopened buds (Serek et al. 1995).

Pretreatments

Gladioli respond very well to pulsing with a preservative containing 20% sugar (sucrose or glucose). Pulse overnight at room temperature or in the cooler. The flowers can be pulsed in the dark. Treatment with 1-MCP or STS provides some protection against the effects of exposure to ethylene, which causes young buds to abort.

Storage Conditions

Although earlier recommendations were to store gladiolus at 5 °C (41 °F) to prevent chill damage to tips, we now know they can safely be stored for a week at 0 to 1 °C (32 to 34 °F). Flowers are negatively geotropic (they bend away from the force of gravity), so they are commonly stored and shipped upright. One beneficial aspect of low temperature handling and transportation is that this negative geotropic response is inhibited, allowing gladioli to be packed in the standard horizontal flower box. For longer storage, gladioli are best stored upright at the lowest safe storage temperature.

Packing

Gladioli are traditionally packed in tall “glad hampers” clearly marked for upright stacking. Since the advent of precooling, some shippers have packed gladioli in normal flower boxes. This practice is fairly safe if the flowers will remain refrigerated throughout the marketing chain and will be removed from the box on arrival. Excessive moisture on the foliage should be avoided so as to minimize the risk of *Botrytis* infection.

Special Considerations

Some cultivars are sensitive to fluoride, which can result in deterioration of the petal margin (bleaching, water soaking, then necrosis), failure of florets to open and develop normally, burning of the floret sheath, and marginal leaf scorch.

Heliconia, Parrot Flower

Scientific Name and Introduction

Heliconia humilis, H. psittacorum. The varied and fantastic forms and rich colors of the different species of *Heliconia* make them an important florist item, particularly prized for large and signature arrangements. Heliconia is named after Mount Helicon, the seat of the Muses, the nine goddesses of the arts and sciences in Greek mythology. Like their god Apollo, the Muses supposedly remained young and beautiful forever like the long-lasting and elegant flowers of heliconia. Lobster claw and crab’s claw are additional common names for flowers in this genus.

Quality Characteristics and Criteria

Heliconia are normally harvested fully mature: The flowers will not open past the stage at which they are harvested. While flowers last longer if the bracts are less open compared to more open, they generally do not open further after harvest and that may reduce their visual appeal. Therefore, the openness of the flower at purchase often is the most it ever will open. Consumer life varies greatly among species and cultivars; thus, learn species and cultivar differences.

Grading and Bunching

Quality flowers of heliconia are fully mature, free of defects (damage or discoloration) on the flowers, and have good quality foliage (when present). Both the smaller, hanging species and the larger, more upright species are packed individually by stem.

Ethylene Sensitivity

There is no evidence of any deleterious effects of ethylene exposure on the vase life of heliconias.

Pretreatments

No pretreatments have proved beneficial for heliconias. Some species may benefit from the flowers being dipped in an antitranspirant, such as those sold in garden centers for use on woody plants. However, no antitranspirant product is presently sold for this use.

Storage Conditions

Heliconias are native to the tropical Americas, and they are therefore very sensitive to chilling injury. They should never be held at temperatures below 10 to 12.5 °C (50 to 55 °F). Flowers may be stored in moist shredded newsprint or in water at 12.5 °C (55 °F).

Packing

Heliconias are normally packed in horizontal fiberboard boxes.

Special Considerations

Heliconias most often die early due to poor water uptake. They can last for up to 2 weeks in plain tap water if the water is free of microorganisms. Larger diameter and longer stemmed specimens last longer. Since insects sometimes make the trip from grower to retailer, make sure flowers are inspected and any insects removed.

Holly, Ilex

Scientific Name and Introduction

Ilex spp. Evergreen shrubs, hedges and small trees prized for their holiday-season dark green leaves and bright red fruits. The plants carry female and male flowers on separate trees, and are therefore termed “dioecious.” Only female plants are harvested for specimens possessing fruit.

Quality Characteristics and Criteria

Holly is harvested when the fruits are already fully red. Avoid purchasing holly in packages if condensation is visible. This indicates poor temperature management and possible fungal growth and ethylene production. Also, avoid specimens showing berry or leaf fall.

Grading and Bunching

Quality holly branches have uniform dark green leaves, are free of blemishes, and have bright red berries. They are seldom gathered into bunches but may be grouped and placed in polyethylene bags.

Ethylene Sensitivity

Exposure to ethylene results in loss of berries and leaves and is a common problem in holly handled through mass-market outlets.

Pretreatments

Because of its ethylene sensitivity, holly should be pretreated with STS or 1-MCP, which prevents bud and leaf loss during marketing (Joyce et al. 1990).

Storage Conditions

Holly should be stored at 0 to 1 °C (32 to 34 °F) and may even be held for longer periods at lower but nonfreezing temperatures.

Packing

Holly may be packed in hampers or horizontal boxes. In the past, the branches were treated with various solutions (containing naphthalene acetic acid, NAA) to reduce their sensitivity to ethylene and were therefore sometimes packed (wet) in wax-treated cartons. The use of 1-MCP should greatly simplify the marketing of this product.

Special Considerations

There are major differences among holly types in their sensitivity to ethylene. For example, 'Burford' is essentially insensitive to ethylene, while Chinese and English types are very sensitive. Therefore, know the type of holly being marketed. Some producers will dip holly into various solutions in an attempt to reduce fruit and leaf fall or to package the product in such a way as to extend life. However, at wholesale or retail levels there is not presently a product to retard fruit loss other than STS. Treating with STS does reduce fruit and leaf fall. Do not pregreen arrangements with holly, as it will not last.

Huckleberry

Scientific Name and Introduction

Vaccinium ovatum. Huckleberry is native to the West Coast in areas from northern California to British Columbia. *Vaccinium* is the ancient Latin name for blueberry, and the specific epithet *ovatum* refers to the oval leaf shape of this species.

Quality Characteristics and Criteria

Harvest branches when fully mature, without soft tips. This species is very long lasting with few postharvest problems. Thus, if it is of good quality at the time of purchase, it should perform well.

Grading and Bunching

N/A.

Ethylene Sensitivity

Huckelberry is not sensitive to ethylene.

Pretreatments

No pretreatments are required for huckleberry.

Storage Conditions

Huckleberry can be stored for an extended period by enclosing precooled bunches in a plastic vapor barrier and holding them near 0 °C (32 °F).

Special Considerations

Watch for excessive storage as depicted by fungal growth (fuzziness) and watersoaked or discolored leaves. The woody stems sometimes make huckleberry difficult to recut. Recutting this species is less critical than for other floral crops.

Iris, Fleur-de-Lis

Scientific Name and Introduction

Iris cvs., hybrids. Because of their intense yellow, blue, and purple colors, and the elegant shape of their flowers and foliage, bulbous (Dutch) iris are in considerable demand as cut flowers. Unfortunately, they are also one of the shortest-lived of the commercial cut flowers, and may not open if handled improperly or held too long before sale. In recent years, other iris species; for example the “flag” or German iris, which have even shorter vase life, have been used in the trade. Iris is Greek for “rainbow” in reference to the range of flower colors.

Quality Characteristics and Criteria

Iris grown at low temperature should be harvested more open than those grown in warmer conditions. Iris flowers are normally harvested at the “pencil stage.” This term describes flowers that exhibit a line of color vertically, as the sheathing leaves covering them unfurls, but before the flower petals reflex. The ‘Blue Ribbon’ cultivar should be harvested more mature, when the edge of one petal is unfurled. Iris are pulled from the field at the correct stage of maturity. The bulb is cut off and the lower foliage removed. The flower stems are then placed in water. Wholesale and retail florists should purchase iris in the pencil stage. A major exception is the cultivar ‘Blue Ribbon,’ which should be more open at the time of purchase.

Grading and Bunching

There are no formal grade standards for iris flowers. Flowers should be uniform in variety, color, and maturity. Foliage should be relatively undamaged and free from disease. Stems should be strong and straight. Flowers are normally bunched in groups of 10 and tied with rubber bands or twist-ties.

Ethylene Sensitivity

Iris are not affected by exposure to ethylene.

Pretreatments

There are no recommended pretreatments for iris flowers.

Storage Conditions

Store iris dry, upright, at 0 °C (32 °F) for no more than 1 week. Some growers store iris with the bulb attached. Prolonged storage may result in failure of flowers to open (especially the ‘Blue Ribbon’ cultivar). Storage at warmer temperatures will result in “popping” of the flower when it is rehydrated.

Packing

Iris are normally packed in upright hampers.

Special Considerations

Some increase in vase life has been realized by including a high concentration of benzyladenine in the vase solution, and pretreatments with gibberellins have been shown to overcome the negative effects of dry storage (Celikel and van Doorn 1995).

Leatherleaf Fern

Scientific Name and Introduction

Rumohra adiantiformis. By far the most popular cut foliage for use in arrangements, with year-round availability and good display life, leatherleaf fern is grown in shade-houses under subtropical conditions. The specific epithet *adiantiformis* indicates the similarity to the fronds of *Adiantum,* the maidenhair fern. The Greek *adianton* means unwettable—a reference to the fact that fern fronds shed water. It is probably the most commonly used floral green.

Quality Characteristics and Criteria

Avoid wilted or yellow fronds.

Grading and Bunching

None.

Ethylene Sensitivity

None.

Pretreatments

None.

Storage Conditions

1 to 6 °C (34 to 42.8 °F)

Packing

N/A

Special Considerations

Frond curl or postharvest wilt is a disorder that occurs more frequently from July to November. The precise cause of this disorder is not known, and it cannot be prevented at grower, wholesale, or retail levels. Water stress can make the frond curl worse; however, leatherleaf is very tolerant to water stress conditions when frond curl is not a problem. The use of some postharvest antitranspirant (wax-type) dips can enhance vase life but does not reduce frond curl. Dipping leatherleaf in plain tap water can reduce vase life. The brown bumps (sori or fruit-dots) found on the back of some fronds have not been reported to reduce life.

Lemonleaf, Salal

Scientific Name and Introduction

Gaultheria shallon. A hardy, long-lived cut foliage, salal was named for Jean-François Gaultier, a naturalist and physician from Quebec, Canada, about 1750.

Quality Characteristics and Criteria

Branches should be harvested when the leaves are mature, without tender young growth at the tips. Salal is very long-lasting and has few postharvest problems. If foliage is of good quality at time of purchase, it should provide satisfaction in the vase.

Grading and Bunching

Quality foliage has uniform mature green leaves with no damage, defects, or disease. Salal is usually sold 20 stems per bunch.

Ethylene Sensitivity

Salal is not affected by exposure to ethylene.

Pretreatments

Salal does not require any pretreatments to perform satisfactorily in the vase.

Storage Conditions

Salal should be stored at -0.5 to 1 °C (31 to 34 °F). Once harvested, bunched and cooled, lemonleaf is normally stored at or slightly below freezing in large bins lined with plastic to reduce water loss.

Packing

Salal is normally packed in horizontal fiberboard boxes.

Special Considerations

Even though the stems are woody, salal is adapted to standard florists' procedures for rehydration and use in arrangements.

Liatris, Gay Feather

Scientific Name and Introduction

Liatris pycnostachya, L. spicata. Native to prairies of North America, liatris was developed as a cut flower in Israel. The bright purple spikes provide interesting texture and line in arrangements, and can open fully if properly treated after harvest. Members of the Asteraceae (chrysanthemum or aster family), these species are also unusual in that flowers open from the top of the stem downwards; delphinium, gladiolus, snapdragon, and most other spiked-type flowers open from the bottom up. *L. spicata* is the taller of the two species. The specific epithet *pycnostachya* means thick-spiked in reference to flowers, while *spicata* means spike.

Quality Characteristics and Criteria

Liatris spikes should be harvested with no more than 25% to 33% of the flowers in the spike open. They may be harvested with only the top buds showing color and will open fully if provided with an effective preservative. However, if preservative solution is properly used, flowers can be harvested with no color showing and subsequently opened.

Grading and Bunching

Quality liatris flowers are of proper maturity (no more than one-third of the flowers on the spike open), are free from defects and damage, and have good quality foliage. They are normally bunched in groups of 10 and sometimes sleeved.

Ethylene Sensitivity

Liatris flowers are not affected by exposure to ethylene.

Pretreatments

Pulsing with preservative containing additional sugar (10 to 20%; about 100 g of sugar per quart or liter of water) will improve opening of tight-cut flowers (Han 1992).

Storage Conditions

Store liatris at 0 to 1 °C (32 to 34 °F).

Packing

Liatris are normally packed in horizontal fiberboard boxes but may also be packed in hampers.

Special Considerations

Be careful of fungal problems such as *Botrytis* (especially for flowers grown outdoors) as well as water stress. Leaf yellowing and reduced life are common when these problems exist and are not easily controlled. Using preservative solution helps open more flowers per stem but doesn't make individual flowers last longer.

Lily of the Nile, Agapanthus

Scientific Name and Introduction

Agapanthus africanus. The globose heads of agapanthus are a pleasing accent for spring and early summer arrangements, providing an alternative source of blue. The most common flower color is blue, but white cultivars are also available. Miniature, dark blue ('Storm Cloud'), and reduced-shatter cultivars have been developed. Agapanthus is Greek for "love flower."

Quality Characteristics and Criteria

Agapanthus flowers are normally harvested when the bud bract has fallen off and no more than three florets are open. Stalks are cut near their base with a sharp knife. Ensure that flowers are of proper maturity. If the neck of flowers is bent upward, they have been transported at warm temperatures and have responded to gravity.

Grading and Bunching

No formal grade standards have been established. Agapanthus flowers are bunched in groups of 5 or 10 stems.

Ethylene Sensitivity

Ethylene exposure results in loss of florets from agapanthus.

Pretreatments

The vase life of freshly cut agapanthus flowers was shown to be significantly extended by pretreatment with a 3 h pulse in 4 mM STS, followed by spraying (to runoff) with 30 µL L^{-1} NAA, followed by a 48 h pulse in a solution containing 10% sucrose, 300 µL L^{-1} citric acid, and 300 µL L^{-1} Physan-20 (Mor et al. 1984). This pretreatment is not sufficient to counteract the decrease in vase life due to even short-term storage and is of no apparent benefit to flowers harvested immature.

Storage Conditions

Store at 0 to 1 °C (32 to 34 °F). Even when pretreated to prevent flower abscission, agapanthus flower stalks stored dry at 1 °C (34 °F) suffer significant decrease in vase life after only 4 days and are frequently unable to achieve a minimally acceptable number of open florets.

Packing

Agapanthus flowers are normally packed in horizontal fiberboard boxes.

Special Considerations

Premature flower fall is caused mainly by ethylene, especially for immature flower buds. The common blue cultivar 'Mooreanus' is much less prone to premature flower fall than the white flowering 'Aldidus.'

Lily, Asiatic Lily, Oriental Lily

Scientific Name and Introduction

Lilium spp. Lilies have long been popular as garden flowers, prized for their stately beauty; and potted white lilies are a tradition in countries that celebrate Easter or Christmas. The brightly colored flowers of hybrid lily cultivars have become increasingly popular as cut flowers and have excellent vase life, especially if pretreated to prevent effects of ethylene. Buds open well if provided with preservative. "Lilium" is from the Greek word *lirion,* used in the naming of certain subdivisions of the genus.

Quality Characteristics and Criteria

Lilies are normally cut when one or two buds are just beginning to "crack." Tight-bud-stage flowers take some time to open, and petals of open flowers are likely to be damaged during transport. Most species and cultivars should be purchased with color showing on at least one flower. Avoid bunches with a number of open flowers, since they probably have been held at warmer temperatures during marketing.

Grading and Bunching

Although there are no grade standards for lilies, the number of buds per stem, the stage of maturity, and the color and quality of the foliage are all important quality parameters. Flowers are normally bunched in groups of 5 or 10.

Ethylene Sensitivity

Exposure of lilies to ethylene results in petal abscission, leaf yellowing, and abortion of young buds.

Pretreatments

After harvest, lilies should be treated with STS or 1-MCP to extend their vase life. Pulsing with a preservative solution containing 10% sucrose can improve subsequent bud opening, and it is also possible to reduce postharvest leaf yellowing in susceptible cultivars by pretreating them overnight with 2,000 $\mu L\ L^{-1}$ GA3.

Storage Conditions

Lilies should be stored at 0 to 1 °C (32 to 34 °F). If flowers are to be stored for any length of time, they should be treated prior to storage with STS or 1-MCP and an appropriate fungicide, the latter to protect against *Botrytis*. Lilies can be stored for up to 4 weeks if they are pulsed for 24 h with 1.6 mM STS plus 10% sucrose and then stored dry at 1 °C (34 °F). Flowers should be properly precooled, and they must be packaged so that water loss during storage is minimized (wrap precooled flowers in polyethylene film). However, some problems with leaf browning or yellowing can occur even after 2 weeks storage.

Packing

Lilies are normally packed in horizontal fiberboard boxes.

Special Considerations

Proper cultivar selection (van der Meulen-Muisers et al. 1997) and the use of antiyellowing postharvest chemical treatments (available commercially in some markets) can diminish leaf yellowing. STS or 1-MCP only reduce leaf yellowing caused by exposure to ethylene. Lily pollen can stain almost anything; removing stamens containing the pollen does not affect flower life. Some new cultivars do not shed pollen.

Lisianthus, Prairie Gentian

Scientific Name and Introduction

Eustoma grandiflora. Introduced into cultivation from Texas, production of lisianthus has increased dramatically, spurred by development, mostly in Japan, of excellent cultivars with a wide range of colors and single and double forms.

Quality Characteristics and Criteria

Stems are harvested when at least one flower is open. Although requiring extra labor, removal of immature shoots, whose buds will not develop, improves display quality. Choose stems with at least one open flower and several large buds.

Grading and Bunching

There are no grade standards for lisianthus, but obvious leaf miners and damage to the flower are quality defects. Bunches consist of 10 flower stems.

Ethylene Sensitivity

Lisianthus is slightly sensitive to ethylene. Exposure of mature flowers to ethylene will decrease their ultimate vase life, but the effect is relatively slight and does not warrant treatment with 1-MCP or STS.

Pretreatments

Lisianthus flowers benefit from sugar in the vase solution and can respond to pretreatment for 24 h with a preservative containing 5 to 10% sugar (Halevy and Kofranek 1984).

Storage Conditions

Lisianthus should be stored at 0 to 1 °C (32 to 34 °F).

Packing

Lisianthus flowers are sensitive to gravity, and their stems will bend upwards if the flowers are held horizontal at ambient temperatures. For this reason, lisianthus flowers that will be transported at warmer temperatures are often packed and transported in vertical hampers.

Special Considerations

Lisianthus is sensitive to some of the biocides in preservatives, which may cause browning of the stems. Aluminum sulfate (200 µL L^{-1}) and hypochlorite (50 µL L^{-1}) are excellent bactericides to use with lisianthus.

Marguerite Daisy, Boston Daisy

Scientific Name and Introduction

Argyranthemum frutescens. The white or yellow flowers of Margeurite daisies are produced year-round outdoors in frost-free areas of California. Borne on a perennial bush, flowers have long been an inexpensive staple for florists, often dip-dyed to provide different colors for special holiday occasions. Their postharvest life is relatively long but often limited by wilting or yellowing of the foliage. The specific epithet *frutescens* means bushy.

Quality Characteristics and Criteria

Flowers are considered to be of proper maturity from the time elongating petals are beginning to reflex back from the vertical position until the elongated petals are fully open and the outer ring of stamens (“fuzz”) is showing. Marguerites are harvested with shears, and harvesting is an important part of management of the bushlike plants. Flowers are often bunched in the field. The practice of laying finished bunches on the ground after harvest should be discouraged, as it may lead to rotting of flowers and foliage. Quality Marguerites have strong stems, healthy dark green foliage, and several flowers and buds on each stem. Purchase when at least two to three flowers per stem are fully open with no yellow foliage present.

Grading and Bunching

Marguerites are usually bunched in the field, and the bunch will contain flowers of varying maturity and size. The cost of grading flowers in a packing shed precludes this practice in such a low-return crop. Each bunch has 20 stems, or sometimes 10 stems when sold to supermarkets. Quality marguerites have strong stems, healthy dark green foliage, and several flowers and buds on each stem.

Ethylene Sensitivity

Margeurite daisies, like other members of the Asteraceae, are not affected by exposure to moderate concentrations of ethylene.

Pretreatments

Research has shown improved performance with flowers that are pulsed overnight at 20 °C (68 °F) with 25 µL L^{-1} silver nitrate and 0.5% sucrose before storage or transport. Sucrose concentrations above 0.5% can accelerate leaf yellowing and cause leaf injury.

Storage Conditions

Margeurites may be stored at 0 to 1 °C (32 to 34 °F) for 3 days in water or more than 1 week if dry. If flowers are well cooled, dry storage can be in standard daisy hampers.

Packing

Marguerites are normally packed in special “daisy hampers.” Flowers are jammed tightly together to increase the number in each package. With present cooling systems, it is almost impossible to cool flowers packed in this way. Poor postharvest temperature management may explain the development of yellow foliage and foliar disease in marguerites.

Special Considerations

Water in which Margeurites are held often develops a bad odor. Keep solutions fresh and buckets clean. Remove dirt and debris from stems prior to cutting them. Preservative solutions offer varying degrees of benefit depending on brand. Avoid preservative solutions containing 8-hydroxyquinoline citrate or sulfate (generally ones that turn the water slightly yellow). Lower foliage often turns yellow, which can be accelerated by improper storage or precooling and excessive or ineffective preservative solution. White flowers often are submerged in dye to get pink, green, red, or blue colors.

Orchids

Scientific Name and Introduction

Cattleya, Cymbidium cvs., and hybrids. Additional genera in the plant family Orchidaceae are *Dendrobium, Phalaenopsis, Vanda,* and *Paphiopedilum.* In addition to their exotic forms and colors, one of the principal attractions of cut orchid flowers is their outstanding longevity. Even out of water, an orchid flower will last for an evening in a corsage. Spikes of cymbidiums will often last a month in a vase.

Quality Characteristics and Criteria

Orchid flowers are usually harvested 3 to 4 days after opening because flowers cut prematurely will fail to develop normally off the plant. Early and late in the season, individual flowers are cut from the spike as they develop because prices are high at these times. In mid season, the whole spike is cut. Virus diseases can be spread from plant to plant during harvest, so cutting tools should be sterilized before being used on the next plant, or disposable razor blades should be used. As individual flowers, purchase when fully open. Spikes should be purchased when at least two flowers per spike are open.

Grading and Bunching

There are no grade standards for orchids. Freedom from defects is a primary measure of quality.

Ethylene Sensitivity

Some genera such, as *Cymbidium* and *Phalaenopsis,* are very sensitive to ethylene; others, such as *Dendrobium,* are less sensitive.

Pretreatments

Pretreatment with 1-MCP is very effective in preventing the effects of ethylene (Heyes and Johnston 1998) and increasing the life of orchid flowers and should be standard practice for these flowers.

Storage Conditions

Temperature can range from 0 to 12.5 °C (32 to 55 °F) depending on cultivar. Many cultivars are not chilling sensitive and therefore can be stored as other cut flowers at 0 to 1 °C (32 to 34 °F). If feasible, leaving flowers on the plants at room temperature is a good storage procedure. Be careful not to remove or knock off the pollinia (anthers) as this causes an immediate surge in ethylene production, which in turn causes premature death.

Packing

Because of their fragility and relatively high value, most orchids are packed as individual flowers or spikes, frequently in shredded paper to cushion and protect them from mechanical injury to the blooms. They are then packed 12 to 24 flowers in each carton. Box inserts hold individual water tubes stationary. Shredded wax paper is tucked around and between the flowers for additional protection.

Special Considerations

Only some species and cultivars are ethylene sensitive, which explains why anti-ethylene treatments like STS and 1-MCP work only some of the time. The two most common ethylene-induced symptoms are flower discoloration and premature wilting and flower fall. Demand has increased for this species prepared as a corsage and sold through mass market outlets at Easter and Mothers' Day. When sold for corsages the use of water picks filled with fresh-flower solution (not plain tap water) is beneficial.

Protea, Pincushion

Scientific Name and Introduction

Proteaceae family. The family Proteaceae includes a diverse range of species of trees and shrubs in the genus *Protea* from southern Africa and of other genera from Australia whose branches and flowers are used for foliage and as cut flowers. The flowers are normally pollinated by birds and produce copious amounts of nectar, explaining the old Afrikaans name of "sugar bush." The family name refers to the diversity of forms of the flowers. Additional genera are *Banksia, Leucospermum,* and *Leucodendron.*

Quality Characteristics and Criteria

Foliage is cut when mature (no soft tips), and the flowers when at least the outer florets are fully expanded. Banksias may be harvested when at least half of the flowers on the cylindrical spike are open. Make sure leaves are not black.

Grading and Bunching

Quality protea flowers and foliage are free of blemishes and have reasonably long, straight stems. Foliage such as 'Safari Sunset' leucodendron is bunched in groups of 10, 15, or 25. Flowers are handled individually or in bunches of 5 or 10, depending on quality, size, and market demand.

Ethylene Sensitivity

Neither foliage nor flowers of the proteas are affected by exposure to ethylene.

Pretreatments

Species that are susceptible to leaf blackening may be pretreated by pulsing overnight at 20 to 25 °C (68 to 77 °F) with 5% sugar (sucrose or glucose) (Dai and Paull 1995). Higher concentrations may cause leaf blackening.

Storage Conditions

Flowers and foliage from the Proteaceae should be stored at 0 to 1 °C (32 to 34 °F). Rapid precooling and maintenance of the proper storage temperature are important tools in preventing leaf blackening, a common postharvest problem in proteas. Care must be taken to ensure that there is no condensation or free water on leaves during storage as this greatly increases the incidence of blackening.

Packing

Proteas are normally packed in horizontal fiberboard boxes.

Special Considerations

Leaves turn black due to lack of carbohydrate (food) and warm temperatures. Use preservative solutions and proper low temperature management to prevent leaf blackening. In addition, this disorder can be reduced if the flowers are held under lighted conditions. Leaf blackening is not due to low temperature (chilling disorder), nor is it due to poor water relations. Many species and cultivars can be easily dried or preserved by just allowing them to dry under warm, low-RH conditions.

Rose, Spray Rose, Sweetheart Rose

Scientific Name and Introduction

Rosa cvs., hybrids. The rose undoubtedly remains the queen of the cut flowers. The historical association of this flower with romance and beauty ensures that roses will continue to be a highly desired cut flower in the future. Properly handled, most of the commercial cut roses will easily last in the vase for 10 days. Unfortunately, many consumers consider roses to have a very short vase life. This is partly because poor water uptake by certain cultivars of purchased roses all too often results in the symptom called “bent neck” in which the flower neck wilts and the bud fails to open. We also found that many commercial cultivars are quite sensitive to ethylene gas. The cut-flower industry has an important stake in overcoming the poor postharvest reputation of cut roses. All that is required is proper postharvest care for those cultivars susceptible to bent neck and appropriate pretreatment of those that are sensitive to ethylene, especially if they are to be sold in supermarkets or other ethylene-polluted areas.

Quality Characteristics and Criteria

Roses are harvested at different levels of maturity, depending on marketing and cultivar. For long-distance transport or storage, roses should usually be harvested with some of the sepals reflexed. Flowers harvested before the sepals reflex may fail to open or may be more susceptible to bent neck. Fast-opening roses, like some yellows and whites, should be harvested just before the sepals start to separate from the bud. The marketing life of roses harvested later will be reduced unless extra care is taken with their postharvest handling.

Harvesting is most convenient using shears provided with auxiliary jaws to hold the bloom after harvest. The cut is normally made so as to leave two five-foliate leaves below the cut. When stem length is an important consideration, the cut may be made below. Roses should be purchased and sold by cultivar name. Avoid blooms that are already open; flowers should normally have some or all of their sepals (the green protective leaves at the base of the flower) folded back, but the petals should not have started unfolding. Brown spots or patches on the outer petals may be an indication of *Botrytis* infection.

Grading and Bunching

Objective grading is based on stem length; subjective grading is based on flower maturity, stem straightness, stem caliper, and quality of flower and foliage. Defects on the outer "guard" petals are not normally a cause for down-grading, because these petals are removed by the retail florist. Leaves and thorns may be removed manually or mechanically if desired. This operation has little effect on vase life if flowers are placed in an effective preservative. The number of stems per bunch and bunch pattern (single layer, staggered two-layer) depend on market preferences.

Ethylene Sensitivity

Some cultivars are ethylene sensitive. Treat with 1-MCP or STS if they are being distributed through the mass markets, especially if being shipped through distribution centers, and also treat to prevent the effects of the ethylene prior to dry storage.

Pretreatments

Roses should be pretreated with 1-MCP or STS to prevent the effects of ethylene, especially if they will be sold through a supermarket. Sugar-containing pretreatments are not particularly useful for roses. Rehydrate after cutting, storage, and on arrival at the retail outlet with a rehydration solution. Commercial rehydration solutions are effective, as is clean water containing 50 µL L^{-1} hypochlorite, preferably below pH 5.0. This solution has proved safe and is inexpensive, so the buckets can be filled to the desired 20 to 30 cm (8 to 12 in) depth (Reid et al. 1996).

Storage Conditions

Roses should be stored dry at 0 to 1 °C (32 to 34 °F). Roses intended for long-term storage should be packed in polyethylene-lined cartons and precooled. They may be held for up to 2 weeks in dry storage if the temperature is maintained close to the freezing point.

Packing

Rose bunches are routinely sleeved in plastic, waxed paper, or soft corrugated card sleeves. The "spiral" bunch used by many off-shore producers increases the difficulty of precooling the flowers, as well as the opportunity for condensation collecting on the outer petals. *Botrytis* infection is a common result of the presence of free moisture on the petals of cut roses.

Special Considerations

Removal of those leaves and thorns below the water line should not reduce vase life if stems are placed into a preservative solution. The fungus *Botrytis* represents a major problem for roses. Symptoms of *Botrytis* infection include brown blotches on petals and gray, fuzzy growth on leaves, stems, or flowers. Postharvest fungicide dips can be helpful—use only registered products according to label instructions. Petal blackening on some red cultivars is due to growing conditions and cannot be corrected at wholesale or retail levels.

Snapdragon

Scientific Name and Introduction

Antirrhinum majus cvs. The many pastel flower colors of the tall spikes of snapdragons allow florists and consumers innumerable design options. Snapdragons used to be considered very sensitive to ethylene, but the newer cultivars have been selected for ethylene resistance, and ethylene normally causes a problem only when present in moderate concentrations. Flower drop (shattering) occurs in 24 h if ethylene is present in air at ≥0.5 µL L^{-1}. Antirrhinum is Greek for "like" and "nose," in reference to the flower shape.

Quality Characteristics and Criteria

For local sales, snapdragons are typically harvested when flowers on the lower half to two-thirds of the spike are open. A less mature stage is desirable for shipping and short-term storage. Purchase those cultivars that are less sensitive to ethylene. At least two to five florets per stem should be open. Avoid flowers with excessive stem bending and yellowing foliage, which indicate poor temperature management after harvest.

Grading and Bunching

Snapdragons are bunched in groups of 10 by color. Flowers must have straight stems and healthy foliage. Foliage on the lower third of the stem should be removed.

Ethylene Sensitivity

Most snapdragon cultivars are sensitive to ethylene. Older flowers on a stem are more susceptible to ethylene than younger ones. However, some cultivars are naturally ethylene resistant and, therefore, respond little to treatment with 1-MCP or STS.

Pretreatments

Treatment with 1-MCP or pulsing with STS protects snapdragon flowers from ethylene-induced shattering. Snapdragons also benefit from an overnight pulse at 20 °C (68 °F) with a preservative fortified with 7% sucrose. Upper flowers on spikes treated in this way open with better color than control flowers. Snapdragons are best stored with only a few flowers open, but this often results in poor development of the flowers on the spike and fading of color at the tip. Spikes cut with only one or two flowers open should be opened in a solution containing 300 µL L^{-1} 8-hydroxyquinoline citrate (8-HQC) and 1.5% sucrose. This bud-opening solution can also be used as a vase solution. Addition of 25 µL L^{-1} of the growth regulator n-dimethylamino succinamic acid increases flower quality and also counteracts the excess spike length that sometimes results from placing snapdragons in 8-HQC and sucrose. Pulse treatments with naphthylpthalamic acid or calcium antagonists (Philosoph-Hadas et al. 1996) can reduce geotropic curvature that results from horizontal storage at warmer temperatures.

Storage Conditions

Snapdragons can be stored at 0 to 1 °C (32 to 34 °F) for 7 to 10 days if they are wrapped in polyethylene film to retard moisture loss. Snapdragons have been satisfactorily stored for up to 3 weeks at -1 °C (30 °F). For long-term storage, bud-harvested flowers should be used. Bud-harvested flowers are ones in which the bottom two or three florets have colored petals emerging about one-quarter of an inch above the calyx. Snapdragons are relatively sensitive to ethylene gas. Flowers on harvested spikes assume a permanent upward bend, thus reducing quality, if held at warmer temperatures for even a short time in a nonvertical position. Snapdragons should always be stored and shipped upright in snapdragon hampers at low temperatures. Pretreatment with naphthyphthalamic acid can overcome this bending, but it is not registered for this purpose.

Packing

Snapdragons are usually packed upright in hampers or proconas, which reduce the likelihood of geotropic bending. If flowers are properly precooled and transported at optimal temperature of 0 to 1 °C, (32 to 34 °F), they can be packed in a normal horizontal flower box.

Special Considerations

Do not remove more leaves than necessary, as this can stimulate flower-fall. Do not use any home brews, such as antifreeze, as replacements for preservative solutions. The many pastel flower colors allow florists and consumers innumerable options. The flower can be made to snap shut after separating and releasing the two-lipped corolla (fused petals). When grown as a garden plant, treat the flowers as an annual, although many will respond as a perennial, depending on location and cultivar.

Statice, German Statice

Scientific Name and Introduction

Limonium spp., *Goniolimon.* A traditional filler flower, the standard statice *(Limonium sinuatum)* comes in a range of pastel colors and is widely used both fresh and dried. Other species of *Limonium* are sold in the trade as German, latifolia, sea foam, and caspia statice. Hybrid *Limonium* cultivars, grown from tissue culture, have become very popular in recent years. Their vase life is greatly improved by pretreatments to prevent the effects of ethylene and to improve bud opening.

Quality Characteristics and Criteria

Standard statice is harvested fully open but before the true flowers (small white flowers within the brightly colored bracts) senesce. Hybrid statice cultivars should be harvested when the first flower on each spike is open. Avoid bunches where flowers have yellowing stems and leaves and bunches with obvious fungal growth or wilted flowers. Remove from shipping boxes and recool flowers immediately. Also remove stem ties and separate stems to improve air circulation and reduce the likelihood of *Botrytis* infection.

Grading and Bunching

Quality statice is of the correct maturity and is free of defects and disease. Standard statice is normally bunched in groups of 25. Sleeves help prevent tangling of the delicate branchlets.

Ethylene Sensitivity

Statice flowers are sensitive to ethylene, which causes accelerated wilting. In standard statice, this effect is not apparent since the “flowers” are papery bracts surrounding the true flowers. In hybrid statice cultivars, effective treatments to inhibit action of ethylene improve flower quality and vase life.

Pretreatments

Hybrid statice benefits enormously from pretreatment with STS or 1-MCP and pulse pretreatment with a solution containing 10% sugar and 200 $\mu L\ L^{-1}$ Physan-20 for 12 h. Sucrose present in the preservative extends the life of individual florets and promotes flower opening, resulting in up to 3-fold increases in longevity of inflorescences (Burge et al. 1998).

Storage Conditions

Store all statice at 0 to 1 °C (32 to 34 °F); when flowers are infected with *Botrytis,* even short-term storage can greatly reduce life.

Packing

Statice is normally packed in horizontal fiberboard boxes.

Special Considerations

Many statice species can be dried and used for years in permanent flower arrangements. Yet when used as a fresh flower, they may last only a few days before leaf yellowing (on statice only, not German statice) or *Botrytis* infestation occurs. Storing statice under lights can retard leaf yellowing, but this may be hard to do in commercial practice.

Stock

Scientific Name and Introduction

Matthiola incana. A very traditional field flower with spikes of aromatic flowers in a wide range of colors, stock continues to be a staple floristry item. Somewhat sensitive to ethylene and prone to bacterial contamination of the vase solution, stock flowers respond to proper postharvest care. The genus is named after Dr. Peter Andrew Matthioli, an Italian physician and botanist, 1500-1577. The specific epithet *incana* means hoary (hairy) in reference to the plant's whitish fuzz or hair.

Quality Characteristics and Criteria

Stock should be harvested with no fewer than six open florets on each spike. To increase stem length, growers may pull the plants from the ground and remove the roots later. Flowers harvested and sold with at least six flowers open per stem generally perform better than ones harvested and sold with fewer open flowers. Avoid spikes with bruised, brown, or infected florets or yellowed leaves.

Grading and Bunching

Quality stock has long straight spikes of uniform unblemished flowers and free of defects.

Ethylene Sensitivity

Exposure to ethylene results in water-soaking of the petals, accelerated senescence of the florets, and epinasty (downward curvature) of the leaves.

Pretreatments

To prevent deleterious effects of ethylene, stock should be pretreated with 1-MCP or STS.

Storage Conditions

Stock should be stored at 0 to 1 °C (32 to 33.8 °F).

Packing

Stock are frequently packed in hampers or aquapacks but may also be packed in horizontal fiberboard boxes.

Special Considerations

Water uptake can be reduced in flowers harvested with the roots. Use a preservative solution to keep the growth of microorganisms in check. As with baby's-breath and Marguerite daisy, the vase and bucket solutions can develop a very unpleasant smell if the correct amount and type of preservative solution is not used and if buckets are not properly sanitized.

Sunflower

Scientific Name and Introduction

Helianthus annuus. Smaller cultivars of sunflower have become a very popular florist item, and a range of forms and colors are now widely available. "Helianthus" is derived from the Greek *helios,* the sun, and *anthos,* a flower.

Quality Characteristics and Criteria

Sunflowers are normally harvested when the petals (the outer flowers or ligules) have unfolded and are at least vertical. For local market, flowers are harvested with ligules fully expanded and horizontal. No yellow, wilted leaves should be present. Storage life is often determined more by leaf yellowing or desiccation than by flower problems.

Grading and Bunching

Quality sunflowers are of uniform maturity, are free from defects, and have straight stems and good quality foliage. Small-flowered cultivars may be bunched in groups of 10 or 12, and large-flowered types are normally packed individually.

Ethylene Sensitivity

Prolonged exposure of sunflowers to low concentrations of ethylene results in abscission of ligules.

Pretreatments

The tendency for sunflowers to wilt prematurely in the vase can be avoided by pretreating flowers for 15 to 30 min with clean water containing 0.02% detergent (Jones et al. 1993).

Storage Conditions

Sunflowers can safely be stored at 0 to 1 °C (32 to 34 °F).

Packing

Sunflowers are normally packed in standard horizontal flower boxes.

Special Considerations

Sunflowers are also somewhat sensitive to gravity. If held horizontally at warmer temperatures, the flower heads will be permanently bent down; so it is important to maintain cool temperatures during transport and storage.

Sweet Pea

Scientific Name and Introduction

Lathyrus odoratus. Once important cut flowers, prized for their aroma and range of colors, sweet peas benefit substantially from anti-ethylene pretreatments. Combined with a sugar pulse, treatment with STS or 1-MCP enables these delicate flowers to be harvested at an earlier stage when the flowers are less susceptible to damage and can give as much as 1 week of display life.

Quality Characteristics and Criteria

Sweet peas are traditionally harvested when the last bud on the stem is about half open. "Bud-stage" flowers are harvested when the petals on the first bud are colored and near full size but have not yet opened. Flowers are harvested by holding the stem between the thumb and forefinger near the base (supporting the vine with two fingers behind and one in front) and then pulling the flower backwards and upwards from the axil of the leaf. Sweet peas should have five flowers per stem, with only one flower open at the time of purchase. Avoid bunches with wilting flowers or from which buds or flowers have fallen.

Grading and Bunching

There are no grade standards for sweet peas, but quality flowers have long, straight stems and at least five buds on each spike. Flowers can be bunched by color, or in mixed colors, in bunches of 10.

Ethylene Sensitivity

Exposure to ethylene results in accelerated wilting of petals, abscission of flowers, and failure of developing buds to open.

Pretreatments

Proper pretreatment greatly improves the vase life of sweet peas. Flowers should be treated with 1-MCP or STS (Sexton et al. 1995), then placed in a preservative solution containing 4% sucrose at 20 °C (68 °F) overnight.

Storage Conditions

Sweet peas should be stored at 0 to 1 °C (32 to 34 °F). Flowers that have been pretreated with 1-MCP and sucrose will open well and have a satisfactory vase life after storage for up to 1 week at 1 °C (34 °F).

Packing

Sweet peas are packed in horizontal boxes or hampers.

Special Considerations

Cultivars vary in the intensity of their aroma, one of the characteristic and appealing features of sweet peas.

Sweet William

Scientific Name and Introduction

Dianthus barbatus. A close relative of the carnation, normally grown in the field, sweet william flowers are borne on a short-stemmed inflorescence. Colors range from white through intense red and purple and provide strong accents in an arrangement. The specific epithet *barbatus* means bearded or barbed in reference to the beardlike growth emerging from the petals.

Quality Characteristics and Criteria

Flowers in the sweet william inflorescence continue developing after harvest, and they should be harvested with the outer ring of flowers open. Flowers should have at least the outer whorl of florets open. Avoid flowers with withered or sleepy florets, as this indicates ethylene-induced problems.

Grading and Bunching

Quality sweet william flowers are of uniform maturity, are free from damage and evidence of pests and diseases, and have reasonable stem length and good quality foliage. Flowers are sold in a grower’s bunch of at least 12 stems.

Ethylene Sensitivity

Flowers are ethylene-sensitive.

Pretreatments

Flowers should be pretreated with 1-MCP or STS to prevent effects of ethylene.

Storage Conditions

Like carnation, flowers should be stored at 2 to 3 °C (36 to 37 °F).

Packing

Sweet william flowers are normally packed in horizontal fiberboard boxes.

Special Considerations

As with many flowers grown in the field, fungal infections resulting from the wet foliage and flower conditions sometimes experienced at harvest can be a problem. Make sure flowers are rapidly unpacked and aerated to reduce possible disease spread.

Tuberose

Scientific Name and Introduction

Polianthes tuberosa. Spikes of ivory flowers much prized in the East for their fragrance and by western florists for accents and bridal bouquets, tuberose flowers bear as many as 50 florets, in pairs, on a tall spike. The postharvest life of these flowers typically is limited by failure of developing buds to open, so that the life is determined by the life of the flowers that were open at harvest. Proper pretreatments can greatly extend the life of tuberose and should routinely be carried out with flowers intended for storage and transport.

Quality Characteristics and Criteria

The flowers are normally harvested with two to four open blooms on the spike. Although earlier harvest provides a spike that is more resistant to transportation, the buds are unlikely to open after transport unless properly pretreated. Flowers for the local market may be harvested with more open flowers on the spike. It is unfortunately difficult to determine whether tuberose flowers have been effectively pretreated prior to purchase. Look for straight stems and unblemished blooms and work with suppliers to ensure that the flowers have been properly pretreated.

Grading and Bunching

Tuberose are sold in bunches of 10 stems.

Ethylene Sensitivity

Floret opening is reduced in spikes exposed to high concentrations of ethylene; but this effect is probably not normally of commercial significance, so 1-MCP or STS treatments are not warranted for tuberose.

Pretreatments

Tuberose flowers should be pulsed for 24 h at 20 to 25 °C (68 to 77 °F) with a preservative solution augmented with 20% sucrose (Naidu and Reid 1989). This pretreatment will significantly improve vase life and opening of buds on the flower spikes. Flowers to be pretreated in this way should preferably be harvested dry; graded, bunched, and recut; then placed immediately in the pulsing solution.

Storage Conditions

The optimal temperature for cooling and storage of tuberose is 0 °C (32 °F), but after only short periods the buds on the spike fail to open. Pulse pretreatment with sucrose overcomes this problem, and after 6 days storage, flowers open as well as on freshly cut spikes.

Packing

Tuberose may be packed in hampers or in horizontal fiberboard boxes. If packed horizontally, they should be held at the proper temperature to avoid geotropic curvature.

Special Considerations

Florists often use individual tuberose blooms in corsages and boutonnieres. Proper pretreatment of the spikes will ensure continued opening of the blooms in the florists' workroom and consequent increased utility of each spike.

Tulip

Scientific Name and Introduction

Tulipa cvs., hybrids. Tulips, one of the classical cut flowers, were the source of tremendous interest when they were first brought to Holland from the Mediterranean countries where they are native.

The most common species, *Tulipa gesnerana,* was named after C. Gesner, a botanist who lived from 1516 to 1565.

Quality Characteristics and Criteria

The entire tulip plant, with bulb attached, is harvested when the tepals show 50% color. It is preferable to harvest in the early morning when temperatures are lower and to cool the harvested flowers immediately. Purchase when flower color is just visible and only by cultivar name since postharvest characteristics vary greatly.

Grading and Bunching

Tulip blooms are graded for uniform maturity (degree of opening), stem length, and freedom from defects. Defects include flower bud blasting, greening of flower buds, and toppling. Bulbs are then removed and the bases of stems are cut to ensure adequate water uptake. Tulips are typically bunched in groups of 10.

Ethylene Sensitivity

Tulips show no response to ethylene nor any response to inhibitors of ethylene actions or synthesis (Sexton et al. 2000).

Pretreatments

No pretreatments are required for tulips.

Storage Conditions

Tulips should be stored at 0 to 1 °C (32 to 34 °F) with 85% RH, upright to prevent stem bending, and with bulbs attached. It has been reported that flowers stored dry in bunches can keep up to 7 weeks if sealed in polyethylene bags or kept in boxes overwrapped with polyethylene. Desiccation of tulips can be a serious problem, causing collapse of the stem below flowers. Control of RH and proper rehydration following storage can minimize the problem.

Packing

Tulips may be packed in hampers or in regular fiberboard flower boxes. Stems and blooms should be securely wrapped to prevent bruising and breakage. Tulips packed horizontally must be held at proper temperature of 0 to 1 °C (32 to 34 °F) to avoid gravity-induced bending.

Special Considerations

End-user life is very species- and cultivar-dependent, as is the flower maturity stage when sold. Preservative solutions are recommended; benefits vary from 0 to 150% increase in vase life, depending on cultivar, flower food brand, and water quality. Do not place in the same bucket with daffodils that have been just recut, as the mucilage exuded by daffodils can reduce the vase life of tulips. Tulip flower stems (scapes) often continue to elongate after harvest and will often grow out of the arrangement. Stems should be maintained in an upright position during handling to prevent stem bending.

Some people may get dermatitis from continual handling of tulip flowers.

Waxflower, Geraldton Waxflower

Scientific Name and Introduction

Chamelaucium uncinatum. A native of western Australia, the ‘Geraldton’ waxflower is available in shades of white through deep purple and has become an important filler material. It is produced in substantial quantities in Israel and more recently in Australia and California. Various techniques have been developed to manipulate the flowering season, and the availability of substantial volumes from the Southern Hemisphere makes waxflower an item that is commonly available in the trade. The specific epithet *uncinatum* means “hooked at the point," in reference to the leaves which are hooked at their ends. The crushed leaves give a pleasing citrus aroma.

The major postharvest problems are the shattering of flowers and petals, an ethylene-related problem that can be controlled by pretreating the flowers with 1-MCP or STS, and *Botrytis* infection, particularly an issue for growing areas with erratic rainfall. Fungicide dips have been used successfully as a control measure.

Quality Characteristics and Criteria

Waxflowers are normally harvested with a mixture of open flowers and mature buds on each branchlet. Branches are harvested to maximize stem length without compromising the following year's crop. Avoid buying if leaves or flowers have fallen off or are turning yellow.

Grading and Bunching

There are no grade standards for the flowers, which are sold in field bunches. Quality waxflowers have numerous flowers on long stems and dark-green unblemished foliage. Waxflower bunches from Australia weigh 300 g per bunch, whereas California bunches usually weigh 400 g.

Ethylene Sensitivity

Waxflowers are very sensitive to ethylene, which causes loss of flowers, buds, and leaves (Joyce 1993).

Pretreatments

Harvested wax flower bunches should be treated with 1-MCP or STS in the same way as carnations.

Storage Conditions

Store waxflower at 0 to 1 °C (32 to 34 °F). If properly precooled and subsequently wrapped in plastic to reduce water loss, flowers can be stored dry for up to 2 weeks at 1 °C (34 °F). There is no benefit of wet over dry storage, and dry storage is therefore the method of choice. The main problem during storage is from growth of *Botrytis* on flowers. Dipping in 1% Rovral (Ipridione) solution prior to storage can prevent *Botrytis* infection.

Packing

Waxflowers are packed in bunches that contain variable numbers of stems (around 10) to provide a satisfactory bunch.

Special Considerations

The major storage problems are flower shatter (flowers fall off) and premature leaf yellowing and desiccation. Treat with anti-ethylene treatments like STS. Leaf yellowing cannot be controlled with STS or other commonly available preservatives.

Yellow Aster

Scientific Name and Introduction

× *Solidaster luteus.* The "×" prior to the generic name indicates that this species is an intergenetic hybrid, the result of crossing two different genera *(Aster* and *Solidago).* The specific epithet *luteus* means yellow. The hybrid originated in 1910 at the Leonard Lille Nursery in Lyon, France.

Quality Characteristics and Criteria

At least 50% of the flowers should be open. Avoid old product, as leaf yellowing and desiccation can be troublesome.

Grading and Bunching

As with other filler flowers, bunches are made by size or weight.

Ethylene Sensitivity

Like other Asteraceae, solidaster flowers are not sensitive to ethylene.

Pretreatments

Like *Solidago*, solidaster flowers probably would benefit from a cytokinin pulse treatment to delay leaf yellowing (Philosoph et al. 1995).

Storage Conditions

Solidaster should be stored at 0 to 1 °C (32 to 34 °F).

Special Considerations

If flowers are too immature when harvested, they may not develop to their maximum beauty. Treat like most other members of the chrysanthemum family. Leaves should be stripped from the stem as they rot underwater and will foul the vase solution. Make sure that buckets, vases, and solution are kept clean.

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References

Bieleski, R.L., J. Ripperda, J.P. Newman, and M.S. Reid. 1992. Carbohydrate changes and leaf blackening in cut flower stems of *Protea eximia*. J. Amer. Soc. Hort. Sci. 117:124-127.

Bovy, A.G., G.C. Angenent, H.J.M. Dons, and A.C. van Altvorst. 1999. Heterologous expression of the Arabidopsis etr1-1 allele inhibits the senescence of carnation flowers. Molec. Breed. 5:301-308.

Burge, G.K., E.R. Morgan, I. Konczak, and J.F. Seelye. 1998. Postharvest characteristics of *Limonium* ‘Chorus Magenta’ inflorescences. NZ. J. Crop Hort. Sci. 26:135-142.

Celikel, F.G., and Y. Karaaly. 1995. Effect of preharvest factors on flower quality and longevity of cut carnations (*Dianthus caryophyllus* L.). Acta Hort. 405:156-163.

Celikel, F.G., and W.G. van Doorn. 1995. Effects of water stress and gibberellin on flower opening in *Iris* × *hollandica*. Acta Hort. 405:246-252.

Cevallos, J.C. 1998. Temperature and the Postharvest Biology of Cut Flowers. M.S. Dissertation, University of California, Davis, CA.

Dai, J., and R.E. Paull. 1995. Source-sink relationship and *Protea* postharvest leaf blackening. J. Amer. Soc. Hort. Sci. 120:475-480.

Halevy, A.H., and A.M. Kofranek. 1984. Evaluation of lisianthus as a new flower crop. HortScience 19:845-847.

Halevy, A.H., A.M. Kofranek, and S.T. Besemer. 1978. Postharvest handling methods for bird-of-paradise flowers (*Strelitzia reginae* Ait.). J. Amer. Soc. Hort. Sci. 103:165-169.

Hammer, P.E., and K.B. Evensen. 1996. Effects of the production environment on the susceptibility of rose flowers to postharvest infection by *Botrytis cinerea*. J. Amer. Soc. Hort. Sci. 121:314-320.

Han, S.S. 1992. Role of sucrose in bud development and vase-life of cut *Liatris spicata* (L.) Willd. HortScience 27:1198-2000.

Heyes, J.A., and J.W. Johnston. 1998. 1-Methylcyclopropene extends *Cymbidium* orchid vase-life and prevents damaged pollinia from accelerating senescence. New Zealand J. Crop Hort. Sci. 26:319-324.

Hicklenton, P.R. 1991. GA3 and benzylaminopurine delay leaf yellowing in cut *Alstroemeria* stems. HortScience 26:1198-1199.

Ichimura, K., and K. Suto. 1999. Effects of the time of sucrose treatment on vase-life, soluble carbohydrate concentrations and ethylene production in cut sweet pea flowers. Plant Growth Regul. 28:117-122.

Jacob, Y., R. Barrade, M.J. Marquier, and E. Botton. 1997. Breeding of *Anemone coronaria* tetraploid hybrids. Acta Hort. 430:503-508.

Jones, R.B., M. Serek, and M.S. Reid. 1993. Pulsing with Triton X-100 improves hydration and vase-life of cut sunflowers (*Helianthus annuus* L.). HortScience 28:1178-1179.

Joyce, D.C. 1993. Postharvest floral organ fall in Geraldton waxflower (*Chamelaucium uncinatum* Schauer). Austral. J. Exp. Agric. 33:481-487.

Joyce, D.C., M.S. Reid, and R.Y. Evans. 1990. Silver thiosulfate prevents ethylene-induced abscission in holly and mistletoe. HortScience 25:90-92.

Kappers, I.F., W. Jordi, F.M. Maas, et al. 1998. Gibberellin and phytochrome control senescence in alstroemeria leaves independently. Physiologia Plantarum 103:91-98.

Kuiper, D., S. Ribot, H.S. van Reenen, and N. Marissen. 1995. The effect of sucrose on the flower bud opening of ‘Madelon’ cut roses. Sci. Hort. 60:325-336.

Macnish, A.J., D.C. Joyce, P.J. Hofman, et al. 2000. 1-Methylcyclopropene treatment efficacy in preventing ethylene perception in banana fruit and grevillea and waxflower flowers. Austral. J. Exp. Agric. 40:471-481.

Mor, Y., A.H. Halevy, A.M. Kofranek, and M.S. Reid. 1984. Postharvest handling of lily of the nile flowers. J. Amer. Soc. Hort. Sci. 109:494-497.

Naidu, S.N., and M.S. Reid. 1989. Postharvest handling of tuberose (*Polianthes tuberosa* L.). Acta Hort. 261:313-317.

Newman, J.P., L.L. Dodge, and M.S. Reid. 1998. Evaluation of ethylene inhibitors for postharvest treatment of *Gypsophila paniculata* L. HortTechnology 8:58-63.

Philosoph-Hadas, S., S. Meir, I. Rosenberger, and A.H. Halevy. 1995. Control and regulation of the gravitropic response of cut flowering stems during storage and horizontal transport. Acta Hort. 405:343-350.

Philosoph-Hadas, S., S. Meir, I. Rosenberger, and A.H. Halevy. 1996. Regulation of the gravitropic response and ethylene biosynthesis in gravistimulated snapdragon spikes by calcium chelators and ethylene inhibitors. Plant Physiol. 110:301-310.

Pritchard, M.K., C.S. Hew, and H. Wang. 1991. Low-temperature storage effects on sugar content, respiration and quality of anthurium flowers. J. Hort. Sci. 66:209-214.

Rajitha, B.S., S.G. Rao, Y.B.N. Rao, and D. Singh. 1999. Post harvest effect of fluoride and other chemicals on the vase-life of *Gaillardia pulchella* cut flowers. J. Phyto. Res. 12:107-108.

Reid, M.S., M. Mokhtari, J.H. Lieth, et al. 1996. Modeling the postharvest life of cut roses. Acta Hort. 424:137-144.

Serek, M., R.B. Jones, and M.S. Reid. 1995. Physiology of flower senescence in gladiolus. Acta Hort. 455-459:16-21.

Sexton, R., A.E. Porter, S. Littlejohns, and S.C. Thain. 1995. Effects of diazocyclopentadiene (DACP) and silver thiosulfate (STS) on ethylene regulated abscission of sweet pea flowers (*Lathyrus odoratus* L.). Ann. Bot. 75:337-342.

Sexton, R., G. Laird, and W.G. van Doorn. 2000. Lack of ethylene involvement in tulip tepal abscission. Physiol. Plant. 108:321-329.

van der Meulen-Muisers, J.J., J.C. van Oeveren, J. Jansen, and J.M. van Tuyl. 1999. Genetic analysis of postharvest flower longevity in Asiatic hybrid lilies. Euphytica 107:149-157.

van der Meulen-Muisers, J.J., J.C. van Oeveren, and J.M. van Tuyl. 1997. Breeding as a tool for improving postharvest quality characters of lily and tulip flowers. Acta Hort. 430:569-575.

van Doorn, W.G. 1998. Effects of daffodil flowers on the water relations and vase-life of roses and tulips. J. Amer. Soc. Hort. Sci. 123:146-149.

van Doorn, W.G. 1999. Water relations of cut flowers. II. Some species of tropical provenance. Acta Hort. 482:65-69.

van Doorn, W.G., R.R.J. Perik, and P.J.M. Belde. 1993. Effects of surfactants on the longevity of dry-stored cut flowering stems of rose, *Bouvardia*, and *Astilbe*. Postharv. Biol. Technol. 3:69-76.

van Doorn, W.G., and A.D. Stead. 1997. Abscission of flowers and floral parts. J. Exp. Bot. 48:821-837.

van Meeteren, U., and H. van Gelder. 1999. Effect of time since harvest and handling conditions on rehydration ability of cut chrysanthemum flowers. Postharv. Biol. Technol. 16:169-177.

van Meeteren, U., H. van Gelder, and A.C. van de Peppel 1995. Aspects of carbohydrate balance during floret opening in Freesia. Acta Hort. 405:117-122.

Wernett, H.C., T.J. Sheehan, G.J. Wilfret, et al. 1996. Postharvest longevity of cut-flower *Gerbera*. I. Response to selection for vase-life components. J. Amer. Soc. Hort. Sci. 121:216-221.

Flower Bulbs

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Introduction

"Flower bulbs" refers to all taxa of ornamental flowering "bulbs" having true bulbs, corms, tubers, rhizomes, tuberous roots, or enlarged hypocotyls as underground storage organs (De Hertogh and Le Nard 1993b). All of them are geophytes (Raunkiaer 1934), a term that not only includes flower bulbs but also most herbaceous perennials, some fruits such as strawberries, and some vegetables such as asparagus. Commercially, over 60 taxa and thousands of cultivars of flower bulbs are grown on approximately 32,000 hectares (De Hertogh and Le Nard 1993a). However, six genera make up over 90% of the total acreage of bulbs produced. In 2000 (Anonymous 2000), the world production of flower bulbs was: *Tulipa*, 39%; *Narcissus*, 20%; *Lilium*, 19%; *Gladiolus*, 8.5%; *Hyacinthus*, 4%; and *Iris*, 3%. This review provides the basic guidelines for postharvest storage of only these six genera. Because of the number of cultivars and their varied usage, details cannot be provided because the precise requirements for all taxa are complex. For example, can a tulip cultivar be "precooled" for very early forcing and based on the growing season should the cultivar be given 34 °C immediately after harvest or placed at 17 to 20 °C? For detailed postharvest information of this nature, users must consult the articles cited.

Commercially, flower bulb usage can be divided into two groups. The first group is "planting stock." These are the propagation materials and are generally grown by specialized bulb growers. Thus, they will only be covered briefly in this review. For additional information, consult De Hertogh and Le Nard (1993a) and specific articles cited. The second group is the "commercial bulbs," which are primarily used for forcing either as fresh-cut flowers or as potted growing and flowering plants, indoor or outdoor container plants, outdoor fresh-cut flower production, and gardens and landscapes (De Hertogh and Le Nard 1993c).

Horticultural Objectives

Optimum postharvest storage conditions in combination with ideal bulb growing conditions and procedures are required to control (prevent, retard, or accelerate) the flowering process from floral initiation to anthesis (Hartsema 1961, Le Nard and De Hertogh 1993a, Theron and De Hertogh 2001) assist in controlling certain diseases and insects (Baker 1993, Byther and Chastagner 1993, Van Aartrijk 1995, 2000) and prevent physiological disorders (De Hertogh and Le Nard 1993e). For each species, it is important to know—

- precisely when flower initiation occurs, which can be before harvest (for example, Hardy *Narcissus*), during postharvest storage (tulips and hyacinths), or after planting (Easter lily);
- length of time required for floral development from initiation to anthesis, which can be a few weeks to several months;
- optimal temperatures required to control the entire flowering process, which can range from -2 to 34 °C, depending on the species etc.;
- sensitivity of the bulb species and cultivar to ethylene, which ranges from none to very sensitive;
- ventilation requirements, which range from none to high;
- moisture requirements, which range from none to high; and
- specific diseases and insects that can be controlled during the postharvest storage period, which can range from none to several.

These and other aspects have been reviewed by De Hertogh and Le Nard (1993a) and Hartsema (1961).

Table 1. Packing and storage temperature requirements of ornamental flower bulbs

Taxon	Requirements		
	Storage	**Packing**	**Storage temperature**
			°C
Achimenes	Prevent from drying	Peat	10 to 15
Acidanthera	Dry and ventilated	None	20
Allium			
giganteum	Dry and ventilated	None	25 to 28
Other alliums	Dry and ventilated	None	20 to 23
Alstroemeria	Prevent from drying	Peat	1 to 3
Amaryllis belladonna	Prevent from drying	Peat	13 to 23
Anemone			
blanda & *fulgens*	Dry and ventilated	None	9 to 17
coronaria			
(summer)	Dry and ventilated	None	15 to 25
(winter)	Dry and ventilated	None	10 to 13
Anigozanthos	Prevent from drying	Not reported	2 to 20
Begonia (Tuberous hybrids)	Prevent from drying	Peat	2 to 5
Caladium	Dry and ventilated	None	23 to 25
Camassia	Prevent from drying	Wood shavings	17 to 20
Canna	Prevent from drying	Peat	5 to 10
Chionodoxa	Prevent from drying	Wood shavings	20
Clivia	Prevent from drying	Peat	13
Colchicum	Prevent from drying	Wood shavings	17 to 23

Table 1. Packing and storage temperature requirements of ornamental flower bulbs—*continued*

Taxon	Requirements		
	Storage	**Packing**	**Storage temperature**
			°C
Convallaria	Keep frozen-in	Peat	-2
Crocosmia	Prevent from drying	Plastic	2 to 5
Crocus	Dry and ventilated	None	17 to 20
Cyclamen	Prevent from drying	Peat	9
Dahlia	Prevent from drying	Peat	5 to 10
Endymion (Scilla campanulata)	Prevent from drying, store in paper bags	Wood shavings	20
Eranthis	Prevent from drying	Peat	5
Eremurus	Prevent from drying	Peat	5 to 7
Erythronium	Prevent from drying	Peat	5 to 9
Eucharis	Prevent from drying	Peat	20
Eucomis	Dry and ventilated	None	13 to 20
Freesia	Dry and ventilated	None	
Preshipping			30
Postshipping			9 to 13
Fritillaria			
imperialis	Prevent from drying	Wood shavings	23 to 25
persica & *meleagris*		Peat	2 to 5
Galanthus	Prevent from drying	Peat	17
Galtonia	Prevent from drying	Wood shavings	17 to 20

Table 1. Packing and storage temperature requirements of ornamental flower bulbs—*continued*

Taxon	Requirements		
	Storage	**Packing**	**Storage temperature**
			°C
Gladiolus	Dry and ventilated	None	2 to 10
Gloriosa	Prevent from drying	Peat	10 to 18
Gloxinia	Prevent from drying	Peat	5 to 9
Haemanthus	Dry and ventilated	None	10 to 15
Hemerocallis	Prevent from drying	Peat	7 to 10
Hippeastrum	Prevent roots from drying	Peat or wood shavings	2 to 13
Hyacinthus	Dry and ventilated	None	17 to 20
Hymenocallis	Prevent from drying	Peat	7 to 10
Iris			
Dutch hybrids	Dry and ventilated	None	20 to 25
English hybrids	Dry and ventilated	None	17
Germanica hybrids	Prevent from drying	Peat	0 to 5
reticulata & *danfordiae*	Dry and ventilated	None	20 to 23
Ixia	Dry and ventilated at 65-70% RH	None	20 to 25
Ixiolirion	Dry and ventilated	None	20
Lachenalia	Dry	Peat	9 to 25
Leucojum			
aestivum	Dry and ventilated	None	20
vernum	Dry and ventilated	None	2 to 5
Liatris	Prevent from drying	None	2 to -2

Table 1. Packing and storage temperature requirements of ornamental flower bulbs—*continued*

Taxon	Requirements		
	Storage	Packing	Storage temperature
			°C
Lilium			
longiflorum	Prevent from drying	Peat	2 to 7
Hybrids & other species	Prevent from drying	Peat and polyethylene	2 to -2
Lycoris	Dry and ventilated	None	13 to 17
Montbretia	Prevent from drying	Plastic	2 to 5
Muscari	Dry and ventilated	None	20
Narcissus			
Hardy cultivars	Dry and ventilated	None	17
Paperwhites	Dry and ventilated	None	2 to 30
Nerine	Prevent from drying		
Short-term storage		Peat	17 to 21
Long-term storage		Peat	5 to 9
Ornithogalum			
dubium	Dry and ventilated	None	9 to 30
thyrsoides	Prevent from drying	Wood shavings	23 to 25
umbellatum & *nutans*	Prevent from drying	Wood shavings	20
Oxalis			
adenophylla	Prevent from drying	Wood shavings	17 to 20
deppei	Dry and ventilated	None	2 to 5
Polianthes	Dry and ventilated	None	20
Puschkinia	Dry and ventilated	Wood shavings	20 to 23
Ranunculus			
Summer	Dry and ventilated	None	17 to 20
Winter	Dry and ventilated	None	10 to 13

Table 1. Packing and storage temperature requirements of ornamental flower bulbs—*continued*

	Requirements		
Taxon	**Storage**	**Packing**	**Storage temperature**
			°C
Scadoxus	Dry and ventilated	None	10 to 15
Scilla siberica	Dry and ventilated	Wood shavings	20 to 23
Sparaxis	Dry and ventilated	None	25
Tigridia	In closed boxes	Peat	2 to 5
Triteleia (Brodiaea) laxa	Dry and ventilated	None	17 to 20
Tulipa	Dry and ventilated	None	17
Zantedeschia	Dry and ventilated	Wood shavings	7 to 10
Zephyranthes	Dry and ventilated	Polystyrene	17 to 20

Adapted from De Hertogh and Le Nard (1993c).

About 75% of the flower bulbs used in the United States are imported, and the remainder are domestically produced. In addition, all production areas are distant from the sites of use, and essentially 99% must be transported for a few days to several weeks. Thus, all trucks and shipping containers must be able to provide the proper temperature, ventilation, and moisture requirements for the bulbs (table 1). The normal rate of air exchange for bulbs requiring ventilation during transport is 150 m^3 h^{-1} (De Hertogh and Le Nard 1993c). In addition, for bulbs like hyacinths and dutch iris, the RH must be controlled to minimize the development of diseases such as *Penicillium*. Therefore, on arrival, all bulb shipments must be carefully inspected for serious diseases and insects, ventilated as needed, and then properly stored (table 1). Also, stage of development of the apical meristem must be determined. De Hertogh (1996) summarized packing, transportation, and storage requirements for forcing bulbs.

Major Postharvest Storage Factors

Temperature

Blaauw and his coworkers (Hartsema 1961) clearly demonstrated that temperature was the most important factor controlling the growth and development and flowering processes of flower bulbs. They demonstrated that precise control was required and that the specific temperature optima varied for each bulb species and the desired time of flowering. The optimal temperatures can range from -2 to 34 °C (28 to 93 °F) depending on the bulb species, use, growing season, and cultivar. Examples for the six major taxa are provided below.

Subsequently, De Hertogh and Le Nard (1993d) classified the hardiness of flower bulbs into seven groups (table 2). This classification is very important for the storage of nonplanted bulbs (table 1) because they have limited protection against extremes in temperatures. If they are stored or transported at temperatures lower or higher than the required temperatures, even for short periods, most bulbs will be physiologically injured (Van Aartrijk 1995 and 2000).

Table 2. Hardiness classifications for ornamental flower bulbs

Hardiness classification	Injured at temperatures below
Tender I	20 °C
Tender II	10 °C
Tender III	2 °C
Semi-hardy	-2 °C
Hardy I	-5 °C
Hardy II	-10 °C
Hardy III	-15 °C

Ventilation

When the taxa require ventilation (table 1), it is essential that the flower bulbs receive proper air circulation and exchange during all periods of postharvest storage. Thus, the application of these requirements must begin immediately after the grower harvests the bulbs and continue during transportation and subsequent handling by the wholesaler, forcer, and retailer. The exact ventilation requirement is generally very specific. It can be very low (*Eremurus* and *Liatris*, which must be prevented from drying out) or very high (tulips, in which ventilation assists in preventing flower abortion and abnormalities and in removing ethylene). In general, ventilation rates must be adapted to the storage temperature; that is, higher temperatures require higher rates of ventilation.

Moisture

There are two basic considerations for the moisture level used for bulb storage (table 1). The first is to provide the optimum moisture level, which will prevent desiccation of susceptible bulbs. Thus, materials such as moist peat or wood shavings are used in combination with the various packaging materials such as polyethylene. The second is the control of RH during storage or transportation, which can minimize root development and prevent the development of diseases such as *Penicillium* on hyacinths, *Narcissus*, tulips, and dutch iris. In addition, this approach is an important technique to minimize the use of fungicides either prior to or after shipping. Since the registration of fungicides varies with each country and is always subject to change, users must consult with their appropriate governmental agency to determine which pesticides are approved.

Ethylene

With the exception of dutch iris (see information below), nonplanted flower bulbs must not be exposed to ethylene. Most bulbs are physiologically sensitive to ethylene levels of 0.1 $\mu L\ L^{-1}$ and higher. In general, when the flower has been formed and is immature, this plant growth regulator causes either floral abnormalities or complete flower abortion. For very sensitive bulbs, such as tulips, it is advisable to have the storage rooms analyzed for ethylene. Commercial ethylene services are available to monitor the level of ethylene in all floriculture facilities.

Modified Atmospheres

Research on the modification of the O_2, N_2, and CO_2 levels of the storage atmosphere has been reported for gladioli, lilies, and tulips (De Hertogh and Le Nard 1993d). In Europe, this system is referred to as “ultra-low oxygen” (ULO) and is used commercially in the Netherlands for lily and tulip bulb storage (Anonymous 1996). However, the specific procedures used and the results have not been published in refereed journals.

Diseases and Insects

All users of flower bulbs must be familiar with the diseases and insects that affect each species (Baker 1993, Byther and Chastagner 1993, Van Aartrijk 1995, 2000). There are many pests, but usually there are only a few major ones for each species. Knowledge of the major pests and the conditions controlling their development can assist in either eliminating and/or minimizing their effects during postharvest storage.

Major Flower Bulb Taxa

***Gladiolus* (Gladioli)**

Cohat (1993) reviewed the physiology, pests, and other aspects of *Gladiolus*. Many diseases can affect gladioli in storage, and prestorage fungicidal dips are generally used. Current registrations must be consulted for approved fungicides. Corms for commercial uses should be transported at 2 to 5 °C (36 to 41 °F) under highly ventilated conditions, about 2 $m^3\ h^{-1}$ per 100 L of corms. With the exception of a hot water treatment (see below), unplanted corms should never be stored at <0.5 °C or >30 °C (Cohat 1993, Van Aartrijk 1995).

Planting stock. After being harvested, cleaned, and then graded, corms and cormlets used as planting stock are initially given 2 to 3 weeks at 15 to 23 °C (59 to 73 °F) followed by 2 °C (24 °F) under highly ventilated conditions for a minimum of 8 to 10 weeks. The latter is required to break the rest period (dormancy) of the corms and cormlets. Prior to planting, they are given 4 to 8 weeks at 20 to 30 °C (68 to 86 °F) to promote sprouting. To control *Fusarium*, cormlets are stored at 20 to 25 °C (68 to 77 °F) for 8 to 12 weeks, then soaked in running water for 1 to 2 days at 20 °C (68 °F), and then given a hot water treatment of 55 to 56 °C (131 to 133 °F) for 30 min.

Commercial bulbs for outdoor use. Horticulturally, the major uses for gladioli corms are outside either for use as commercial fresh cut flowers or in gardens and landscapes. The large flowering corms for these uses must be provided with the same storage temperatures and conditions as the planting stock. Corms used for very long storage and thus for very late flowering must be stored at 2 °C (36 °F) until planted.

Hyacinthus (Hyacinths)

Nowak and Rudnicki (1993) reviewed the physiology, pests, and other aspects of hyacinths. Commercially, the Netherlands produces almost all of the bulbs used world wide. The major storage disease for commercial sized hyacinth bulbs is *Penicillium.* It can be controlled with optimum ventilation conditions and a RH of 85 to 90%. Hyacinth bulbs should be transported and subsequently stored at 17 °C under highly ventilated conditions. With the exception of the heat treatment to control *Xanthomonas hyacinthii* (see below), unplanted bulbs are never stored at <0 °C or >25.5 °C (78 °F) (Nowak and Rudnicki 1993, Van Aartrijk 2000).

Planting stock. The postharvest handling and storage of small hyacinth bulbs require precise conditions to control the bacterium *Xanthomonas hyacinthii* (yellow disease). After harvest, the bulbs are stored at 30 °C under highly ventilated and dry conditions until September 1; they are then given 2 weeks at 38 °C, followed by 3 days at 44 °C, and subsequently 25.5 °C (78 °F) until planted. Bulbs used for scooping and scoring and other large planting stock bulbs are stored under dry and highly ventilated conditions at 25.5 °C (78 °F) from harvest until planted.

Commercial bulbs for forcing. Two types of commercial bulbs are available for greenhouse forcing as either potted plants or fresh cut flowers. The first is "prepared bulbs," which are used for very early forcing. After being harvested in early June, the bulbs are stored under dry and highly ventilated conditions for 2 weeks at 30 °C (86 °F), followed by 3 weeks at 25.5 °C (78 °F), and then 23 °C (73 °F) until the uppermost floret reaches stage A2. Subsequently, they are stored at 17 °C (63 °F) until planted. "Regular bulbs," which are used for medium and late forcing, are given 25.5 °C (78 °F) followed by 4 weeks at 17 °C (63 °F) prior to planting. De Hertogh (1996) provided detailed forcing programs for hyacinths in North America.

Commercial bulbs for gardens and landscaping. After being harvested, bulbs for these uses are stored dry and under highly ventilated conditions at 25.5 °C (78 °F). They are shipped and subsequently stored at 17 °C (63 °F).

Iris hollandica (Dutch Iris)

De Munk and Schipper (1993) reviewed the physiology, pests, and other aspects of dutch iris. The two major storage diseases of dutch irises are *Fusarium* and *Penicillium*. To assist in controlling these diseases, it is essential to always handle the bulbs carefully to minimize mechanical damage, which provides sites for disease development. Prestorage and preplanting fungicidal dips are generally used for dutch iris. Current registrations must be consulted for approved fungicides.
After harvest and up to planting, dutch iris bulbs should be stored at 50 to 60% RH to minimize root growth and development of *Penicillium*. In general, unplanted bulbs should never be stored at <0 °C (32 °F) or >30 °C (86 °F) (De Munk and Schipper 1993, Van Aartrijk 1995).

Planting stock. The primary objective during postharvest storage of the bulbs is to prevent flower formation in order to produce round, commercial-sized bulbs in the field. In addition, the conditions should prevent the development of diseases. The control of flower initiation is very critical in 7/8-cm circumference planting stock bulbs. This size group is known as "the in-between size," since larger bulbs flower readily and smaller ones do not. These bulbs should be provided with the following postharvest temperatures: 23 °C (73 °F) from harvest to 1 September, followed by 2 weeks at 30 to 35 °C (86 to 95 °F), and then, depending on the cultivar and bulb size, 5 to 9 °C (41 to 48 °F). Bulbs that are smaller than 7/8 cm in circumference should be stored at 18 to 20 °C (64 to 68 °F).

Commercial bulbs for forcing. Generally, bulbs for very early forcing are stored at 30 °C for a few days after being harvested. This is necessary for bulb drying, cleaning, and grading. They are subsequently exposed to 500 µL L^{-1} ethylene for 24 h. This treatment stimulates flower initiation, especially with small bulbs of some cultivars and bulbs not receiving sufficient heat in the field before being harvested. Bulbs for late and retarded (up to 1 year) forcing are placed at 30 °C (86 °F) to suppress their growth and development. Prior to planting, they are "precooled" at 5 to 9 °C (41 to 48 °F) for 6 to 11 weeks, depending on the cultivar. After being precooled, bulbs should be planted as quickly as possible and, if transported, the period should be as short as possible. De Hertogh (1996) provided forcing programs for dutch iris used as fresh cut flowers in North America.

Commercial bulbs for outdoor uses. Dutch irises are grown outdoors as commercial fresh cut flowers and in gardens and landscapes. After being harvested, these bulbs are initially stored at 30 °C (86 °F) and then shipped and stored at 17 °C (63 °F) until planted. When necessary, bulbs can be precooled for 3 to 4 weeks at 5 to 9 °C (41 to 48 °F).

Lilium (Lilies)

In North America two basic types of commercial lilies are generally used: the Easter lily *(L. longiflorum),* which is mainly used as a flowering potted plant, and a wide range of hybrid and species lilies, which are used either as fresh-cut flowers, as flowering potted plants, or in gardens and landscapes. When properly packed in moist peat, unplanted lily bulbs can be stored at -1 to -2 °C (28 to 30 °F), but are normally never stored above 17 °C (63 °F) (Beattie and White 1993, Miller 1993, Van Aartrijk 2000).

Easter lily. Miller (1993) reviewed the physiology of forcing and bulb production, pests, and other aspects of the Easter lily. These bulbs are produced in the coastal areas of Northern California and Southern Oregon. Immediately after being harvested and graded, the "planting stock" is planted in the field. The "commercial-sized bulbs" are immediately packed in moist peat in wooden cases and then sent to either the forcer or commercial bulb jobber. To flower properly, the bulbs must receive 6 weeks at 2 to 7 °C (36 to 45 °F) either by case precooling in moist peat or by being controlled-temperature forced in pots in a moist planting medium. De Hertogh (1996) provided forcing schedules for Easter lily in North America.

Hybrid lilies. Beattie and White (1993) reviewed the physiology, pests, and other aspects of the hybrid and species lilies. Breeding of these lilies is expanding rapidly and many new cultivars are continuously being released. After being harvested, the bulbs are graded and cleaned. To properly flower them, the bulbs must be packed in moist peat, wrapped in polyethylene, and packed in trays for storage and shipping. Subsequently, they require at least 6 to 8 weeks at 2 °C (36 °F) before being planted for early forcing. For late and year-round forcing the bulbs are "frozen-in" at -1 to -2 °C (28 to 30 °F) after being precooled for 6 to 8 weeks. Modified atmospheres (ULO) systems, although not new (Stuart et al. 1970), are being used for long storage of some hybrids (Anonymous 1996). This system is being used because there are fewer negative effects of the long-term period of being frozen-in (Van Aartrijk 2000). An alternative to this system is to produce the bulbs in the Southern Hemisphere for fall planting in the Northern Hemisphere (Anonymous 2001). Planting stock is stored at 2 °C (36 °F) in moist peat until planted. De Hertogh (1996) provided forcing guidelines for Asiatic and Oriental lilies in North America.

Narcissus (Hardy Daffodils and Paperwhites)

There are two basic groups of *Narcissus*, the "Hardy *Narcissus*" (daffodils) and the nonhardy "Paperwhite *Narcissus.*" Hanks (1993) reviewed the physiology, pests, and other aspects of these groups. With the exception of the hot water treatment (see below), nonplanted hardy *Narcissus* bulbs are never stored at >34 °C (93 °F) (see early forcing below), while paperwhites are not stored at >30 °C (86 °F) (Hanks 1993). Neither group of bulbs is stored at <0 °C (32 °F) (Van Aartrijk 1995).

Hardy Narcissus. By far, the largest group of *Narcissus* comprisesthe hardy cultivars, and hundreds are grown in many countries. The major storage diseases are *Fusarium* and *Penicillium* (Byther and Chastagner 1993, Van Aartrijk 1995). To control *Fusarium* in the planting stock, approved fungicides are added during a hot water treatment (HWT) of 1 to 2 h at 44 °C (112 °F). This treatment also controls nematodes and bulb flies. *Penicillium* can be controlled by use of proper ventilation conditions and a RH of 85 to 90%. Except for the HWT, planting stock bulbs are stored at 17 to 20 °C (63 to 68 °F). Commercial bulbs for early forcing are given 1 week at 34 °C (93 °F) followed by 17 °C (63 °F). All of the other bulbs are provided 17 to 20 °C (63 to 68 °F). De Hertogh (1996) provided forcing programs for hardy *Narcissus* cultivars in North America. Transportation of hardy daffodils either for forcing or garden and landscape use should be at 17 °C (63 °F) under highly ventilated conditions.

Paperwhite Narcissus. Most cultivars of paperwhite *Narcissus* bulbs are produced in Israel. They are not considered to be hardy bulbs but can be planted outdoors in USDA Climatic Zones 9 to 11 (Cathey 1990). Planting stock and commercial bulbs are stored at 25 to 30 °C (77 to 86 °F) after being harvested. Commercial bulbs should be shipped at 25 to 30 °C (77 to 86 °F) under highly ventilated conditions. After arrival, bulbs should be stored at 25 to 30 °C (77 to 86 °F) until shoots begin to emerge. Subsequently, they should be placed at 2 °C (36 °F). Prior to planting, they require 2 weeks at 9 to 17 °C (48 to 63 °F). De Hertogh (1996) provided forcing programs for Israeli-grown paperwhites in North America.

Tulipa (Tulips)

Le Nard and De Hertogh (1993b) reviewed the physiology, pests, and other aspects of tulips. Without question, tulips are the largest taxa of flower bulbs grown and used throughout the world. Hundreds of cultivars are produced for forcing as fresh cut flowers, as potted growing plants, and in gardens and landscapes. The major storage diseases are *Fusarium* and *Penicillium*. Normally, *Fusarium* infections begin in the field and continue during postharvest storage. There are substantial differences in cultivar susceptibility, but it is important to reduce the number of infected bulbs in storage because of the ethylene they produce. This can lead to flower abortion and abnormalities. Thus, the bulbs must be routinely inspected and the rooms monitored for ethylene; levels in the storage rooms must not exceed 0.1 $\mu L\ L^{-1}$. In storage, *Penicillium* can be controlled with high rates of ventilation and RH of 85 to 90%. Regardless of the horticultural use, tulip bulbs should be shipped at 17 °C (63 °F) under a ventilation rate of 150 $m^3\ h^{-1}$. With the exception of the 34 °C (93 °F) treatment for early forcing (see below), nonplanted bulbs are never stored at >25 °C (77 °F) or <0 °C (32 °F) (Le Nard and De Hertogh 1993b, Van Aartrijk 2000).

Planting stock. After being harvested, bulbs are initially placed at 23 to 25 °C (73 to 77 °F) for 3 to 4 weeks. Subsequently, depending on the cultivar, they are stored at progressively lower temperatures, from 23 to 20 °C (73 to 68 °F) down to 17 to 15 °C (63 to 59 °F), until just before being planted. These temperatures are used to encourage enhanced production of large sized bulbs from the planting stock.

Forcing bulbs. For very early forcing, most cultivars are given 34 °C (93 °F) for 1 week immediately after lifting. Subsequently, they are stored under dry and well-ventilated conditions at 17 to 20 °C (63 to 68 °F). It is very important to be able to identify the stages of flower initiation (Hartsema 1961), since most cultivars must reach stage G prior to being precooled at 5 to 9 °C (41 to 48 °F). For medium and late forcing, bulbs are placed at 17 to 23 °C (63 to 73 °F) prior to planting at low temperatures. De Hertogh (1996) provided forcing programs for cut and potted tulips in North America. However, bulbs are also grown in the Southern Hemisphere for planting in the fall in the Northern Hemisphere (Anonymous 2001). As with the hybrid lilies, this eliminates the need for and effects of long storage periods.

Garden and landscaping bulbs. The key to use of tulip bulbs in North America is the USDA Climatic Zone (Cathey 1990). In northern climatic zones, they naturally receive adequate cold exposure to satisfy their low temperature requirement. In warm climatic zones, they must be precooled at 5 °C (41 °F) for 8 to 10 weeks prior to planting. Normally after being harvested, tulip bulbs for gardens and landscape use are stored at 20 to 23 °C (68 to 73 °F) and then shipped and stored at 17 °C (63 °F) prior to being planted.

References

Anonymous. 1996. Resultaten ULO-bewaring lelies hoopvol. CNB INFO 551:19.

Anonymous. 2000. Inventarisatie wereldbollenareaal. Bloembollencultuur 21:4.

Anonymous. 2001. Bollenareaal: Wereldwijde groei. Bloembollencultuur 21:7,17-19.

Baker, J. 1993. Insects. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 101-153. Elsevier Science Publishers, Amsterdam, Netherlands.

Beattie, D.J., and J.W. White. 1993. *Lilium*—Hybrids and Species. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 423-454. Elsevier Science Publishers, Amsterdam, Netherlands.

Byther, R., and G. Chastagner. 1993. Diseases. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 71-99. Elsevier Science Publishers, Amsterdam, Netherlands.

Cathey, M. 1990. USDA Plant Hardiness Zone Map. Miscellaneous Publication 1475, U.S. Department of Agriculture, Washington, DC.

Cohat, J. 1993. *Gladiolus*. *In* A.A. De Hertogh, and M. Le Nard, eds. The physiology of flower bulbs. pp. 297-320. Elsevier Science Publishers, Amsterdam, Netherlands.

De Hertogh, A.A. 1996. Holland Bulb Forcer’s Guide, 5th ed. Intl. Flower Bulb Centre, Hillegom, Netherlands.

De Hertogh, A.A., and M. Le Nard. 1993a. The Physiology of Flower Bulbs. Elsevier Science Publishers, Amsterdam, Netherlands.

De Hertogh, A.A., and M. Le Nard. 1993b. Botanical aspects of flower bulbs. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 7-20. Elsevier Science Publishers, Amsterdam, Netherlands.

De Hertogh, A.A., and M. Le Nard. 1993c. World production and horticultural utilization of flower bulbs. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 21-28. Elsevier Science Publishers, Amsterdam, Netherlands.

De Hertogh, A.A., and M. Le Nard. 1993d. Physiological and biochemical aspects of flower bulbs. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 53-69. Elsevier Science Publishers, Amsterdam, Netherlands.

De Hertogh, A.A., and M. Le Nard. 1993e. Physiological disorders. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 155-160. Elsevier Science Publishers, Amsterdam, Netherlands.

De Munk, W.J., and J. Schipper. 1993. *Iris*—bulbous and rhizomatous. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 349-379. Elsevier Science Publishers, Amsterdam, Netherlands.

Hanks, G.R. 1993. *Narcissus*. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 463-558. Elsevier Science Publishers, Amsterdam, Netherlands.

Hartsema, A.M. 1961. Influence of temperatures on flower formation and flowering of bulbous and tuberous plants. *In* W. Ruhland, ed., Handbuch der Pflanzenphysiologie, pp. 123-167. Springer-Verlag, Berlin.

Le Nard, M., and A.A. De Hertogh. 1993a. Bulb growth and development. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 29-43. Elsevier Science Publishers, Amsterdam, Netherlands.

Le Nard, M., and A.A. De Hertogh. 1993b. *Tulipa*. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 617-682. Elsevier Science Publishers, Amsterdam, Netherlands.

Miller, W.B. 1993. *Lilium longiflorum*. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 391-422. Elsevier Science Publishers, Amsterdam, Netherlands.

Nowak, J. and R.M. Rudnicki. 1993. *Hyacinthus*. *In* A. De Hertogh and M. Le Nard, eds., The Physiology of Flower Bulbs, pp. 335-347. Elsevier Science Publishers, Amsterdam, Netherlands.

Raunkiaer, C. 1934. Life Forms of Plants and Statistical Plant Geography. Clarendon Press, Oxford, U.K.

Stuart, N.W, S. Parsons, and C.J. Gould. 1970. The influence of controlled atmospheres during cold storage on the subsequent flowering of Easter lilies and bulbous Iris. HortScience 5:356.

Theron K.I., and A.A. De Hertogh. 2001. Amaryllidaceae: geophytic growth, development and flowering. Hort. Rev. 25:1-70.

Van Aartrijk, J. 1995. Ziekten en Afwijkingen bij Bolgewassen. Deel 2: Amaryllidaceae, Araceae, Begoniaceae, Cannaceae, Compositae Iridaceae, Oxalidaceae, Ranunculaceae. Tweede Druk. Laboratorium voor Bloembollenonderzoek, Lisse, Netherlands.

Van Aartrijk, J. 2000. Ziekten en Afwijkingen bij Bolgewassen. Deel 1: Liliaceae. Derde Druk. Laboratorium voor Bloembollenonderzoek, Lisse, Netherlands.

Flowering Potted Plants

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Transporting and storing flowering potted plants challenges commercial growers' continuing ability to provide a high quality product. Quality suffers when plants are exposed to adverse shipping and storage conditions, such as exclusion from light in closed containers and sleeves, exposure to harmful gases and temperature extremes, poor air ventilation, high RH, and vibration. These conditions can lead to deterioration of even the highest quality plants. Further, the environmental and physical stresses imposed on plants during transit are worsened if plants are improperly produced, incorrectly packaged, or mishandled during shipping or upon receipt.

Flowering potted plants represent a significant portion of floriculture production in the United States (20.3% of production), with 53% of the production in six States: California, Florida, Texas, Pennsylvania, North Carolina, and New York. Plants are often produced at locations distant from the point of marketing; Thus shipping, often for long distances, has become commonplace in the industry. The extended shipping or storage times may result in loss of quality and reduced longevity.

Flowering potted plants range from cold tolerant to chilling sensitive and from ethylene insensitive to ethylene sensitive. Quality and longevity are based on flower longevity and leaf quality. A flowering potted plant with yellow leaves has little value even if the flowers last for a long period. Likewise, plant quality is diminished when the flower dies rapidly though the leaves remain green. Problems with shipping may not be apparent immediately following shipping: Buds or flowers may drop several days after unboxing, or leaves may turn yellow or flowers die prematurely 1 to 2 weeks after shipping. Research over the last 25 years has concentrated on factors providing for retention of leaf color while maximizing flower longevity.

Cultivar selection and production conditions affect the response of flowering potted plants to shipping conditions. Chrysanthemum and poinsettia cultivars vary considerably in their ability to withstand shipping. Hibiscus cultivars drop buds and flowers as a result of improper shipping conditions. It is likely that differences in cultivar response of other flowering potted plants to shipping conditions exist, but extensive research has not been conducted to elucidate these responses.

Production conditions can play a major role in the ability of potted flowering plants to withstand shipping conditions. High fertilizer levels during production decreases the quality of chrysanthemums, campanula, poinsettia, and other plants during and following shipping. In chrysanthemum, terminating fertilizer at flower color (3 weeks prior to marketing) resulted in a 7- to 11-day increase in longevity, depending on cultivar and fertilizer rate. With potted roses, overwatering of the plants during the final 1 to 2 weeks of production results in rapid losses in plant and flower quality following shipping as a result of damage to the root system.

Four factors—disease, improper temperature, extended shipping duration, and exposure to ethylene—result in either rapid loss of quality during shipping or reduced longevity and quality following shipping. All of these factors can be interrelated in their effects. For instance, packing flowering potted plants in a warm greenhouse or packing area then placing the box into a cooler will result in condensation on the flowers and leaves, providing ideal conditions for botrytis, powdery mildew, or other diseases. Similarly, use of optimum temperatures may cause problems during long shipping times.

Production and shipping practices should minimize the potential incidence of diseases. For instance, calcium sprays and reduced fertilizer have been shown to minimize the incidence of poinsettia bract edge burn in the greenhouse, during shipping, and in the retail setting. In most cases, diseases, especially botrytis and powdery mildew, will become worse during shipping because of the high RH microclimate created in the closed shipping box.

Temperature management is one of the best methods of maintaining quality during shipping. Reduced temperatures lead to lower respiration, conservation of carbohydrate reserves, and minimize problems associated with ethylene. Optimum shipping temperature varies with species, but plants should be shipped at the lowest possible temperature (table 1). Chilling-sensitive crops are generally shipped at 50 to 53 °F (10 to 12 °C), while those that are not chilling sensitive are shipped at 35 °F (2 °C) to maximize plant and flower quality.

Ethylene can adversely affect quality. Plants may produce ethylene, or plants may be exposed to ethylene from external sources, such as combustion engines and dead and decaying organic matter (fruit, vegetables, or flowers). Ethylene is a colorless, odorless gas that can cause many undesirable effects on flowering potted plants at very low levels—25 to 100 nL L^{-1} (ppb). Typical ethylene injury symptoms include leaf and bud drop, premature aging, and leaf yellowing, but other disorders have also been identified (table 2).

Regardless of concentration, ethylene becomes more damaging as temperature increases during the exposure period. Of course, injury is worse with higher concentrations and longer exposure periods. For example, open carnations are 1,000-fold more sensitive to ethylene at 21 °C (70 °F) than at 2 °C (36 °F). One of the most effective means of minimizing ethylene damage is to reduce temperature, being cautious not to ship chilling-sensitive crops at too low temperatures. Also, open flowers are often more sensitive to ethylene than buds.

Table 1. Recommended shipping temperatures for flowering potted plants

Shipping temperature	
35 to 40 °F (2 to 5 °C)	**50 to 60 °F (10 to 15 °C)**
Amaryllis	African violet
Azalea	Begonia-elatior
Calceolaria	Bougainvillea
Chrysanthemum	Browallia
Cineraria	Christmas cactus
Crocus	Clereodendron
Cyclamen	Crossandra
Daffodil	Cymbidium
Easter lily	Easter cactus
Freesia	Exacum
Grape hyacinth	Gloxinia
Hyacinth	Hibiscus
Hydrangea	Poinsettia
Kalanchoe	Streptocarpus
Oxalis	
Regal geranium	
Rose	
Tulip	

Adapted from Sterling and Molemaar (1985) and Nell (1993).

Table 2. Response of flowering potted plants to ethylene[1]

Crop	Symptoms
Achimenes	Flower/bud drop
African violet	Flower wilting
Azalea	Leaf drop
Begonia-elatior	Flower drop
Bougainvillea	Flower/bract drop
Browallia	Flower/bud drop
Carnation	Failure of flower to open
Calceolaria	Flower/bud drop
Clereodendron	Flower/bract drop; leaf drop
Crossandra	Flower drop
Cyclamen	Flower drop; flower wilting
Cymbidium	Wilting of the sepal
Exacum	Flower wilting
Geranium	Floret drop
Gardenia	Flower/bud drop
Gloxinia	Flower drop
Hibiscus	Flower/bud drop
Kalanchoe	Failure of flowers to open; petal drying
Pachystachus	Petal wilting; bud blasting; leaf yellowing
Poinsettia	Petiole droop[2]
Streptocarpus	Flower drop

Adapted from Woltering (1987).

[1] The degree of sensitivity to ethylene varies with plant species, variety, ethylene concentration, and temperature during exposure and duration of exposure.

[2] Petiole droop (epinasty) of poinsettia is caused by upward bending of leaf and bract petioles during sleeving.

Several chemicals are available commercially that will minimize the detrimental effects of ethylene. Application procedures and effectiveness on ethylene-sensitive crops vary, but these chemicals can be a valuable tool for crops that exhibit ethylene injury. The use of anti-ethylene chemicals is especially valuable on chilling-sensitive crops, since temperature cannot be reduced.

Flowering potted plant quality can be maintained during shipping provided that production practices and cultivar are selected properly and optimum shipping conditions are maintained, including temperature management and prevention of injury from ethylene. However, regardless of the conditions, shipping and storing flowering potted plants for extended periods will lead to decreased longevity. Ideally, flowering potted plants should be stored and shipped for brief periods at optimum conditions.

References

Nell, T.A. 1993. Flowering Potted Plants: Prolonging Shelf Performance. Ball Publishing Co., Batavia, IL

Sterling, E.P., and W.H. Molemaar. 1985. The influence of time and temperature during simulated shipment on the quality of potplants. Rapport Sprenger Instituut no. 2286, Springer Institute, Wageningen, The Netherlands

Woltering, E.J. 1987. Effects of ethylene on ornamental pot plants: classification. Scientia Hort. 31:283-294

Foliage Plants

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Foliage plant production and sales represent a significant part of ornamental plant production in the United States. In 1998, sales were $509 million, with the greatest production in Florida (61%), California (18%), and Texas (4%). Consequently, foliage plants are shipped long distances to supply retail markets throughout North America and Europe.

Temperature control is critical to successful shipping and quality retention in the darkness of transport vehicles. The shipping environment is not conducive to maintaining foliage plant quality. Although it is difficult to generalize, the best shipping temperature is in the range of 15 to 18 °C (59 to 64 °F) with 85 to 90% RH. Temperatures of 10 to 13 °C (50 to 55 °F) are the lowest that should be considered for shipping, and even at this range some chilling injury may occur with some plants.

Foliage plants should be acclimatized by growers prior to shipment. Acclimatization is the process of making plants more tolerant to environmental changes during or after shipment. Growers acclimatize plants using lower fertilizer levels and temperatures or reduced light and water during the last 2 to 4 weeks before shipment. Acclimatized plants are better adapted to dark storage in transit and reduced light in stores than nonacclimatized plants. Requirements and length of shipping tolerated vary because of the wide diversity of foliage plants. Shipping temperatures have been identified for some acclimatized plants in temperature-controlled containers (table 1). These guidelines are based on simulated shipping tests in darkness.

In simulated shipping tests at 10, 13, 16, and 19 °C (50, 55, 61, and 66 °F) for 1 to 4 weeks in the dark, *Scheffiera arboricola* shipped best at 19 °C, *Ficus benjamina* at 10 or 13 °C, and *Dracaena marginata* equally well at 13, 16, and 19 °C. These plants withstood shipment for 3 weeks without a significant loss of quality and for 4 weeks, at some temperatures, without severe quality reduction. *Shefflera* plants recovered from dark storage within 17 days after transfer to light. *Ficus* plants are damaged by holding at 4 °C (39 °F) for 6 or more days. Similar chilling injury can occur on many foliage plaints at temperatures of 7 °C (45 °F) for long periods or 2 to 5 °C (36 to 41 °F) for even short periods. Although 1 day at 5 °C (41 °F) may not damage most foliage plants, severe damage can occur when plants are subjected to cool temperatures over a 3- to 5-day transit time. Coleus is very cold sensitive. *Dracaena sanderana* and *Spathiphyllum clevelandii* are severely injured after 1 day at 2 °C (36 °F) and slightly after 1 day at 10 °C (50 °F). *Aglaonema* is very intolerant of temperatures <10 °C (<50 °F). Exposure to 4.4 °C (40 °F) for 2 days causes severe damage to *Scindapsus pictus* (satin pothos) and *Maranta leuconeura* (prayer plant). *Fittonia verschaffeitii* (silvernerve plant) is severely damaged within 8 h at 2 °C (36 °F).

Foliage plants should be turned over rapidly in marketing and should not be overordered. Plants should not be stored in back rooms for extended periods or in severe drafts of heat or cold. Foliage plants should not be transported with fruits, vegetables, or cut flowers, most of which emit ethylene and are shipped at low temperatures. Plants such as scheffleras, crassulas, fittonias, and ficuses are very sensitive to ethylene.

Table 1. Suggested shipping temperatures for acclimatized foliage plants to maintain quality in refrigerated vans[1]

Plant name	1-15 days shipment		16-30 days shipment[2]	
	°C	°F	°C	°F
Aglaonema, cv. 'Fransher'	13-16	55-60	16-18	60-65
Aglaonema, cv. 'Silver Queen'	16-18	60-65	16-18	60-65
Ardisia crispa	10-13	50-55	—	—
Aspidistra elatior	10-13	50-55	—	—
Brassaia actinophylla	10-13	50-55	10-13	50-55
Chamaedorea elegans	13-16	55-60	—	—
Chamaedorea seifrizii	13-16	55-60	—	—
Chrysalidocarpus lutescens	13-18	60-65	16-18	60-65
Codiaeum variegatum	16-18	60-65	16-18	60-65
Cordyline terminalis	16-18	60-65	—	—
Dieffenbachia picta	16-18	60-65	—	—
Dracaena deremensis	16-18	60-65	—	—
Dracaena fragrans	16-18	60-65	—	—
Dracaena marginata	13-18	55-65	16-18	60-65
Ficus benjamina	13-16	55-60	13-16	55-60
Ficus nitida	13-16	55-60	—	—
Howeia forsteriana	10-18	50-65	10-18	50-65
Nephrolepis exaltata	16-18	60-65	—	—
Peperomia bicolor	16-18	60-65	—	—
Philodendron selloum	13-16	55-60	—	—
Philodendron oxycardium	16-18	60-65	—	—
Phoenix roebelenii	10-13	50-55	—	—
Pleomele reflexa	16-18	60-65	—	—
Rhapis excelsa	10-13	50-55	—	—
Schefflera arboricola	10-13	50-55	10-13	50-55
Scindapsus aureus	16-18	60-65	—	—
Spathiphyllum, Mauna Loa	10-13	50-55	13-16	55-60
Yucca elephantipes	10-13	50-55	10-13	50-55

[1] Data are for plants in containers in the dark. Some plants stored without lights for 10 to 14 days will show slight to severe leaf loss and/or yellowing but will recover.
[2] Blanks indicate that plant's tolerance to shipping beyond 15 days is unknown.

Herbaceous Perennials

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Introduction

Herbaceous (nonwoody) perennials are a diverse group of plants grown primarily for their ornamental value in gardens throughout the world. Storage of herbaceous perennial plant material may be required at several steps during the production and marketing of the final product, which is often a containerized flowering plant for retail sales. Some herbaceous perennials such as strawberry, rhubarb, potato, and asparagus are grown as food crops, but the storage of their underground organs is discussed separately in this handbook. Many herbaceous perennials have succulent stems and leaves that, in cold or dry climates, die back in fall to an overwintering crown or root structure, while others cease growth but do not go dormant in response to inclement weather.

Herbaceous perennials include species in just about every plant family and vary greatly in adaptability, growth patterns, and tolerance to heat and cold. In fact, it is the great diversity that presents the most problems, including that of postharvest storage. Some nurseries carry hundreds if not thousands of species, and methods of production vary greatly.

Storage of Bare-Root Crowns

Seedlings, rooted cuttings, or divisions can be field-planted, grown, and harvested as bare-root (crowns and roots with soil removed) plants in fall. Storage of the bare-root plants is convenient, since they can be trimmed, processed, and packaged during winter when harvest may not be practical because of snow, ice, or rain. Throughout winter and spring, bare-root plants are removed from storage and shipped to wholesale and retail nurseries.

Grower experience and research results have established that many hardy herbaceous perennials will retain excellent regrowth quality after several months of storage when properly packed to control moisture loss and stored at -2 °C (28 °F) (Walters 1983). Mahlstede and Fletcher (1960) published an excellent and comprehensive summary of the requirements for storage of nursery stock (unfortunately out of print).

Field Conditions and Harvesting of Bare-Root Crowns

Rain and excess moisture in the field can cause serious problems during storage, particularly if any free water from the harvested plants is not removed before storage. Crowns and roots can be difficult to dry and can quickly develop surface molds and rots. Many growers prefer to grow plants on sandy soils so that harvesting is interrupted as little as possible during wet periods (Walters 1983).

Field-grown herbaceous perennials should be harvested after the crowns are fully mature for optimum storage success. Peony, iris, mertensia, and poppy can be harvested even before the first freeze, since they tend to mature early in the fall. However, many other hardy herbaceous perennials enter dormancy later in the season or not at all and should be harvested as late in fall as possible for best storage success (Mahlstede and Fletcher 1960, Hanchek and Cameron 1995). For most hardy herbaceous perennials, sugars and nutrients accumulate in the roots, crowns, and other underground organs, while leaves and above-ground tissues senesce in response to short days, low temperatures, or both in a process similar to that in potato, sugar beet, and certain other edible herbaceous perennials.

If harvested before complete maturation, bare-root plants will have a much shorter storage life because of various factors such as incomplete carbohydrate accumulation, insufficient suberization of the roots and crowns, lack of overwintering buds, and ultimately the development of molds and rots (Hanchek and Cameron 1995). In practice, however, growers often harvest prematurely in fall, especially in northern regions, since snow can quickly end the harvest season. Growers must accept the extra risk of reduced storage life imposed by the earlier harvest.

When possible, plants should be harvested after tops have at least begun to die back, often after the first hard freeze. Some species never really go dormant and do not completely die back to the ground except in the coldest of winters. In some instances, the tops can be cut with a rotary mower to remove excess leaves and stems before harvest to reduce postharvest cleaning and grading and potentially increase storage success. However, most species that do not attain full dormancy are difficult to store for long periods, since many have wounded green tops with a high respiration rate, fibrous roots, and insufficient carbohydrate storage reserves. Also, the more green tissue removed, the more likely that the crowns are not fully mature.

Classification of Perennials by Root Characteristics

Mahlstede and Fletcher (1960) suggested several categories of perennials based primarily on structural or physical characteristics of the overwintering underground structures. Considering the diversity of herbaceous perennials, the overwintering root structure can provide one additional piece of information that can be used to develop storage recommendations.

Greentops are one group of herbaceous perennials that overwinter with at least some above-ground leaf and stem tissue remaining. Green tissue increases the storage difficulty for a great percentage of the plants in this category. Difficult-to-store greentops include ajuga, arabis, alyssum, creeping phlox, coreopsis, dianthus, and gaillardia.

Numerous difficult-to-store herbaceous perennials have fibrous roots. During the natural cycle of growth, it is not uncommon for plants to recycle fibrous roots, meaning that most small roots die during winter and are replaced the following spring as growth commences. The dead and dying roots do not usually create problems outdoors but can feed numerous surface molds while in storage. The molds are unsightly and can lead to loss of product (Hanchek et al. 1990). Fungicides are seldom used to control molds, in part because of the great diversity of plant types and sensitivity.

Some herbaceous perennials such as *Dicentra spectabilis* (bleeding hearts) have more specialized crowns and roots. These enlarged roots hold substantial food reserves and can be successfully stored for several months when harvested mature. However, when harvested immature, bleeding hearts are very susceptible to surface molds (Hanchek et al. 1990). In many respects, this process is similar to maturation and storability of potato tubers.

Postharvest Grading and Packaging

Ideally, harvested roots and crowns should be processed, packed, and immediately cooled for long-term storage. In practice, herbaceous perennials are often harvested in fall faster than they can be processed. Crowns, roots, and remaining above-ground tissue are rapidly respiring immediately after harvest because of wounding, and to prevent fermentation it is critical to keep plants cool and to provide adequate ventilation for the tissue. Initial plant temperature depends on soil and air temperatures during harvest. Harvested plants should be quickly cooled to 0 °C (32 °F) to reduce respiration and moisture loss, though precooling seldom occurs in practice. Temperatures of harvested material should be monitored closely with hand-held or automated thermometers. There is a real possibility of fermentation when O_2 movement is restricted in large piles or tightly packed crates of plants, particularly those with green tops or fibrous root systems. If temperatures rise in stacks of plant material, then it is critical to add refrigeration, improve ventilation, or both.

Excess green tissue is usually removed during grading, and plants may be cut into smaller divisions for propagation. The wounds caused during division can be a source of subsequent infection if not properly healed before storage. Even typically easy-to-store plants such as hosta and daylily can be lost during long-term storage because of fungal and bacterial wound infection. Conditions favoring wound healing could be useful for these crops after grading. No studies have been published on wound healing of harvested herbaceous perennials, but wound healing and suberization of potato tubers occurs most rapidly at 15 to18 °C (60 to 65 °F) and <90% RH.

Packaging depends on the intended means of storage. Unsealed polyethylene liners (1.5 to 3 mils thick) are used for -2 °C (28 °F) storage. At below-freezing storage temperatures, these liners permit O_2 movement adequate to supply the needs of respiration and protect against water loss (Cameron 1988). These same liners can lead to fermentation and loss of product at higher temperatures, since they may limit air movement to such an extent that the supply of O_2 can not meet the increased demands of respiration. Many herbaceous perennials are packaged in multiples of 25 with the liners in a cardboard box ready for shipping later in the season. It is important to match box size to crown size since overpacking can also lead to fermentation and loss of product, particularly for plants with green tops, fibrous roots, or both. Wood fibers or other dry fillers (such as shredded paper) should be added inside the polyethylene liner to absorb free moisture (condensation etc.) and improve gas exchange inside the package.

In some cases, bare-root plants are stored in bulk bins (often the same as bins used for storage of apples). Although appropriate for some otherwise difficult-to-store plants, bulk bins can lead to problems if extra care is not taken to ensure that the entire contents are cooled quickly. Temperatures at the center of the bin need to be monitored closely, especially for the first 2 to 3 weeks. Heating, fermentation, and eventually decay will start at the middle of the piles. Boxes, crates, or bins should be placed into cold storage in rows that maximize air movement and cooling rate. They can be restacked closer together after they reach storage temperature.

Optimum Storage Conditions

The optimum storage temperature for most hardy herbaceous perennials is between -2.8 and -2.2 °C (27 to 28 °F) (Mahlstede and Fletcher 1960, Maqbool and Cameron 1994). At these temperatures, tissues are generally not frozen, and respiration and water activity are minimized. However, not all herbaceous perennials can withstand subfreezing temperatures, and the following are best stored at 0 to 2 °C (32 to 34 °F) (Mahlstede and Fletcher 1960, Maqbool and Cameron 1994): aconitum, agapanthus, althaea, anchusa, aentranthus, helleborus, hibiscus, malva, shasta daisy.

Some perennials have very poor regrowth following storage, regardless of pretreatments and storage conditions, and are best overwintered as potted plants. These plants, such as gaillardia and coreopsis, can be stored as small containerized plants packed into polyethylene-lined boxes up to several months. Hibiscus, alcea, sidalcea, and other malvaceous plants are sensitive to low temperature storage, even in minimally heated greenhouses. Short-term storage of these genera should be at warmer temperatures. Herbaceous perennials considered very difficult to store for extended durations (Mahlstede and Fletcher 1960) are alcea rosea, anemone, anthemis, asclepias, clematis, coreopsis, epimedium, gaillardia, helleborus, hibiscus, lavender, lithospermum, malva, primula, sidalcea.

Problems During Storage of Bare-Root Perennials

Some herbaceous perennials are difficult to store as bare-root plants for extended periods. Even closely related plants can have different overwintering capacities. Much depends on the species, overall plant vigor, and size in the field before harvest. Problems encountered during storage of bare-root plants include development of rots and surface molds, desiccation, and growth of fragile buds after the dormancy requirement has been met. Each of these problems increases with storage duration and temperature. Hourly or daily temperature fluctuations can increase tissue desiccation, condensation on the package, and ultimately surface molds and rots, so it is important to maintain constant temperature into spring.

Molds and bacteria can establish on dead roots or wounded tissue early during storage, especially if plants are not cooled rapidly. Some surface molds do not seriously harm the regrowth capacity of the crowns (Maqbool and Cameron 1994). However, they are unsightly and often cause rejection of a shipment, which can represent a substantial loss of revenue, considering the time and effort spent producing and storing the plants up to the time they are sold. Molds are invariably more severe at elevated temperatures or when there is significant condensation, particularly if packages are poorly ventilated or stacked without sufficient air circulation. Free water must be absorbed or it will increase mold and rot development. Limited trials with fungicides for control of surface molds have been inconclusive (Hanchek et al. 1990).

Bud-break can occur on many perennials such as asters, shasta daisies, geums, lupines, bleeding hearts, and astilbes kept at 1 °C (34 °F) after their dormancy requirement has been satisfied. New growth is usually etiolated and extremely fragile (Maqbool and Cameron 1994). Bud-break can occur during shipping, since lack of temperature control is common. Astilbes and bleeding heart, often shipped from the Netherlands, commonly have new shoot growth in the packages, presumably because of long shipping times at elevated temperatures. Storage temperatures below 0 °C (32 °F) completely prevented bud-break for all herbaceous perennial species tested (Maqbool and Cameron 1994). In some instances, refrigerated storage facilities do not have adequate cooling capacity, so temperatures can rise in spring as the cooling requirement increases. Premature bud-break can be a serious problem in these storage facilities.

Storage of Herbaceous Perennials in Plug Trays

There has been a complete transition in herbaceous perennial production over the past two decades. Most herbaceous perennials are now propagated, from either seeds or cuttings, in plug trays with anywhere from 32 to 516 small plugs (one plug is an individual cell with one plant) per 30×60 cm (12×24 in) tray by using techniques borrowed largely from the bedding plant industry. The shift to plug production has been hastened by improved uniformity of seed-propagated herbaceous perennials and increased demand for large numbers of plants. Typically, plugs are finished within 6 to 12 weeks of seeding or placement of the cutting. Producers often sell their product to finishers—greenhouse growers who pot plugs into larger containers and grow them for retail sale. Traditionally, plugs are purchased and containerized in fall, and finished plants are sold the following spring or summer.

When started from seeds or cuttings, many young herbaceous perennial plants require a period of cold, or vernalization, before they can achieve optimum regrowth potential (Whitman et al. 1996, Runkle et al. 1998). A cold period of 10 to 15 weeks may be needed to fulfill the vernalization requirement for some herbaceous perennials (Whitman et al. 1996), though 6 to 8 weeks is more common (Cameron et al. 2000). The cold requirement is delivered to containerized plants in overwintering greenhouses with supplemental heating to prevent severe cold damage. Bedding plants are sometimes stored as plugs, though most traditional bedding plants do not have a cold requirement. It is becoming increasingly common to store plugs at low temperatures to economize on the amount of controlled temperature space required. Plugs can be stored for convenience (as when the finish date precedes the marketing date) or to provide a physiological requirement for subsequent flowering. Cooled plugs can be sold at a premium price when there is no need for further cooling.

Many species of perennials can be stored as plugs for more than 3 mo at 5 °C (41 °F), but only when provided with sufficiently intense light to perform photosynthesis. Photosynthesis supplements carbohydrate supplies, which can be depleted during storage, particularly in small plugs. Engle (1994) studied storage of plugs at -2.5 °C (28 °F) in a manner analogous to that described for bare-root plants. Plug trays were packed in polyethylene liners and stored in the dark without any additional water. Many perennial species grown as plugs did not survive direct transfer from the greenhouse to subfreezing temperatures. However, 3 to 6 weeks of hardening at 0 or 5 °C (28 or 41°F) improved storage success for many. As for bare-root storage, plugs with significant green tissue were more difficult to store.

Several growers are experimenting with plug storage under controlled conditions, though most storage still takes place in minimally heated greenhouses. If growers rent storage facilities, they should ensure that refrigeration capacity is adequate to reduce storage temperatures to at least 2 °C (35 °F). Insufficient cooling will increase respiration and plant demand for photosynthetic light. Lighting the plugs will improve success.

References

Cameron, A.C. 1988. Postharvest handling of bareroot plants: desiccation control of bare root stock. Perennial Plants 16:16–18.

Cameron, A.C., B. Fausey, R. Heins, and W. Carlson. 2000. Firing up perennials—beyond 2000. Greenhouse Grower 18(8):74-78.

Engle, B.E. 1994. The Use of Hardening Temperatures and Lighting of Herbaceous Plugs Prior to Storage at -2.5 °C. M.S. Thesis, Michigan State University, East Lansing, MI.

Hanchek, A.M., and A.C. Cameron. 1995. Harvest date and storage quality of herbaceous perennials. HortScience. 30:573-576.

Hanchek, A.M., K. Everts, M. Maqbool, and A.C. Cameron. 1990. Storage molds of herbaceous perennials. J. Environ. Hort. 8(1):29–32.

Mahlstede, J.P., and W.E. Fletcher. 1960. Storage of Nursery Stock. Amer. Assn. Nurserymen, Washington, DC.

Maqbool, M., and A.C. Cameron. 1994. Regrowth performance of field-grown herbaceous perennials following bare-root storage between -10 and +5 °C. HortScience 29:1039–1041.

Runkle, E.S., R.D. Heins, A.C. Cameron, and W.H. Carlson. 1998. Flowering of *Leucanthemum* × *superbum* ‘Snowcap’ in response to photoperiod and cold treatment. HortScience 33:1003–1006.

Walters, J. 1983. Overwintering in the field and in storage. *In* E.M. Smith, and S.M. Still, eds., Proceedings of the Herbaceous Perennial Symposium, July 1983, Columbus, OH. Ohio Cooperative Extension Service Bull. no. 717, Ohio State University, Columbus, OH.

Whitman, C.M., R.D. Heins, A.C. Cameron, and W.H. Carlson. 1996. Cold treatment, photoperiod, and forcing temperature influence flowering of *Lavandula angustifolia*. HortScience 31(7):1150–1153.

Orchids

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Introduction

For years, potted orchids were produced mainly for hobbyists. They are usually shipped in containers and arrive in buyers' hands by overnight delivery or within a few days. Many orchid growers do not ship orchids during winter months to avoid chilling or freezing injury to the plants. However, during the past decade, there has been a tremendous worldwide boom in orchid production for sale as potted blooming plants for the public, particularly the *Phalaenopsis* and *Dendrobium* orchids. Potted, blooming orchids represent a $100 million industry in the United States alone (NASS 2001). However, for the most part, research in proper postharvest handling of orchids has lagged behind the increase in production and demand.

Ethylene Sensitivity

Orchid flowers are extremely sensitive to ethylene, even at very low levels (Davison 1949, Beyer 1976, Goh et al. 1985). Pollination and removal of pollen caps (emasculation) trigger ethylene production by flowers and result in rapid wilting. Blooming orchids should be handled carefully so that accidental pollination and emasculation do not occur. Accelerated flower wilting as a result of ethylene evolution following pollination in *Cymbidium*, *Dortitaenopsis*, *Dendrobium*, and *Phalaenopsis* orchids is induced by a loss of water from cells of the upper layer of the petals, leading to their in-folding and water-soaked appearance (Lee and Lin 1992, Porat et. al. 1994). Treating orchid flowers with the ethylene biosynthesis inhibitor aminooxyacetic acid (AOA) did not alter their sensitivity to ethylene. Research also showed that pulsing excised *Dendrobium* flowers with 0.5 mM AOA for 24 h before exposing them to 0.2 µL L^{-1} ethylene did not prolong their life (Wang and Wang 2000); all treated flowers wilted within 3 days after exposure. Thus, AOA has no effect on longevity when wilting is triggered by exogenous ethylene.

Treatments for Extending Shelf-Life

It was found that shelf-life of *Oncidium* Goldiana cut sprays increased after pulsing with silver nitrate for 30 min (Ong and Lim 1983). Pulsing *Arranda* cut inflorescences for a short 10 min with a 4 mM solution of STS prolonged their display-life (Hew et al. 1987). Exposing excised *Dendrobium* and *Phalaenopsis* flowers to 0.1 µL L^{-1} 1-methylcyclopropene (1-MCP, an ethylene action ihibitor) for 12 h, or pulsing them with 0.5 mM silver thiosulfate (STS, an ethylene inhibitor) for 24 h completely blocked the deleterious effect of ethylene (Wang and Wang 2000). *Phalaenopsis* flowers that were treated with 0.1 to 0.4 µL L^{-1} of 1-MCP are protected against ethylene as high as 10 µL L^{-1}. However, the protective effect of 1-MCP lasts for no longer than 7 days at room temperature. Commercially, cut *Phalaenopsis* inflorescences are pulsed with 0.5 mM STS immediately following cutting.

When used at 50 to 100 mg L^{-1}, 8-hydroxiquinoline sulfate (8-HQS) extended shelf-life of *Dendrobium* Pompadour cut flowers (Kesta and Amutiratana 1986). Conflicting results were reported on the effect of sucrose in keeping solutions as a carbon source for extending vase life of cut orchid flowers.

Sprays of tropical orchids should be stored and transported at 12 to 18 °C (54 to 64 °F) (Akamine 1976), whereas flowers of temperate orchids such as *Cymbidium* may be stored at temperatures as low as 5 °C (41 °F) (Sheehan 1954).

Optimum Storage Conditions

Minimal research has been conducted on optimum orchid storage conditions. In one study (Wang 1997a), bare-root *Phalaenopsis* plants were packed in boxes and subjected to temperatures of 15, 20, 25, or 30 °C (59, 68, 77, or 86 °F) for 4, 7, or 14 days. Weight loss from plants increased with increasing temperature and storage duration. Symptoms of chilling injury were inversely related to 15 and 20 °C storage temperatures. Chilling injury became more severe as storage duration increased. Plants had little or no chilling injury at 25 or 30 °C, regardless of the duration. Leaf loss was most severe on plants stored at 15 °C for 7 or 14 days or 30 °C for 14 days. Plants that have severe leaf loss after storing at 30 °C have delayed spiking and flowering.

Preconditioning greenhouse-grown potted *Phalaenopsis* plants at 25 °C (77 °F) for 10 days, followed by another 10 days at 20 °C (68 °F), reduced severity of chilling injury after storage at 15 °C (59 °F) for 2 weeks. Therefore, *Phalaenopsis* orchids harvested during the warm period of the year should be held above 20 °C (68 °F), and preferably closer to 25 °C (77 °F), during shipping. Under such conditions, plants can lose as much as 20% of their fresh weight at harvest without subsequent performance being adversely affected. While most *Phalaenopsis* species and hybrids need relatively cool air to initiate the flowering process, plants do not respond to cool air while being shipped in the absence of light (Wang 1995).

Although prolonged duration in complete darkness is not recommended for keeping plants in bloom (Wang and Blessington 1989), *Phalaenopsis* orchids tolerate low light levels once they have started flowering. One study show that exposing them to irradiance levels between 10 and 50 $\mu mol\ m^{-2}\ sec^{-1}$ for 12 h daily produced orchids with similar longevity (individual flowers lasting over 120 days) and flower size (Wang 1997b). Therefore, most retail stores have adequate light levels to maintain blooming *Phalaenopsis* while they are being marketed.

Shipping Information

Because of quarantine regulations, internationally shipped orchids are often removed from their potting medium. The bare-root plants are allowed to dehydrate slightly before packing. This is done for several reasons. Slight dehydration allows for packing more plants per box, avoids breaking leaves, and reduces the chances of moisture buildup to weaken shipping boxes. Dryer plants also reduce incidence of rotting before boxes are opened. Plants are usually packed in layers alternating with shredded paper or other material. Often, plants are individually wrapped in newspaper, particularly those that have developed inflorescences.

Millions of bare-root *Phalaenopsis* orchids are shipped domestically and internationally each year. After the orchids are planted in pots and placed on greenhouse benches, yellow spots occasionally develop on either side of the mid-rib near the base of leaves due to chilling injury. Irregular yellow blotches also occur on other parts of leaf blades. Other times, leaves turn yellow and fall off, resulting in weak plants that do not produce flowers.

References

Akamine, E.K. 1976. Postharvest handling of tropical ornamental cut crops in Hawaii. HortScience 11:125-126.

Beyer, E.M. 1976. A potent inhibitor of ethylene action in plants. Plant Physiol. 58:268-271.

Davison, O.W. 1949. Effect of ethylene on orchid flowers. Proc. Amer Soc Hort Sci. 53:440-446.

Hew, C.S., K.H. Wee, and F.Y. Lee. 1987. Factors affecting the longevity of cut *Aranda* flowers. Acta Hort. 205:195-202.

Goh, C.J., A.H. Halevy, R. Engel, and A.M. Kofranek. 1985. Ethylene evolution and sensitivity in cut orchid flowers. Sci. Hort. 26:57-67.

Kesta, S., and D. Amutiratana. 1986. Effect of sucrose, silver nitrate, and 8-hudroxyquinoline sulfate on postharvest behavior of *Dendrobium* Pompadour flowers. *In* Proceedings of the 6th ASEAN Orchid Congress, Bangkok, Thailand, pp. 124-129. Association of Southeast Asian Nations, Bangkok, Thailand.

Lee, N., and Y.S. Lin. 1992. Respiration of *Phalaenopsis* flowers. J. Chinese Soc. Hort. Sci. 38:228-240.

NASS [USDA National Agricultural Statistics Service]. 2001. Floriculture Crops, 2000 Summary. National Agricultural Statistics Service, Washington, DC.

Ong, H.T., and L.L. Lim. 1983. Use of silver nitrate and citric acid to improve shelf-life of *Oncidium* Golden Showers flowers. Orchid Rev. 90:264-266.

Porat, P., A. Borochov, H. Halevy, and S.D. O'Neill. 1994. Pollination-induced senescence of *Phalaenopsis* petals. Plant Growth Regul. 15:129-136.

Sheehan, T.J. 1954. Orchid flower storage. Amer. Orchid Soc. Bul. 23:579-584.

Wang, Y.T. 1995. Phalaenopsis orchid light requirement during the induction of spiking. HortScience 30:59-61.

Wang, Y.T. 1997a. Effect of postharvest temperature and storage duration on growth and flowering of the *Phalaenopsis* orchids. HortScience 32:517.

Wang, Y.T. 1997b. *Phalaenopsis* light requirements and scheduling of flowering. Orchids 66:934-939.

Wang, Y.T., and T.M. Blessington. 1989. Dark-storage temperature and duration influences flowering and quality retention of hibiscus. HortScience 24:646-647.

Wang, M.K., and Y.T. Wang. 2000. 1-MCP and STS counteract ethylene effects on cut orchid flowers. HortScience 35(3):349.

Seeds and Pollen

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Introduction

Seeds of all of the species covered in this handbook must be stored for some length of time after harvest. Some seeds are used as food (for example, cereals and legumes) and stored before consumption, while others are stored to maintain viability and used to produce the next season's crop. This section describes basic procedures to maintain seed and pollen viability. More detailed descriptions or procedures to maintain seed viability for extended periods (for example, for genetic stocks) are published in Agriculture Handbook 506, *Principles and Practices of Seed Storage* (Justice and Bass 1978) or review articles (Priestley 1986, Hong and Ellis 1996, Walters 1998a).

Classification of Seed Storage Behavior

Mature seeds generally have higher tolerance for low moisture levels or temperatures than fresh fruits, vegetables, or flowers. They acquire this tolerance during maturation on the parent plant, presumably as a strategy to survive adverse climatic conditions such as drought and winter. The degree of tolerance varies among species, but three general categories exist: orthodox, recalcitrant, and intermediate.

Orthodox seeds are produced by most annual or biennial crops and horticultural species. Some examples are grains, pulse crops, vegetables, floral crops, and temperate tree fruit, as well as many temperate forest tree and shrub species. Orthodox seeds can survive complete water removal and can be easily stored for many years by drying and cooling.

Recalcitrant seeds are produced by herbaceous plants from aquatic habitats (for example, wildrice, watercress, and wasabi), perennials from tropical areas (examples include avocado, mango, coconut, cocoa, and jackfruit), and some deciduous forest trees from temperate areas (such as oak, chestnut, buckeye, and silver and sycamore maple). As the name implies, recalcitrant seeds are difficult to store and have shelf-lives usually <1 year unless they are cryopreserved.

Intermediate seeds are produced by perennials of tropical and subtropical origin (such as coffee, citrus, macadamia, and papaya) and by some tree nut species (such as walnut, hickory, pecan, hazelnut, and pistachio). (Hazelnut and pistachio may belong to the recalcitrant category.) With proper handling and excellent quality seeds, the viability of seeds with intermediate storage behavior can be maintained for a few years. These seeds can be stored over a single winter with a stratification treatment such as damp media at 5 °C (41 °F).

The best way to identify whether a seed is recalcitrant or not is to monitor survival while drying (Hong and Ellis 1996). Seeds that are recalcitrant lose viability within minutes of drying below 85 to 90% RH. Intermediate seeds lose viability within days of drying below 20% RH. Seeds that are orthodox can survive many months or even years when dried to 5% RH. The ability of orthodox seeds to survive drying is acquired during development, so seeds harvested prematurely will appear to be recalcitrant (Vertucci and Farrant 1995). Mature seeds must be dried sufficiently rapidly—within a few days—to avoid deterioration at intermediate water contents (Pammenter and Berjak 1999). Often drying experiments are inconvenient to perform, and growers resort to anecdotal information or guidelines (table 1) to identify storage behavior of their seeds. Guidelines exist to help identify seed storage behavior, but there are no hard and fast rules. A compendium listing storage guidelines for over 7,000 species is now available (Hong et al. 1996). Also, useful information on woody species grown in the United States can be gleaned from Agricultural Handbook 450 (Schopmeyer 1974).

Table 1. Guidelines to identify storage behavior of seeds

Trait	Guideline	Some exceptions
Growth habit	Most herbaceous plants produce orthodox seeds	Aquatic species
Habitat	Many aquatic species, tropical rainforest species, and temperate climax forest species produce recalcitrant seeds	Most native Hawaiian species, temperate conifers, some maples
Water content at harvest	Most orthodox seeds dry naturally on the parent plant	All immature seeds, Solanaceae, Cucurbitae
Seed size	Recalcitrant seeds are often large	Some aquatic species, Rutaceae, some Rubiaceae
Desiccation sensitivity	Orthodox seeds can survive complete water loss; recalcitrant seeds cannot	Orthodox seeds dried very slowly (for >2 weeks) can be severely damaged

Seed Storage Behavior and General Storage Principles

Because they are sensitive to drying, recalcitrant seeds must be stored at 92 to 98% RH. The best storage temperature depends on the chilling sensitivity of the species. Seeds from many tropical fruits (mango, avocado, cocoa, jackfruit) are sensitive to chilling and should be stored at ≥15 °C (59 °F). These seeds have the shortest potential shelf-life, remaining viable for 2 weeks to 3 mo. Seeds produced from temperate species such as oaks, buckeye, or chestnut can survive for 0.5 to possibly 2 years by storing them at 2 to 5 °C (36 to 41 °F). Microbial contamination is always a problem at high RH, and seeds often survive longer if a fungicide is applied. Storage in damp peatmoss is often beneficial. The RH required for safe storage of recalcitrant seeds often allows seeds to germinate. Once this has occurred, procedures for storage of seedlings should be adopted.

Seeds with intermediate storage behavior are more amenable to drying and consequently can be preserved for longer periods than recalcitrant seeds. RH of 40 to 60% appears to provide maximum longevity. Intermediate seeds survive 1 to 6 mo if stored at 25 °C (77 °F) and 2 to 5 years if stored at 5 °C (41 °F). These seeds rapidly lose viability if frozen (stored at -18 °C [0 °F]).

Seeds that exhibit orthodox behavior are easily stored by drying and cooling. The extent to which drying and cooling extends shelf-life is best described by Harrington's "Thumb rules" which state that the life of a seed is doubled for every 1% decrease in water content or every 5 °C (41 °F) decrease in temperature (Harrington 1963, Justice and Bass 1978). The "100s Rule" states that adequate longevity for commercial seed storage purposes (<5 yr) can be achieved by ensuring that the sum of the RH and temperature in °F during storage does not exceed 100.

These rules were developed as guidelines for commercial seed storage. They are not valid for extremely dry conditions, and their applicability at extremely cold temperatures has not been adequately tested.

A relatively new rule is that seeds store optimally at 15 to 25% RH. Storing seeds with RH <15% will not increase shelf-life and may actually accelerate deterioration (Walters 1998b). Seed water content achieved at 15 to 25% RH varies from about 2 to 10%, depending on seed lipid composition and storage temperature.

Storage at -18 °C (0 °F) (the temperature of a standard freezer) enhances shelf-life 4- to 5-fold over that of seeds stored at 5 °C (41 °F) (Walters 1998a). Storage temperature should be dictated by the required longevity for the seed: Storage at 15 °C (59 °F) may be adequate for most species to maintain quality for 3 to 5 years; longevities of 5 to 10 years may require refrigeration at 5 °C (41 °F); while storage at -18°C (0 °F) is required if seeds are to be maintained for 15 to 20 years.

Seed Quality Factors Influencing Longevity of Orthodox Seeds

Harrington's rules are approximations and give relative, rather than absolute, longevities. Absolute longevity depends on initial seed quality. Seed quality is controlled by genetic and environmental factors such as seed structure and composition, maturity, dormancy, purity, mechanical damage, and initial viability and vigor (Justice and Bass 1978). Field conditions during seed development and harvest and postharvest treatment, such as drying temperature, cleaning procedures, and priming, affect overall seed quality and hence seed longevity (Walters 1998a). Infestations of storage fungi, insects, and rodents significantly curtail seed quality and lifespan. Reducing RH or temperature can ameliorate the deleterious effects of infestations. For example, insect activity is retarded at <10 °C (<50 °F) and almost ceases at 0 °C (32 °F). Exposure of seeds to -18 °C (0 °F) kills most insects and their eggs.

Numerous factors during seed development and maturation affect the potential longevity of seeds. Seeds harvested prematurely may have shorter shelf-life than seeds harvested fully mature (defined as having completed maturation drying). Shelf-life may be shorter because immature embryos are not fully tolerant of desiccation and are damaged when dried, or because maximum seed quality is acquired during the final stages of development on the parent plant. The high temperatures, >40 °C (>104 °F), frequently used to rapidly dry immature seeds can severely damage them. Some drying procedures call for exposure to 35 °C (95 °F) for several days. This treatment can initiate seed aging processes. An initial treatment that dries immature seeds slowly enhances seed desiccation tolerance (Vertucci and Farrant 1995, Pammenter and Berjak 1999) and potentially seed longevity. If seeds must be harvested prematurely, holding them for 2 to 5 days in their fruiting structures can simulate slow drying. Once immature seeds receive a slight and slow desiccation treatment, they can be threshed with less damage.

While a brief period of slow drying of <5 days at 20 °C (68 °F) enhances quality of prematurely harvested orthodox seeds, prolonged exposure of fully mature seeds to RH >75% promotes deterioration, encourages microbial infection, and at RH >95% allows precocious germination (Pammenter and Berjak 1999). Seeds may be exposed to high RH in the field if harvest is delayed by rain or if, after harvest, there is inadequate RH control. Generally, exposure of seeds to high RH first results in a reduction of seed vigor (slower germination) and then a reduction in germination percentage. The higher the RH or temperature, the faster seeds deteriorate (refer to Harrington's rules). Germination percentages of vegetables and grains may decline to 0% within 3 to 6 mo of storage at 20 °C (68 °F) with 90% RH. It is generally assumed that reduction in seed quality leads to a reduction in shelf-life once seeds are placed under more favorable storage conditions. Preharvest and postharvest treatments may explain the variability in longevity among seed lots of the same cultivar (Walters 1998a).

Seed priming is a procedure used to accelerate germination rates of planted seeds. Seeds are usually held at <10 °C (<50 °F) with water potentials close to -1 MPa for a few days. While this treatment gives the appearance of improving seed vigor—seeds germinate faster or more uniformly—it exposes mature seeds to high RH and likely reduces their shelf-life if they are redried and then stored (Walters 1998a).

Anecdotal evidence suggests that seeds harvested from the wild have a shorter shelf-life than seeds harvested from cultivated plants. There are numerous possible explanations. Through agricultural practices, humans may have selected for seeds with superior quality. Cultivated plants may have received optimum growth conditions—irrigation, fertility, and pest management—and are therefore more robust. Seeds collected from the wild are often highly immature because maturation of uncultivated seeds is less uniform and mature fruits often dehisce.

Seed dormancy is often linked to seed longevity. Seeds with hard seed coats store longer (Justice and Bass 1978), probably because the seed coats restrict the movement of air and water. Seeds of Leguminosae and Malvaceae have a tendency toward hard-seededness. The linkage between embryo dormancy and longevity is difficult to verify since seed dormancy confounds measurements of viability for longevity tests. Clearly, dormant seeds survive longer in the soil, but this is more likely because they fail to germinate under moist conditions than because they have more efficient mechanisms to survive in the dry state.

Given similar storage and harvest conditions, seeds from orthodox species exhibit different inherent longevities. For example, lettuce and onion seeds are fairly short-lived, whereas tomato and barley seeds show substantial longevities. Generally, orthodox species from Leguminosae and Malvaceae are long lived, while many species in Asteraceae or Umbelliferae produce short-lived seeds. Longevity of seeds from annual crops is better described than that from herbaceous or woody perennials. Sample longevities of different seed species are listed in table 2. More exhaustive species lists and detailed storage conditions can be found in Justice and Bass (1978) and Priestley (1986).

Table 2. Approximate longevity for various seed storage behaviors and seed species

Storage type	Species	Optimum RH	Optimum moisture content of seed[1]	Time to 50% loss in viability[2]
		%	g H_2O per g dw	
Recalcitrant	Tea *(Camellia sinensis)*	95 to 98	0.6 to 0.8	2 weeks to 2 months
	Buckeye *(Aesculus hippocastanum)*	95 to 98	0.5 to 0.7	6 to 8 months
	Trifoliate orange *(Poncirus trifoliata)*	90 to 95	0.5 to 0.7	6 to 14 months
	Wildrice *(Zizania palustris)*	90 to 95	0.35 to 0.45	9 to 18 months
Intermediate	Coffee *(Coffea arabica)*	40 to 60	0.10 to 0.13	2 to 4 years at 5 °C; damage at <0 °C
	Papaya *(Carica papaya)*	40 to 60	0.09 to 0.11	3 to 6 years at 5 °C; damage at <0 °C.
	Hickory (*Carya* spp.)	80 to 90		3 to 5 years
	Citrus *(Citrus limon)*			6 to 18 months
Orthodox	Lettuce *(Lactuca sativa)*	20	0.04 to 0.05	>4 years at 5 °C, >20 years at -18 °C
	Onion *(Allium cepa)*	20	0.06 to 0.08	>4 years at 5 °C, >20 years at -18 °C
	Peanut *(Arachis hypogeae)*	20	0.04 to 0.05	>4 years at 5 °C, >20 years at -18 °C
	Soybean *(Glycine max)*	20	0.07 to 0.08	>5 years at 5 °C, >20 years at -18 °C
	Sunflower *(Helianthus annuus)*	20	0.03 to 0.04	>6 years at 5 °C, >25 years at -18 °C
	Corn *(Zea mays)*	20	0.07 to 0.09	>8 years at 5 °C, >25 years at -18 °C
	Chickpea *(Cicer arietinum)*	20	0.07 to 0.08	>8 years at 5 °C, >25 years at -18 °C
	Pea *(Pisum sativum)*	20	0.09 to 0.12	>10 years at 5 °C, >25 years at -18 °C
	Barley *(Hordeum vulgare)*	20	0.09 to 0.12	>10 years at 5C, >25 years at-18C
	Tomato *(Lycopersicum esculentum)*	20	0.05 to 0.06	>12 years at 5 °C, >25 years at -18 °C

[1] For orthodox seeds, the lower value in the water content range is more appropriate for 5 °C (41 °F) storage, and the higher value approximates optimum water contents for constant storage at -18 °C (0 °F). Water content on a percentage dry weight or fresh weight basis are often used in the seed industry. To calculate percentage water content on a dry weight basis, multiply water contents in the table by 100.

[2] Values for approximate longevity are given for 5 °C (41 °F) storage for all species except *Camellia sinensis*, which is chilling sensitive and should be stored at 15 °C (59 °F).

While species have characteristic longevities, variability among cultivars and among lots of the same cultivar may be so great that it precludes prediction of shelf-life. For example, germination of sesame seeds with initial germination rates of 70 to 80% ranged from 0 to 80% after 18 years storage at the National Center for Genetic Resources Preservation. Similar results were obtained for potato, pepper, sorghum, onion, and tomato: initial rates of germination from 90 to 100% and rates after 18 years of 0 to 100%. The source of this variability is unknown. Suppliers should monitor seed viability periodically to ensure quality.

Additional Storage Factors Affecting Shelf-Life

In addition to RH and temperature, the gas composition of the storage environment may be important, but evidence for a clear relationship is lacking. Low O_2 should enhance longevity since aging reactions are either oxidative or linked to respiration. Storage under higher O_2 tensions causes rapid deterioration (Ohlrogge and Kernan 1982), but the converse has not been demonstrated. Freeze-drying or vacuum packaging may be beneficial (Woodstock et al. 1976, Justice and Bass 1978, Ellis et al. 1993), but it is not clear whether these treatments control moisture level or O_2 level. Reducing the RH is a far more effective method of limiting respiratory processes than lowering O_2. The time and expense of using low O_2 is probably not worthwhile for short-term storage of orthodox seeds.

Exposure to light, even at low intensities, appears to damage dry seeds. Seeds intended for nursery stock should not be dried under the sun and should not be stored in a lighted room without a protective container.

Procedures to Dry Orthodox Seeds

At storage temperatures >0 °C (32 °F), seed water content or RH are the most important factors determining seed longevity. Seed producers must consider two factors when drying seeds: the rate at which seeds are dried and the level to which they are dried. With the exception of immature seeds that benefit from a short, slow, drying period, orthodox seeds with high water content, >18%, should be dried to about 12% as rapidly as possible. Temperatures >35 °C (95 °F) can be damaging, so lower temperatures and high air flow are recommended. Seeds should be spread out in a thin layer to allow air to circulate through the seed mass and gently mixed daily to ensure even drying.

In temperate or cold climates, no special storage conditions are required if seeds are to be planted the next season, that is, within 6 mo. Storage of dried seeds in open bins with no RH control is called "open storage," and the water content of the seed will fluctuate according to the RH and temperature in the warehouse. Open storage is not recommended in warm humid regions or if seeds will be planted several years after harvest.

The water content of seeds must be controlled if seeds are to retain high quality for >2 years. This is easily accomplished by placing seeds at a known RH once they have been dried to a safe water content of <12%. There are two strategies: Dried seeds can be packed in moisture-permeable bags and stored in rooms where the RH is controlled, or they can be equilibrated at the desired RH and then packaged in moisture-impermeable containers (for example, glass, foil laminate, or aluminum cans). The RH in the moisture-proof containers is a function of the water content of the seeds and the temperature at which they are stored.

A RH of 20 to 25% produces optimal seed water content for storage of most orthodox species (Walters 1998a,b). The equilibrium water content varies among seeds according to lipid composition and storage temperature. For example, peanut seeds with 45% lipid will contain 2 to 5% water, while pea seeds with 2% lipid will contain 8 to 12% water. When RH during storage is controlled, water content of seeds need not be monitored. The simplicity of this method may cause some producers to use it exclusively; however, constant dehumidification, especially in conjunction with refrigeration, may be prohibitively expensive (Walters-Vertucci and Roos 1996). Depending on volume of seeds handled and risk of mechanical failure, it may be safer and more cost-effective to store seeds in moisture-proof containers.

When seed producers opt to store seeds in moisture-proof bags, they increase the complexity of water content adjustments but also the flexibility in choosing drying and storage conditions. The interested reader may refer to more in-depth literature on water sorption isotherms of seeds (Walters 1998a,b). The guiding principle is that 20 to 25% RH provides optimum storage. However, since RH is a function of temperature, both the drying and storage temperature need to be considered. Generally, seeds are dried at ambient temperatures or slightly higher to speed up the drying process and to reduce refrigeration costs (Walters-Vertucci and Roos 1996). The greater the temperature differences between drying and storage temperatures, the higher the allowable RH for drying. For instance, if seeds are dried at 25 °C (77 °F) and stored at 15, 5, or -18 °C (59, 41, or 0 °F), they should be equilibrated to about 30, 38, or 45% RH, respectively. Table 3 gives a brief summary of recommended drying conditions for given storage temperatures. To date, these guidelines have proven reliable for all species tested.

Table 3. Recommended drying conditions for seeds subsequently stored in moisture-proof containers at various temperatures*

	Drying RH for storage at—		
Drying temperature	**15 °C (59 °F)**	**5 °C (41 °F)**	**-18 °C (0 °F)**
°C		*%*	
25	30	38	45
15	22	30	38
5	15†	22	30

*The given drying temperature and RH combinations give storage RH of 20-25% at the indicated storage temperature.

†Drying seeds at temperatures less than the storage temperature is not cost effective and therefore is strongly discouraged; dehumidification is more difficult at lower temperatures, and the refrigeration costs used during drying might be more effectively spent during storage.

Cost-Benefit Analyses

Drying and storage conditions used by seed producers and suppliers largely depend on a balance between the cost of seed preservation and the necessity to maintain high quality seeds for a certain period. The three main questions that should be considered when deciding appropriate storage conditions are—

- What is the required longevity of the seed?
- What is the volume of seed to be produced, processed, and stored?
- Are the resources available?

The answer to the first question is the major determinant of seed storage procedures.

Maintaining seed quality for ≥5 years usually requires storage at ≤5 °C (41 °F). Refrigeration is expensive, but only moderately so if the quality of the seed would be destroyed by substandard storage conditions. Generally, dehumidification requires less energy than refrigeration, making controlled RH environments a less expensive alternative to refrigeration for the short term (Walters-Vertucci and Roos 1996). However, because there is a limit to beneficial effects of drying at 20 to 25% RH, extended longevity can only be achieved through refrigeration (Walters 1998b). Moisture-proof packaging may be expensive, but it may be more cost-effective over the long term than constant dehumidification in a warm, humid climate. Seeds equilibrate faster at ambient temperatures, allowing more seeds to be processed in a shorter period if labor is available to package seeds for low-temperature storage. Alternatively, seeds can be equilibrated at lower temperatures, thereby increasing energy costs but allowing a longer processing period without compromising quality.

Assessing Changes in Seed Quality

No storage procedure guarantees that seeds will remain viable forever. Seeds eventually lose vigor and then viability with time. The extent to which aging occurs can be monitored with initial and subsequent germination assays. Different seed species have different germination requirements that are cataloged in Rule Books published by the Association of Official Seed Analysts (1999). Assessments of seed vigor are more difficult than assessments of germination percentage but usually provide an early warning of deterioration.

Pollen

Pollen can be stored for facilitating seed production and breeding. Pollen from some families is desiccation-tolerant—Liliaceae and Solanaceae, for example—and fairly easy to store, but pollen from other families is desiccation sensitive and is more difficult to store—for example, Cucurbitaceae, Gramineae (Poaceae), and Compositae (Asteraceae) (Hanna and Towill 1995, Hoekstra 1995, Barnabas and Kovacs 1997). As with seed, the major factors affecting longevity are water content, storage temperature, and storage atmosphere. Desiccation-tolerant pollens are best stored at moisture levels of ≤10%, obtained by either air-drying or by equilibration at known RH. Greater longevities occur at lower temperatures, with more than 2 years often feasible with -18 °C (0 °F) storage. Cryogenic storage at -80 to -196 °C (-112 to -320 °F) greatly increases longevity.

Storage in a vacuum or with a N_2 atmosphere also enhances longevity.

Storage of desiccation-sensitive pollen is more problematic, but some can be desiccated to 10 to 15%. Reports of storage at 4 °C (39 °F) and -20 °C (-4 °F) are sparse, and the expected longevities are short: from hours to a few days. If the pollen is not over-dried, cryogenic storage is possible.

References

Association of Official Seed Analysts. 1999. Rules for Testing Seeds. Association of Official Seed Analysts, Lincoln, NE.

Barnabas, B., and G. Kovacs. 1997. Storage of pollen. *In* K.R. Shivanna and V.K. Sawhney, eds., Pollen Biotechnology for Crop Production and Improvement, pp. 293-314. Cambridge University Press,Cambridge, U.K.

Ellis, R.H, T.D. Hong, M.C. Martin, et al. 1993. The long term storage of seeds of seventeen crucifers at very low moisture contents. Plant Var. Seeds 6: 75-81.

Hanna W.W., and L.E. Towill. 1995. Long-term pollen storage. *In* J. Janick, ed., Plant Breeding Reviews, vol. 13, pp. 179-207. Wiley & Sons, New York, NY.

Harrington, J.F. 1963. Practical advice and instructions on seed storage. Proc. Intl. Seed Test. Assoc. 28:989-994.

Hoekstra, F.A. 1995. Collecting pollen for genetic resources conservation. *In* L. Guarino, V.R. Rao, and R. Reid, eds., Collecting Plant Genetic Diversity: Technical Guidelines, pp. 527-550. CAB Intl., Oxfordshire, U.K.

Hong, T.D., and R.H. Ellis. 1996. A protocol to determine seed storage behaviour. IPGRI Tech. Bull. 1, International Plant Genetic Resources Institute, Rome, Italy.

Hong, T.D., S. Linnington, and R.H. Ellis. 1996. Seed Storage Behaviour: A Compendium. Handbooks for Genebanks no. 4, International Plant Genetic Resources Institute, Rome, Italy.

Justice, O.L., and and L.N. Bass. 1978. Principles and Practices of Seed Storage. Agriculture Handbook 506, U.S. Department of Agriculture, Washington, DC.

Ohlrogge, J.B., and T.P. Kernan. 1982. Oxygen-dependent aging of seeds. Plant Physiol. 70: 791-794.

Pammenter, N.W., and P. Berjak. 1999. A review of recalcitrant seed physiology in relation to desiccation-tolerance mechanisms. Seed Sci. Res. 9:13-37.

Priestley, D.A. 1986. Seed Aging: Implications for Seed Storage and Persistance in the Soil. Cornell University Press. Ithaca, NY.

Schopmeyer, C.S. 1974. Seeds of Woody Plants in the United States. Agriculture Handbook 450, U.S. Department of Agriculture, Washington, DC.

Vertucci, C.W., and J.M. Farrant. 1995. Acquisition and loss of desiccation tolerance. *In* J. Kigel and G. Galili, eds., Seed Development and Germination, pp. 237-271. Marcel Dekker, New York, NY.

Walters, C. 1998a. Understanding the mechanisms and kinetics of seed aging. Seed Sci. Res. 8:223-244.

Walters, C., ed., Recent Advances on Ultra-dry Research. *In* Seed Science Research, vol. 8, Supplement 1, International Society for Seed Science, Cambridge UniversityPress, Cambridge, U.K.

Walters-Vertucci, C., and E.E. Roos. 1996. Seed moisture, seed drying and energy costs of a seed bank. *In* Report of the 50th Annual Corn and Sorgham Research Conference, pp. 243-255. American Seed Trade Association, Alexandria, VA.

Woodstock, L.W., J. Simkin, and E. Schroeder. 1976. Freeze drying to improve seed storability. Seed Sci. Technol. 4: 301-311.

Almond

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Scientific Name and Introduction

Prunus amygdalus is a member of the family Rosaceae. The sweet cultivated almond originated from bitter-seeded species that evolved in the deserts and foothills of central and southwest Asia. Almonds have been cultivated for over 4,000 years, and starting about 450 BC were cultivated around the Mediterranean coastline from Turkey to Tunisia. Almonds were first introduced to California through the missions, but the large commercial industry was built with trees brought by settlers from the Eastern United States that have thrived in the Mediterranean climate of the Central Valley of California (Kester and Ross 1996).

The edible kernel (primarily two cotyledons whose cells are filled with oil bodies and a small embryo) is surrounded by a shell and hull tissue. Almonds are relatively high in oil: 36 to 60% of kernel dry mass (Guadagni et al. 1978, Abdallah et al. 1998). Most of the fatty acids in almond oil (about 90%) are unsaturated, with the ratio of monounsaturated to diunsaturated ranging from 2:1 to almost 5:1 (Abdallah et al. 1998). There are hard- and soft-shell varieties; the soft-shell varieties are the basis of the industry. Nuts are dislodged from the tree by shaking and allowed to dry on the ground before being swept into windrows, picked up, and transported to the huller. Some harvested nuts are dried after removal from the orchard (Thompson et al. 1996). This is common if late season rains threaten a delay in harvest. If limited huller capacity leads to stockpiling of nuts, they will likely be covered and subjected to periodic fumigation to limit insect damage. Nuts must be dried to <10% moisture prior to stockpiling.

Quality Characteristics and Criteria

In-shell almonds should have hulls that are uniform, with a bright color, and be free of adhering hull material or debris. The hull should be intact and free of damage caused by the hulling operation, insects, or fungi. Kernels should be fully formed rather than shriveled. Kernels of larger size are preferred. The “skin” of the kernel should be unbroken (free of damage caused during shelling or by insects or pathogens) and of uniform dark brown color. Almond flavor should display a combination of sweet and oily notes. There should be no stale or rancid flavors. Optimal kernel texture is from crisp to chewy. Kernels should have <8% moisture, but kernels with <4% moisture tend to be brittle and hard (Kader 1996). Currently over 95% of the California almond crop is sold as shelled products, but developing export markets include substantial interest in in-shell product.

Caveletto et al. (1985) used an assortment of physical, chemical, and sensory methods to evaluate the quality attributes of 23 almond varieties in terms of their use as in-shell, raw, roasted, and blanched nuts. They determined composition of fats and sugars, described flavor notes and textural characteristics, and evaluated the ability to tolerate processing procedures and suitability for various products.

Horticultural Maturity Indices

Almond maturation can be monitored externally by evaluating the extent of hull dehiscence. In the absence of pressure from insects such as the naval orangeworm *(Amyelois transitella)*, harvest can be delayed until the two halves of the hull are fully bent back to expose the shell. At this point, hulls readily separate and moisture content is low enough that nuts can be immediately picked up from the orchard floor. Yield is maximized because the kernel’s dry weight is no longer increasing and nut removal is close to 100%. Nut maturation on a given tree is not uniform; development tends to be most rapid on the south and southwestern faces of the tree higher in the canopy.

The California industry favors a timely (early) harvest that limits naval orangeworm egg-laying in split hulls. Thus, harvest should be matched to the time that the last nut on a tree has begun to split. Nut removal can be near maximum, and minor decreases in kernel size are acceptable due to reductions in insect damage (Connell et al. 1996, Reil et al. 1996). Early harvested nuts (hulls and kernels) contain more water than is acceptable and must be dried on the orchard floor for 1 to 2 weeks before they are picked up and hulled.

Grades, Sizes, and Packaging

In-shell and shelled grades are defined by USDA standards. For the in-shell product, emphasized characteristics include the integrity, shape, and hardness of the shell as well as the brightness and uniformity of its color. Freedom from foreign material and signs of insect damage or decay are also important. Shelled almonds should be free of shell debris and foreign material and from insect or fungal damage. The kernel skin should be intact and should show no shriveling or discoloration. Double, split, or broken kernels are negative factors. There should be no indication of rancid flavor. A complete description of Federal quality standards can be found at http://www.ams.usda.gov/AMSv1.0/standards.

Optimum Storage Conditions

The low water and high fat contents of the kernel make it relatively stable metabolically and able to tolerate low temperatures. The primary objectives of storage regimes are to maintain the low water content. Federal regulations define a safe moisture level for nuts as a water activity <0.7 at 25 °C (77 °F) to retard microbial growth. The recommended storage RH is 65% because too low a water content negatively affects flavor, color, and texture (Kader 1996). Cold storage is useful to minimize lipid oxidation (rancidification). In-shell almonds can be stored for up to 20 mo at 0 °C (32 °F), 16 mo at 10 °C (50 °F), and 8 mo at 20 °C (68 °F). Shelled nuts can be stored for about half as long as nuts in the shell (about 6 mo), and pieces for even less. Almonds should not be stored with commodities that have strong odors because their high lipid content allows them to readily absorb odors.

Modified Atmosphere Considerations

Kernels are less stable than in-shell almonds, and better fresh almond flavor is maintained in a low O_2 and elevated CO_2 atmosphere. Flavor was maintained for 12 mo at 18 and 27.5 °C (64.5 and 81.5 °F) in insect-controlling atmospheres of <1% O_2 and 9 to 9.5% CO_2 (Guadagni et al. 1978). Reduction in the O_2 content of the storage atmosphere will improve oil stability. The stability difference between in-shell nuts and shelled kernels was eliminated in 0.5% O_2 (Kader 1996).

Chilling Sensitivity

Almonds are not sensitive to chilling.

Ethylene Production and Sensitivity

Almonds produce very little ethylene. There are no documented responses to ethylene that might directly affect kernel quality.

Respiration Rates

The low water content of properly stored kernels makes them relatively inert metabolically. Respiratory rates are very low.

Physiological Disorders

Two important quality problems of almond kernels are influenced by failure to maintain low water content. Harvested nuts are often stockpiled and fumigated to control naval orangeworm prior to hulling and shelling. Temperatures in covered stockpiles that are open to the sun can reach 60 °C (140 °F). If nuts have not been dried to <10% moisture in the orchard, or have been wetted by late-season rains, they should not be fumigated. The combination of elevated moisture and temperature leads to a problem called concealed damage, which is marked by inversion of sucrose, lipid oxidation, and internal kernel darkening. Elevated temperature alone does not cause the problem. Wetting of freshly harvested almonds followed by heating can cause the problem, and forced-air drying of rain-wetted kernels can prevent it. However, almonds that have been held in dry storage for several months and then wetted and heated do not develop the problem (Reil et al. 1996).

Another kernel quality problem is premature sprouting (growth of the embryo between the unopened cotyledons).

While the almond kernel's content of polyunsaturated fatty acids is much less than walnuts or pecans, failure to maintain proper storage lead to rancidification. Factors contributing to rancidification were studied by Zacheo et al. (1998).

Postharvest Pathology

Most infections with pathogens are initiated in the orchard, and because clean-up following harvest is not absolute, the potential problems are transferred to the postharvest environment. In-shell product is relatively protected unless the shell has been broken or penetrated by insects. The most serious pathogens are fungi such as *Aspergillus flavus* and *A. parasiticus,* which can produce aflatoxins that are both toxic and carcinogenic. Damaged kernels must be discarded prior to storage and low temperature and RH conditions must be maintained. Phillips et al. (1979) and King et al. (1983) have described the variety of fungi (primarily *Aspergillus* spp., but also *Alternaria*, *Rhizopus*, *Cladosporium,* and *Penicillium* spp.) that are found on almonds, and the latter work and King and Schade (1986) have described the effect of various water activities and temperatures on the competition between these fungi on stored kernels. Because of the relationship between insect damage and pathogen presence, sorting to eliminate whole kernels with insect damage will reduce the number of whole kernels with excess levels (>1 ng/g) of aflatoxins. However, lower grades and broken kernels or kernels sold as animal feed or processed for oil can still present problems (Schatzki 1996). Sampling of kernels to test for aflatoxin presents statistical problems because contamination is centered in individual kernels.

Quarantine Issues

The most serious almond postharvest insect problem is with naval orangeworm. The insect lays its eggs in newly split nuts just before harvest, and the resulting larvae can cause substantial losses. Fumigation with methyl bromide, which has a limited future, or phosphine is used to control the insect. In-home control of insects can use treatment at freezing temperatures of -5 to -10 °C (14 to 23 °F) for a few days. Irradiation can also be used (30 kilorad). The most useful nonchemical insect control approach appears to be a <1% O_2 and 9 to 9.5% CO_2 CA regime (Guadagni et al. 1978).

References

Abdallah, A., M.H. Ahumada, and T.M. Gradziel. 1998. Oil content and fatty acid composition of almond kernels from different genotypes and California production regions. J. Am. Soc. Hort. Sci. 123:1029-1033.

Cavaletto, C.G., A.A. Kader, and D.E. Kester. 1985. Quality in relation to marketability of almond varieties. Report to the California Almond Board. Pomology Department, University of California, Davis, CA.

Connell, J.H., G.S. Sibbett, J.M. Labavitch, and M.W. Freeman. 1996. Preparing for harvest. *In* W.C. Micke, ed., Almond Production Manual, pp. 254-259. Pub. no. 3364, Division of Agriculture and Natural Resources, University of California, Davis, CA.

Guadagni, D.G., E.L. Soderstrom, and L. Storey. 1978. Effect of controlled atmosphere on flavor stability of almonds. J. Food Sci. 43:1077-1080.

Kader, A.A. 1996. In-plant storage. *In* W.C. Micke, ed., Almond Production Manual, pp. 274-277. Pub. no. 3364, Division of Agriculture and Natural Resources, University of California, Davis, CA.

Kester, D.E., and N.W. Ross. 1996. History. *In* W.C. Micke, ed., Almond Production Manual, pp. 1-2. Pub. no. 3364, Division of Agriculture and Natural Resources, University of California, Davis, CA.

King, A.D. Jr., W.U. Halbrook, G. Fuler, and L.C. Whitehand. 1983. Almond nutmeat moisture and water activity and its influence on fungal flora and seed composition. J. Food Sci. 48:615-617.

King, A.D., Jr., and J.E. Schade. 1986. Influence of almond harvest, processing and storage on fungal population and flora. J. Food Sci. 51:202-205, 215.

Phillips, D.J., B. Mackey, W.R. Ellis, and T.N. Hansen. 1979. Occurrence and interaction of *Aspergillus flavus* with other fungi on almonds. Phytopathology 69:829-831.

Reil, W., J.M. Labavitch, and D. Holmberg. 1996. Harvesting. *In* W.C. Micke, ed., Almond Production Manual, pp. 260-264. Pub. no. 3364, Division of Agriculture and Natural Resources, University of California, Davis, CA.

Schatzki, T.F. 1996. Distribution of aflatoxin in almonds. J. Ag. Food Chem. 44:3595-3597.

Thompson, J.F., T.R. Rumsey, and J.H. Connell. 1996. Drying, hulling and shelling. *In* W.C. Micke, ed., Almond Production Manual, pp. 268-273. Pub. no. 3364, Division of Agriculture and Natural Resources, University of California, Davis, CA.

Zacheo, G., A.R. Cappello, L.M. Perrone, and G.V. Gnoni. 1998. Analysis of factors influencing lipid oxidation of almond seeds during accelerated ageing. Lebensm.-Wiss. Technol. 31:6-9.

Hazelnut

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Scientific Name and Introduction

Corylus avellana L., the filbert or hazelnut, is a member of the birch family (Betulaceae). The edible seed is surrounded by a round to slightly oblong shell that must be separated from a husk during or after harvest. All important world cultivars originated from human selections of wild *C. avellana* in Europe and Turkey. The common name "filbert" originated in England and was originally applied to the long-husked types of *Corylus avellana* to distinguish them from the short-husked types and has since been used in the U.S. to distinguish the cultivated *Corylus avellana* from other native wild species of *Corylus*. The common name "hazelnut" is more commonly applied worldwide for nuts produced by all *Corylus* species.

Whatever the chosen common name, nuts from this genera represent one of the world's major nut crops, second only to almonds (Thompson et al. 1996). Turkey produces most of the world supply (70%), followed by Italy (22%), Spain (5%), and the United States (3%). By far the largest production area in the United States is the Pacific Northwest, with 99% of production in the Willamette Valley of Oregon (Mehlenbacher and Olsen 1997). Market uses for the U.S. crop have been roughly evenly divided between in-shell and kernel markets, but trends are shifting towards kernel markets. The major variety in the U.S. is Barcelona, followed by Davinia, Ennis, and Willamette.

Two wild species, *C. americana* and *C. cornuta*, are found in the United States. *C. americana* has been used in breeding programs for crossing with *C. avellana* in attempts to provide genotypes with sufficient cold hardiness and eastern filbert blight tolerance or resistance to allow production east of the Rocky Mountains with some success.

Quality Characteristics and Criteria

In-shell hazelnuts should be properly sized to meet the stated market type and should be properly filled with at least 50% of the shell cavity occupied by nutmeat. Shells should be free of cracks and noticeable mechanical injury and clean and brightly colored; coloring patterns should be characteristic of the stated variety. The pellicle should be smooth and devoid of husk attachments.

Kernels should meet the stated market type, be free of any misshapen or underdeveloped kernels, and be free of any shell or foreign material and off odor, off flavor, or mold. Water content of kernels should not exceed 6% if shelled or 7% if in-shell, and the total water content of unshelled nuts should not exceed 10 to 12%. Size is specified with grade as a determinant of quality, and minimum sizes are used for specification of classes "Extra" and "Class I" in international trade.

For in-shell markets, larger and particularly rounded types are preferred. Shelled markets accommodate both rounded and oblong types, and size preference depends on the intended end use. Hazelnut kernel oil content ranges from 57 to over 70%, and total sugars average about 4%; both vary with variety and growing location (Botta et al. 1994). Hazelnuts are highest among tree nuts in α-tocopherol content (366 μg/g oil) and are also a rich source of vitamin B_6 (0.54 to 0.89 mg per 100 g) (Richardson 1997).

Horticultural Maturity Indices

In areas where hazelnuts are mechanically harvested, nuts are usually allowed to naturally drop from trees prior to sweeping from the orchard floor, and harvesting may commence after 90% of the nuts have dropped (Lagerstedt 1979). Kernels are considered mature after oil accumulation is complete and when the nut detaches from the base of the husk (Thompson et al. 1996). In the United States, most nuts are mature during or by the end of August but may be prevented from dropping by an immature, clasping husk. In production areas where hand harvesting from trees is still practiced, or for varieties in which husks fail to open and allow nut drop, nuts are considered mature when they will rattle inside the husk, indicating detachment of the nut from the base of the husk.

Grades, Sizes, and Packaging

U.S. standards exist for hazelnuts in the shell and for importation of in-shell or shelled hazelnuts, and international UN/ECE standards exist for both in-shell and shelled hazelnuts. Grades are primarily determined by size, degree of kernel fill, color, and freedom from defects and foreign material. U.S. No. 1 filberts must contain no more than 20% filberts of a different type (round shaped versus long type); no more than 10% defective nuts, provided that no more than 5% are poorly filled (blanks), no more than 5% are rancid, decayed, moldy or insect injured, and no more than 3% are insect injured; and not more than 15% filberts that fail to meet the specified size and of which no more than 10% are undersized. Furthermore, shells are free from surface moisture and the combined shell and kernel moisture content is not greater than 10%; shells are well formed, unbroken, not discolored, have adhering husk covering not more than 5% of the shell area and are practically free of adhering dirt and other foreign material.

Size is specified in connection with the grade in terms of minimum and maximum diameters that will pass through round openings of a screen and are specified separately for round-type varieties and long-type varieties. See following:

Size	Round-type		Long-type	
	Minimum	Maximum	Minimum	Maximum
	in. (mm)			
Jumbo	56/64 (22.2)	—	47/64 (18.6)	—
Large	49/64 (19.4)	56/64 (22.2)	48/64 (19.0)	44/64 (18.6)
Medium	45/64 (17.9)	49/64 (19.4)	45/64 (17.9)	34/64 (13.5)
Small	—	45/64 (17.9)	—	35/64 (13.9)

All hazelnuts imported into the United States in lot quantities which exceed 115 lb (52.2 kg) net weight must meet minimum grade standards as specified under section 8e of the Agricultural Marketing Agreement Act. In-shell hazelnuts must meet U.S. No. 1 grade and be at least medium size with a tolerance for insect injury of 2% or less. Shelled hazelnuts must be well dried and clean; free from foreign material, mold, rancidity, decay, or insect injury; and free from serious damage caused by serious shriveling or other means. Stated tolerances for shelled hazelnuts include not more than 0.0002% foreign material; not more than 5% of kernels or pieces of kernels which are below grade, including not more than 2% for mold, rancidity, decay, or insect injury; and no more than 1% with rancidity or insect injury.

International grade standards are exercised at the export control stage and are specified for both in-shell and shelled hazelnuts. For in-shell nuts, UN/ECE classifications of Extra, Class I, and Class II exist in which the shell of all nuts must be well formed, intact, sound, and clean and the kernels must be sound, clean, sufficiently developed, and free from mold, visible damage from insects or pests, presence of live or dead insects or pests, rancidity, foreign smell or taste, and blemishes. All hazelnuts must contain less than 12% moisture and kernels not more than 7% moisture, and foreign material may not exceed 0.25% of the total in-shell weight. Sizing and statement of variety, commercial type, or shape is compulsory for Extra and Class I but is optional for Class II. For specified sizes in nuts of all classes, a total tolerance by count of 5% for rounded types and 10% for oblong types for nuts not meeting the specified size is allowed.

Extra hazelnuts must be 16 mm in diameter or more and be of superior quality, must be characteristic of the variety and/or commercial type, and must be practically free from defects with the exception of very slight superficial defects, provided they do not affect general appearance, quality, or keeping quality. They must contain no more than 4% empty nuts on a count basis; not more than 3% of the weight of in-shell nuts may contain shell defects; and not more than 5% of the kernels may be defective, of which not more than 3% may be moldy, rotten, rancid, or damaged by insects.

Class I hazelnuts must be 14 mm or more in diameter and be of good quality, must be characteristic of the variety and/or commercial type, and may contain only slight defects that do not affect the general appearance, quality, or keeping quality. They must contain not more than 6% empty nuts on a count basis; not more than 5% of the weight of in-shell nuts may contain shell defects; and not more than 8% of the kernels may be defective, of which not more than 5% may be moldy, rotten, rancid, or damaged by insects.

Class II hazelnuts may be of any size (if size is specified, tolerances apply) and be of marketable quality; they may contain defects provided that the in-shell nuts retain their essential characteristics as regards general appearance, quality, and keeping quality. They must contain not more than 8% empty nuts on a count basis; not more than 7% of the weight of in-shell nuts may contain shell defects; and not more than 12% of the kernels may be defective, of which not more than 6% may be moldy, rotten, rancid, or damaged by insects. Sizing or screening is used to specify market size in 2 mm increments from 22 mm to 14 mm or less. Sizing for nuts less than 22 mm in diameter must include the maximum and minimum size range, mention the minimum size followed by the words “and over,” or mention the maximum size followed by the words “and less.” For nuts for final consumers under the classification “screened,” the size “and less” is not allowed.

For hazelnut kernels, UN/ECE classifications of Extra, Class I, and Class II also exist; and requirements are similar to those stated for kernels of in-shell nuts with the addition of provisions for intactness of kernels and a slightly reduced tolerance for kernel moisture content from not more than 7% for in-shell kernels to not more than 6% for shelled kernels. Foreign material may not exceed 0.25% for kernels in any classification. Sizing and statement of variety is also compulsory for Extra and Class I kernels but optional for Class

II. For kernels in all classes, a total tolerance of 10% is allowed for kernels other than the specified variety and/or type, and a size tolerance by weight of 5% is allowed for rounded types and 10% for oblong types. To be designated either Extra or Class I, hazelnut kernels must have a minimum diameter of 9 mm, with the exception of hazelnuts of the piccolo type or hazelnuts having a similar designation for which a diameter of 6 to 9 mm is allowed.

Extra hazelnut kernels must be of superior quality, must be characteristic of the variety and/or commercial type, and must be practically free of defects with the exception of very slight superficial defects provided they do not affect the general appearance, quality, or keeping quality. Total tolerances for defects are 5% by weight or 6% if the lot is specified as “Old Crop.” Of the total tolerance, no more than 1% may be rancid, rotten, moldy, have off odor or off flavor, or be damaged by insects or rodents; no more than 2% may be not fully developed, including shrunken and shriveled, stained, and yellowish kernels; and not more than 3% may be mechanically damaged and pieces. Not included in the total tolerance is that not more than 2% may be twin hazelnuts.

Class I hazelnut kernels must be of good quality, must be characteristic of the variety and/or commercial type, and may have slight defects of form and color provided that these do not affect the general appearance, quality, or keeping quality. Total tolerances for defects are 12 to 13% if the lot is specified as “Old Crop.” Of the total tolerance, no more than 1.5% may be rancid, rotten, moldy, have off odor or off flavor, or be damaged by insects or rodents; no more than 4% may be not fully developed, including shrunken and shriveled, stained, and yellowish kernels; and not more than 8% may be mechanically damaged and pieces. Not included in the total tolerance is that not more than 5% may be twin hazelnuts.

Class II hazelnut kernels may be of any size (if size is specified, tolerances apply) and be of marketable quality; they may contain defects provided that kernels retain their essential characteristics as regards general appearance, quality, and keeping quality. Total tolerances for defects are 16 to 18% if the lot is specified as “Old Crop.” Of the total tolerance, no more than 3% may be rancid, rotten, moldy, have off odor or off flavor, or be damaged by insects or rodents; no more than 8% may be not fully developed, including shrunken and shriveled, stained, and yellowish kernels; and not more than 10% may be mechanically damaged and pieces. Not included in the total tolerance is that not more than 8% may be twin hazelnuts.

Hazelnut kernels may be sized or screened, with the size expressed in increments of 2 mm. All sizes are allowed, subject to the minimum designations for Extra and Class I hazelnut kernels. For kernels for final consumers under the classification “screened,” the size “and less” is not allowed.

Optimum Storage Conditions

Soon after harvest, nuts should be dried to below 10 to 12% moisture, with kernels below 6 to 7% moisture to deter mold growth. In-shell and unroasted kernels may be stored for 24 mo with minimal loss in quality at temperatures up to 10 °C (50 °F). Roasted kernels may only be held for 6 mo prior to development of detectable rancidity stored at 0, 5, or 10 °C (32, 41, or 50 °F). However, reduced temperature may be effective in combination with other protective measures such as vacuum packaging in extending roasted kernel shelf-life to 1 year or more (Ebraheim et al. 1994).

Retail Outlet Display Considerations

Hazelnuts are normally marketed at ambient temperature. Use of vacuum or low-O_2 MAP is recommended to extend shelf-life. In-shell hazelnuts may be marketed in bulk containers. Exposure to moisture and high RH should be avoided.

Chilling Sensitivity

Hazelnuts are not sensitive to chilling and are commonly stored at temperatures at or below freezing for long term storage.

Ethylene Production and Sensitivity

Ethylene may be used as a harvest aide to enhance maturation of husks for earlier harvest (Lagerstedt 1979). During storage hazelnuts produce very low levels of ethylene.

Respiration Rates

Properly dried hazelnuts exhibit very low respiration rates during storage.

Physiological Disorders

Black tips on kernels appears to be associated with nuts having split or weak sutures. It appears to be caused by an oxidation process that occurs on the pellicle only and may or may not be associated with moldy kernels (Thompson et al. 1996).

Twin kernels occur when two kernels develop within one nut shell, and is an undesirable trait because of the small size and irregular shape of affected kernels.

Blank nuts are in-shell hazelnuts devoid of normal kernels. It results from defective embryo sacs, unviable eggs, failure of fertilization, or embryo abortion at varying stages of development. Owing to the alternate bearing cycles for hazelnuts, poorly filled nuts may also result during an overproduction year, and poor kernel fill appears to be a heritable trait (Thompson et al. 1996).

Postharvest Pathology

The most common decay found in hazelnuts is molds, with *Romularia* spp. most prevalent throughout nut development. It is the major pathogen associated with kernel tip mold (Ebraheim et al. 1997, p. 483). Although *Romularia* spp. appear to infect hazelnuts during nut development and may be quiescent prior to maturity and storage, many molds require breakage of the shell to contaminate the nut; thus, intactness of the shell offers some natural defense against mold infestation.

The dominant flora during storage are *Penicillium* and *Aspergillus* spp. *A. flavus,* capable of producing aflatoxin, has been isolated from hazelnuts in storage (Eke and Goktan 1987). Reduction of in-shell moisture content to below 10% and nutmeat moisture content to less than 6% is an effective means of deterring mold growth. Sanitation with chlorine dips may also be effective in reducing the incidence of mold infestation by reducing the amount of innoculum carried into postharvest storage. Because of the high amounts of organic material on the surface of shells, chlorine concentrations should be monitored and replenished as necessary to maintain chlorine at concentrations necessary to kill microorganisms.

Quarantine Issues

To prevent spread of eastern filbert blight *(Anisogramma anomala),* all trees, plants, cuttings, and scions of all species and varieties of the wild and cultivated filbert or hazelnut, *Corylus* spp., may not be transported into Oregon from States and districts of the U.S. east of and including the States of Montana, Wyoming, Colorado, and New Mexico; the entire State of Washington; and all provinces, districts, and territories of Canada east of and including the province of Alberta.

Special Considerations

Hazelnuts marketed in-shell should be sampled periodically to assess nutmeat quality. Although the most common nut causing allergy in children and adults is peanut, hazelnuts may also be an allergenic food additive (Ewan 1996), and the presence of hazelnut in foods must be declared.

An ELISA test can be used to detect hazelnut presence in complex food mixtures (Holzhauser and Vieths 1999). Shelling, blanching, or roasting decreases hazelnut shelf-life compared to storage in-shell (Ebraheim et al. 1994). Roasting temperature and duration interact to decrease shelf-life with increasing roasting temperature and duration (Richardson and Ebraheim 1997). Hazelnuts absorb lipophilic compounds that can induce off flavor. Although frozen storage may be used to increase shelf-life, once out of storage hazelnuts should be used as soon as possible due to reduced shelf-life at room temperature.

References

Botta, R., C. Gianotti, D. Richardson, et al. 1994. Hazelnut variety, organic acids, sugars and total lipid fatty acids. Acta Hort. 351:693-699.

Ebraheim, K.S., D.G. Richardson, and R.M. Tetley. 1994. Effects of storage temperature, kernel intactness and roasting temperature on vitamin E, fatty acids and peroxide value of hazelnuts. Acta Hort. 351:677-684.

Ebraheim, K., D.G. Richarson, J. Stone, and R. Tetley. 1997. Hazelnut mold identification and timing of infestation. Acta Hort. 445:483-484.

Eke, D., and D. Goktan. 1987. Aflatoxin production in hazelnuts. Ege Univeritesi Ziraat Fakultesi Dergisi 24:289-297.

Ewan, P.W. 1996. Clinical study of peanut and nut allergy in 62 consecutive patients: new features and associations. Brit. Med. J. 312:1074-1078.

Holzhauser, T., and S. Vieths. 1999. Quantitative sandwitch ELISA for determination of traces of hazelnut *(Corylus avellana)* protein in complex food mixtures. J. Agric. Food Chem. 47:4209-4218.

Lagerstedt, H.B. 1979. Filberts. *In* R.A. Jaynes, ed., Nut Tree Culture in North America, pp. 128-147. Northern Nut Growers Association, Hamden, CT.

Mehlenbacher, S.A., and J. Olsen. 1997. The hazelnut industry in Oregon, USA. Acta Hort. 445:337-346.

Richardson, D.G. 1997. The health benefits of eating hazelnuts: implications for blood lipid profiles, coronary heart disease and cancer risks. Acta Hort. 445:295-300.

Richardson, D.G., and K. Ebraheim. 1997. Hazelnut kernel quality as affected by roasting temperatures and duration. Acta Hort. 445:301-304.

Thompson, M.M., H.B. Lagerstedt, and S.A. Mehlenbacher. 1996. Hazelnuts. *In* J. Janick and J.N. Moore, eds., Fruit Breeding, vol. 3, Nuts, pp. 125-184. John Wiley and Sons, New York, NY.

Macadamia Nut

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Scientific Name and Introduction

The family Proteaceae includes about 10 species of the genus *Macadamia*, 2 of which produce edible nuts: *M. integrifolia* and *M. tetraphylla* or hybrids of these. The major species of commerce is *M. integrifolia*. Macadamia nuts are native to Australia and are produced there as well as in Hawaii, Central and South America, and parts of Africa. Nearly all production consists of grafted trees of cultivars developed in Hawaii or Australia. The edible kernel is enclosed in a thick, hard shell that, in turn, is enclosed in a husk that separates from the tree at about the time the seed is mature. The kernel is nearly spherical, consisting of joined equal-sized halves (cotyledons).

Quality Characteristics and Criteria

Kernels should be a light cream color, nearly spherical in shape, and free of blemishes, rancidity, mold, decay, insect damage, extraneous material, hollow centers, discoloration, and adhering shell. Fully developed macadamia kernels should contain ≥72% oil; the highest quality kernels contain 72 to 78% oil and 1.5% moisture. Kernels of *M. tetraphylla* typically contain less oil. Oil content is a major quality factor that varies with cultivar and maturity and is inversely related to sugar content (Ripperton et al. 1938).

Horticultural Maturity Indices

Following a prolonged flowering season, macadamia nuts mature over a long period from late summer until late spring. Kernels are mature when oil accumulation is complete. Shortly after this time, the nuts fall to the ground and are harvested. Sometimes shake-harvesting is employed to facilitate the harvest while minimizing the amount of immature nuts harvested. Recommended harvest interval for ground-harvested nuts is 1 mo. Damage by the tropical nut borer (*Hypothenemus obscurus* [F.]) can begin to increase rapidly after 3 weeks on the ground (Jones 1992).

Grades, Sizes, and Packaging

No U.S. grades are established for macadamia nuts, but the State of Hawaii has standards and grades for shelled macadamia nuts, in-shell macadamia nuts, and roasted macadamia nuts (Hawaii Department of Agriculture 1984). The minimum export grade for shelled nuts is Hawaii No. 1, which defines defects and damage, development, and cleanliness as well as maximum moisture content of 1.5% by weight. Off-grade is not a grade, but is a descriptive term applicable to shelled nuts which have a market value and designates a quality lower than the lowest applicable Hawaii grade for shelled nuts. The standards also define eight styles: Style I (wholes), Style II (wholes and halves), Style III (cocktail), Style IV (halves and pieces), Style V (large diced), Style VI (chips), Style VII (bits, diced), and Style VIII (fines). There are also standards for in-shell nuts and for roasted kernels. Shelled nuts are usually packaged in 11.4 to 22.7 kg (25 to 50 lb) vacuum-packed or nitrogen-flushed foil bags for the wholesale market. Larger nitrogen-flushed containers are sometimes used.

Optimum Storage Conditions

Macadamia nuts should be husked within 24 h of harvest, after which the drying process should be initiated. Freshly fallen nuts contain about 25% kernel moisture, although nuts that have remained on the ground for extended periods may have as little as 10 to 15% moisture. Drying should begin with ambient air, followed by a gradual increase in temperature that will not exceed 60 °C (140 °F) in the final stage of drying. Drying may be completed in-shell (to 1.5% kernel moisture); or the nuts can be dried partially in-shell (to about 5 to 6% kernel moisture), followed by cracking and finish drying of kernels alone to 1.5% moisture. It is important to protect the dry kernels from moisture and O_2, so packaging in a material that is impervious to moisture is important. Vacuum packaging or nitrogen flush offers protection from O_2. Exposure to moisture results in loss of crispness and shelf-life. Likewise, prolonged exposure to O_2 results in rancidity. Cold storage is normally not necessary for short-term storage but might be desirable for extended periods. Frozen storage (-18 °C, 0 °F) can be very effective in extending shelf-life.

Retail Outlet Display Considerations

Packaging should protect kernels from moisture and O_2. Storage temperature is less critical. Nuts are rarely sold in-shell due to difficulty in cracking.

Chilling Sensitivity

Macadamia nuts are not sensitive to chilling provided they have been dried. Dry kernels are commonly stored below 15 °C (59 °F) for bulk storage and can successfully be frozen to extend shelf-life. Care must be taken in thawing frozen nuts to prevent condensation and resulting moisture gain.

Physiological Disorders

Nuts that fail to develop properly will produce kernels that are low in oil content and may appear shriveled or small. If too immature, kernels are very small and become hard upon drying. Immature kernels also have high sugar content and will brown excessively when roasted. High-moisture kernels dried at higher temperatures develop brown centers when roasted as a result of high reducing sugar levels. It is necessary to begin the drying process at ambient temperature or with circulating air heated to no more than 38 °C (100 °F) when the kernels are very wet. Minimum reducing-sugar levels can be obtained if kernel moisture content is reduced to 8% before increasing the temperature to 52 °C (126 °F) and to 6% before increasing the temperature to 60 °C (140 °F) (Prichavudhi and Yamamoto 1965).

Postharvest Pathology

Extended harvest intervals may result in mold, yeast, or bacterial contamination in the field, as well as insect damage. Southern green stinkbug (*Nezara* viridula [L.]), tropical nut borer (*Hypothenemus obscurus* [F.]) koa seed worm (*Cryptophlebia illepida* [Butler]), and litchi fruit moth *(C. ombrodelta)* are the major insect pests causing damage to macadamia nuts in Hawaii, resulting in an unmarketable kernel (Jones and Aihara-Sasaki 1999). Delay in husking the nuts following harvest can also result in mold growth and fermentation. Husking should occur within 24 h of harvest. The thick shell provides considerable protection for the kernel, but cracked shells and open micropyles can provide entry of fungi and bacteria as well as ants. When the nuts fall from the tree, the kernels contain about 25% moisture. At harvest, moisture level can range from about 10 to 25%. Once the nuts have been dried to 1.5% kernel moisture, the water activity is 0.3 (Beuchat 1978), insufficient to support the growth of mold or bacteria.

Quarantine Issues

There are no significant quarantine issues. A possible issue is the occasional presence of storage insects such as almond moth *(Ephestia cautella)*, merchant grain beetle (*Oryzaephilus mercatur* [Fauvel]), and the dried fruit beetle (*Carpophilus hemipterus* [Linnaeus]) (Cavaletto 1983).

Special Considerations

Kernel stability is related to moisture content and to oxidative rancidity. Of these, moisture content is the most critical. Raw kernels with moisture content exceeding 2% have poor stability (Cavaletto et al. 1966). These kernels brown excessively when roasted and have poor texture. Likewise, roasted kernels must be well protected from moisture to ensure preservation of texture and flavor. Protection from O_2 is usually accomplished with vacuum or nitrogen packing.

References

Beuchat, L.R. 1978. Relationship of water activity to moisture content in tree nuts. J. Food Sci. 43:754-755,758.

Cavaletto, C.G. 1983. Macadamia nuts. *In* H.T. Chan Jr., ed., Handbook of Tropical Foods, pp. 361-397. Marcel Dekker Inc, New York, NY.

Cavaletto, C.G., A. Dela Cruz, E. Ross, and H.Y. Yamamoto. 1966. Factors affecting macadamia nut stability. I. Raw kernels. Food Technol. 20(8):108-111.

Hawaii Department of Agriculture. 1984. Standards for roasted macadamia nuts. *In* Standards for Processed Foods, ch. 44. SS 4-44-13.

Jones, V.P. 1992. Effect of harvest interval and cultivar on damage to macadamia nuts caused by *Hypothenemus obscurus* (Coleoptera:Scolytidae). J. Econ. Ent. 85(5):1878-1883.

Jones, V.P., and M. Aihara-Sasaki. 1999. Macadamia insect pests. *In* Proceedings of the Hawaii Macadamia Nut Association Annual Conference, 39:23-28. Hawaii Macadamia Nut Association, Hilo, HI.

Prichavudhi, K., and H.Y. Yamamoto. 1965. Effect of drying temperature on chemical composition and quality of macadamia nuts. Food Technol. 19(5):129-132.

Ripperton, J.C., R.H. Moltzau, and D.W. Edwards. 1938. Methods of evaluating the macadamia nut for commercial use and the variation occurring among seedling plantings in Hawaii. Bull. 79, Hawaii Agricultural Experiment Station. Honolulu, HI.

Peanut

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Scientific Name and Introduction

Arachis hypogaea L., the peanut or groundnut, is an annual herb of the Leguminosae family. Two subspecies are grown commercially, and four market types are of greatest economic importance. *A. hypogaea* subsp. *hypogaea* includes the market types "runner" and "Virginia," and *A. hypogaea* subsp. *fastigata* includes the market types "Spanish" and "Valencia." In the United States in the 1980s, 70% of the peanuts grown were runners, while 20, 10, and <1% were Virginia, Spanish, and Valencia market types, respectively (Knauft and Gorbet 1989). According to the USDA national peanut tonnage report, U.S. production in 1999 included 78% runners, 18% Virginia, 3% Spanish, and 3% Valencia.

The edible portion is a seed which develops underground inside a pod containing two to four seeds. Peanuts originated in South America and are now cultivated worldwide, with the majority of production in India, Asia, and the United States. In the United States, about 60% of peanuts are used in a variety of food products, with the reminder used in approximately equal proportions for export and for production of edible oil. Major chemical constituents of peanuts are oil (44 to 56%) and protein (22 to 33%), with large influences by environment, genotype, and maturity on their concentrations (Holaday and Pearson 1974).

Quality Characteristics and Criteria

Shelled peanuts should be properly sized to meet market type, be free of misshapen or underdeveloped kernels, and be free of any shell or foreign material and off odor or flavor. Raw peanuts should be surrounded by a tan, pink, or red seedcoat (testa) that fully encapsulates the seed, and the interior color of each half-seed should be ivory. Moisture content for in-shell peanuts should be <10% to prevent mold growth (Diener and Davis 1977). Prior to shelling, peanuts should contain 7 to 10% moisture to reduce splitting and kernel breakage during milling. After milling, moisture content for maximum shelf-life is ≤7%. Seed may be stored at ambient temperature for up to 11 years with good viability if seed moisture content is <3.3% (Cheng et al. 1997). Peanuts marketed without seedcoats (blanched) should have an ivory-colored raw kernel. Peanuts are most commonly consumed following roasting, which may be accomplished in-shell or after shelling. Roasted peanut kernels should be light yellow in color, free of external oil, contain <6% moisture, and be free of dark-colored kernels.

Peanut seed, and particularly peanut seedcoats, are a source of resveratrol, a compound that reduces cardiovascular disease and cancer incidence. Resveratrol ranges from 0.02 to 1.79 $\mu g\ g^{-1}$, compared to 0.6 to 8.0 $\mu g\ mL^{-1}$ in red wines (Sanders et al. 2000). Fatty acid composition of peanut oil is predominantly oleic and linoleic acids, found in roughly equal amounts and making up 80% of total fatty acids. Certain genotypes may contain substantially more oleic than linoleic acid, with ratios as high as 40:1 (oleic:linoleic). Peanuts with a high oleic:linoleic ratio are less susceptible to oxidative deterioration and off flavor development caused by oxidative cleavage of polyunsaturated fatty acids. The ratio of oleic to linoleic is influenced primarily by genotype, but interactions exist between genotype and the environment.

Horticultural Maturity Indices

Peanuts are an indeterminant plant, with flowering followed by underground seed development over a range of time. Assessment of peanut maturity should be conducted using multiple plants at

Table 1. Comparison of screen sizes and tolerances (by weight) for American Peanut Shellers Association (APSA) and USDA Grades for shelled Spanish peanuts

Grade and minimum screen size	Fall-through prescribed screens %	Other types	Splits	Damage and minor defects	Damage	Foreign material	Moisture
No. 1 (15/64 x 3/4” slot)							
APSA	2.00	1.00	3.00	0.75	1.25	0.10	9.00
US	2.00	1.00	3.00	1.50	2.00	0.10	-----
Splits (16/64” round)							
APSA	*	2.00	----	1.50	2.00	0.20	9.00
US	**	2.00	----	2.00	2.00	0.20	----
No. 2 (16/64” round)							
APSA	6.00***	2.00	----	1.00	2.00	0.20	9.00
US	6.00***	2.00	----	----	2.50	0.20	----

* (APSA) 2.00% sound portions of peanuts which pass through the prescribed screen; and 4.00% for sound whole kernels, not over 3.00% which will pass through a 13/64×3/4 in screen. This fall-through combined with percentage of sound portions shall not exceed 4.00%.

** (US) 2.00% sound portions of peanuts which will pass through the prescribed screen; and 4.00% for sound whole kernels.

*** Combined fall-through of sound portions through a 16/64 in round screen and sound whole kernels through a 13/64×3/4 in screen shall not exceed 4.00%

Table 2. Comparison of screen sizes and tolerances (by weight) for American Peanut Shellers Association (APSA) and USDA Grades for shelled runner peanuts

Grade and minimum screen size %	Fall-through prescribed screens	Fall-through 16/64 x 3/4” slot screen	Other types	Splits	Damage	Damage and minor defects	Foreign material	Moisture
Jumbo 38-42 ct. per oz.*** or 21/64 x 3/4” slot	5.00	3.00	1.00	3.00	1.00	2.00	0.10	9.00
Medium 40-50 ct. per oz.*** or 18/64 x 3/4” slot (Report % riding 21/64 x 3/4” slot)	5.00	3.00	1.00	3.00	1.00	2.00	0.10	9.00
Select 16/64 x 3/4” slot (Report % riding 21/64 x 3/4” slot)	----	3.00	1.00	3.00	1.00	2.00	0.10	9.00
No. 1 16/64 x 3/4” slot (Report % riding 18/64 x 3/4” slot)								
APSA	----	3.00	1.00	3.00	1.00	2.00	0.10	9.00
US	----	3.00	1.00	3.00	1.50	2.00	0.10	----
Mill run 16/64 x 3/4” slot	----	3.00	1.00	3.00	1.00	2.00	0.10	9.00

Table 2. Comparison of screen sizes and tolerances (by weight) for American Peanut Shellers Association (APSA) and USDA Grades for shelled runner peanuts—*continued*

Grade and minimum screen size %	Fall-through prescribed screens	Fall-through 16/64 x 3/4" slot screen	Other types	Splits	Damage	Damage and minor defects	Foreign material	Moisture
Splits 17/64" round								
APSA	*	*	2.00	----	1.50	2.00	0.20	9.00
US	**	**	2.00	----	2.00	2.00	0.20	----

* (APSA) 2.00% sound portions pass through 17/64 in round screen. 4.00% for sound whole kernels, not over 3.00% which will pass through 14/64×3/4 in slot screen. This fall-through combined with sound portions passing 17/64 in round not to exceed 4.00%.

** (US) 2.00% sound portions pass through 17/64 in round. 4.00% for sound whole kernels.

*** American count per ounce shall be within the specified range.

Each of the above grades may be certified "with splits" providing all requirements of the grade are met, except that a tolerance of 15% is allowed for split kernels of which not more than 3% will pass through 17/64 in round screen.

Table 3. Comparison of screen sizes and tolerances (by weight) for American Peanut Shellers Association (APSA) and USDA Grades for shelled Virginia peanuts

Grade and minimum screen size	Fall-through prescribed screens %	Other types	Sound Split or broken kernels	Damage	Damage and minor defects	Foreign material	Moisture	Count per pound maximum
Extra large 20/64 x 1” slot APSA & US	3.00	0.75	3.00	1.00	1.75	0.10	----	**512
Medium Virginia 18/64 x 1” slot APSA & US	3.00	1.00	3.00	1.25	2.00	0.10	----	**640
No. 1 Virginia 15/64 x 1” slot APSA & US	3.00	1.00	3.00	1.25	2.00	0.10	----	**864
Virginia splits 20/64” round APSA & US	*3.00	2.00	Not less than 90.00	----	2.00	0.20	----	----
No. 2 Virginia 17/64” round APSA & US	*6.00	2.00	As graded	----	2.50	0.20	----	----

* (APSA & US)—includes both sound split and broken and sound whole kernels which pass through prescribed screens.
** Unless otherwise specified.

Each of the above APSA whole grades may be certified as “with splits” providing all requirements of the grade are met, except that a tolerance of 15% is allowed for split kernels of which not more than 3% will pass through 17/64 in round screen.

Table 4. Comparison of screen sizes and tolerances (by weight) for American Peanut Shellers Association (APSA) and USDA Grades for in-shell Virginia peanuts

Grade and minimum screen size	Fall-through prescribed screen	Cracked or broken shells, pops, paper, and foreign material	Damaged kernels	Count per pound
		%		
Jumbo				
37/64 x 3”				
APSA	5.00	*10.00	3.50	**176 (U.O.S.)
US	5.00	*10.00	3.50	**176 (U.O.S.)
Fancy				
32/64 x 3”				
APSA	5.00	*11.00	4.50	**225 (U.O.S.)
US	5.00	*11.00	4.50	**225 (U.O.S.)

* (APSA & US)—not more than 0.5% shall be allowed as dirt or other foreign material.
** Unless otherwise specified.

various locations within a field. Peanut maturity may be judged by the shell-out procedure, involving separation of peanut seed into mature or immature categories. Using the shell-out procedure, a peanut is considered mature if the inner hull is brown and the seed coat is pink to red. Optimum maturity is reached for runner and Spanish types when 75 to 80% of the inner hull has turned brown and for Virginia types when 65% of the seed coat has turned deep pink. Runner peanut maturity can be determined by a hull-scrape method, in which maturity profiles for samples are estimated based on degree of change in pod mesocarp from white to brown to black (Williams and Drexler 1981).

Grades, Sizes, and Packaging

U.S. grade standards and industry grade standards from the American Peanut Shellers Association exist for shelled Spanish, shelled runner, shelled Virginia, and in-shell Virginia peanuts. A comparison of tolerances as provided by the American Peanut Shellers Association fficial Trade Rules for shelled peanuts based primarily on size, peanuts of other types, amount of split or broken kernels, freedom from foreign material, damage, minor defects, and in some cases moisture percentage are presented in tables 1 to 4. Tolerances for in-shell Virginia peanuts based on maturity; freedom from loose shelled peanuts; discoloration of shell; presence of dirt, shell, and other foreign material; and degree of kernel fill inside the shell are compared.

Raw in-shell peanuts are typically stored as “farmer stock peanuts” in flat, ventilated warehouses or grain bins in bulk or, less commonly, in 50-lb (23 kg) burlap bags for a week to 10 mo prior to shelling (Smith et al. 1995). After shelling, raw peanuts are often shipped in bulk containers but may be packaged in burlap or nylon tote bags of various sizes. Peanuts for human consumption must be free of visible *Aspergillus flavus* mold, containing less than 15 ppb (nL L^{-1}) aflatoxin. Lots imported into the United States may be designated “segregation 1” or “segregation 2” depending on degree of kernel damage and concealed damage from rancidity, mold, or decay. Segregation 1 peanuts may *not* contain more than 2.00% damaged kernels nor more than 1.00% concealed damage, while segregation 2 peanuts *may* contain more than 2.00% damaged or more than 1.00% concealed damage. Segregation 3 peanuts are those which contain visible *Aspergillus flavus* mold or 15 ppb (nL L^{-1}) or more aflatoxin.

Optimum Storage Conditions

In-shell farmers-stock peanuts should be dried to about 7.5% moisture. If stored at 10 °C (50 °F), these can be stored for up to 10 mo without significant quality loss (Davidson et al. 1982). High losses in milling quality may occur if peanuts are dried to below 7% moisture or if kernel temperature is below 7 °C (44.6 ºF) during shelling (McIntosh and Davidson 1971). Peanut moisture content >10% should be avoided to prevent mold growth (Diener and Davis 1977). Adequate ventilation in a warehouse storage facility, preferably providing one air change every 3 min, is also desirable to prevent excess moisture and heat from accumulating in the storage facility (Smith and Davidson 1982).

Quality of raw shelled peanuts can be maintained for at least 1 year at 1 to 5 °C (34 to 41 °F) with moisture content of <7%, or for 2 to 10 years at -18 °C (0 °F) and <6 % moisture. Maintaining RH between 55 and 70% at 1 to 5 °C (34 to 41 °C) will maintain peanut moisture content at 7 to 7.5%. Careful handling of peanuts equilibrated to <5 °C (41 °F) is necessary to prevent bruising and subsequent oil seepage from damaged cells within the cotyledon. Upon removal of raw shelled peanuts from refrigerated or frozen storage, equilibration to ambient temperature should be gradual in conditioning rooms, with RH, temperature, and air-flow adjusted to prevent moisture condensation onto peanuts.

Controlled Atmosphere Considerations

Low-O_2 storage shows promise for delaying rancid flavor development and insect infestation (Slay et al. 1985). High-CO_2 storage appears to limit growth of *Aspergillus flavus* in short-duration storage of high-moisture, noncured peanuts. Peanuts at 20% moisture stored at 0.6 to 3 °C (33 to 37 °F) in a high-CO_2 environment had acceptable quality for 4 days but deteriorated after 8 days of storage (Moseley et al. 1971). For longer-term storage of high-moisture, shelled peanuts under ambient temperature conditions, <1.5% O_2 was required to slow *Aspergillus flavus* growth; but no CA totally eliminated aflatoxin production (Wilson and Jay 1976).

Retail Outlet Display Considerations

Peanuts are normally marketed at ambient temperature. Using low O_2 and preventing excessive exposure to light is recommended. In-shell peanuts may be displayed and marketed in bulk containers. Exposure to moisture or high RH should be avoided.

Chilling Sensitivity

Prior to or during harvest and prior to postharvest drying, exposure to chilling temperatures of 0.9 to 1.6 °C (33.6 to 35 °F) caused increased ethanol production, and the effect was greater for small seeds than for large seeds within a genotype. This was accompanied by increased seed leachate, suggested by the authors to be indicative of induction of anaerobic respiration and cell membrane damage (Singleton and Pattee 1989). Following postharvest drying and during storage, peanuts do not appear to be sensitive to chilling and may be stored at or below freezing.

Ethylene Production and Sensitivity

Peanut seeds exhibit dormancy periods following harvest of 63 to 84 days, varying with genotype and temperature during pod maturation and storage. Soaking seeds in GA3 or ethephon at 50 to 200 $\mu g\ mL^{-1}$ was effective in breaking dormancy (Kapur et al. 1990). Nondormant peanuts exhibit a climacteric-like rise in ethylene production during seed germination (Whitehead and Nelson 1992).

Respiration Rates

Properly cured peanuts in storage exhibit a relatively low rate of respiration. During harvest and prior to curing, especially for high-moisture peanuts, respiration rates may be substantial and significant losses in quality can ensue. Freshly harvested peanuts should be dried soon after harvest to <10% moisture to assure optimum quality.

Physiological Disorders

Shriveled seed trait has been identified as a heritable condition for peanuts. Seed mature normally but appear shriveled and thus appear to have been harvested while immature. Seeds of shriveled lines exhibit up to 67% less oil and double the amount of sucrose, and defatted meal contained less protein (Jakkula et al. 1997). Improper curing of peanuts results in loss of quality and off-flavor development.

Fermented, fruity off flavor is caused by freezing temperatures during harvest while peanuts are still windrowed (Singleton and Pattee 1991) or by too high a temperature during curing (Sanders et al. 1989). Effects of improper curing are greatest on smaller seed, perhaps indicating greater effect on immature seed (Sanders et al. 1990).

Postharvest Pathology

Peanuts are susceptible to infection by various molds and fungi, and a combination of storage at 1 to 5 °C (33.8 to 41 °F) and reduction of moisture content to <7.5% may be effective in reducing mold and fungi growth in storage. The presence of toxic fungal metabolites (mycotoxins) are a particular concern. The name "aflatoxin" refers to four metabolites found in contaminated peanuts and designated aflatoxin B1, B2, G1, and G2. Aflatoxins B1 and B2 are metabolites of *Aspergillus flavus,* and all four aflatoxins may be produced by *Aspergillus parasiticus* (Cole et al. 1995). A fifth mycotoxin, cyclopiazonic acid, is somewhat less toxic than aflatoxin and is produced by *Aspergillus flavus*, other *Aspergillus* species, and several species of *Penicillium* (Dorner et al. 1985).

Preharvest conditions favoring aflatoxin contamination are high temperatures and drought stress during the last 3 to 6 weeks of the growing season (Cole et al. 1989). Late-season irrigation may be effective in reducing aflatoxin contamination (Dorner et al. 1989). When aflatoxin contamination occurs, it is common for most of the harvested seed to be free of contamination with only a few highly contaminated seeds. Although monitoring at the point of sale for *Aspergillus flavus* is mandated by the USDA Peanut Marketing Agreement, and detection of ≥15 ppb (nL L^{-1}) aflatoxin leads to positive aflatoxin identification, the irregular distribution of infection may lead to false negative designations.

Storage conditions to deter growth of the causal organisms and subsequent metabolic production of the mycotoxins primarily involve prevention of rehydration during storage. Decontamination of contaminated lots is most effectively done with electronic color sorting, although size and density separation may also be effective in removal of the most susceptible underdeveloped seed.

Quarantine Issues

Importation of peanut seed into the United States for planting is prohibited from Burkino Faso, the People's Republic of China, Cote d'Ivoire, India, Indonesia, Japan, the Phillipines, Senegal, Thailand, and Taiwan because of peanut stripe virus. During import of peanuts, all lots must be labeled with a positive lot identification and must meet the requirements for segregation 1 peanuts if used for human consumption. Peanuts with visible *Aspergillus flavus* mold, or those containing ≥15 ppb aflatoxin, may not be used for edible purposes; they may be used for oil stock. Such peanuts may be blanched and reseparated into aflatoxin-negative lots, which may be used for edible purposes.

Special Considerations

Peanuts are a major allergenic food among adults and children in the United States (Taylor 1992). Allergen activity has been identified for at least six allergens by phage display technology and is known to be in association with the two major storage proteins, arachin and conarachin, and in profilin (Kleber et al. 1999). Allergens may also be present in refined peanut oil (Olszewski et al. 1998). Due in large part to allergenicity, any food product containing peanuts or peanut oil must be labeled as such.

Careful handling of cured farmers-stock peanuts to prevent breakage of shells reduces the risk for spread of fungal contamination and maintains the grade. Conveyors, cleaners, sizers, and other handling equipment should be padded where appropriate and properly maintained to prevent excessive breakage during handling. Once shelled and roasted, peanuts should be handled carefully to prevent separation of the half kernels and breakage since splits and pieces are more susceptible to oxidative deterioration and rancidity development. Peanuts will absorb lipophilic volatiles from their surroundings or from inappropriate packaging that can induce off flavors. Absorption of ammonia can cause darkening of nutmeats.

References

Cheng, H.Y., G.H. Zheng, X.M. Jing, et al. 1997. Storage of peanut seeds with low moisture content for 11 years in ambient temperature. Plant Gen. Resour. Newsletter 110:35-40.

Cole, R.J., J.W. Dorner, and C.C. Holbrook. 1995. Advances in mycotoxin elimination and resistance. *In* H.E. Pattee and H.T. Stalker, eds., Advances in Peanut Science, pp. 456-474. American Peanut Research and Education Society, Stillwater, OK.

Cole, R.J., T.H. Sanders, J.W. Dorner, and P.D. Blankenship. 1989. Environmental conditions required to induce preharvest aflatoxin contamination of groundnuts: summary of six years research. *In* Proceedings of the ICRISAT International Workshop on Aflatoxin Contamination of Groundnut, 1989, pp. 279-287. International Crops Research Institute for the Semi-Arid Tropics Center, Patancheru, Peru.

Davidson, J.I., T.B. Whitaker, and J.W. Dickens. 1982. Grading, cleaning, storage, shelling and marketing of peanuts in the United States. *In* H.E. Pattee and C.T. Young, eds., Peanut Science and Technology, pp. 571-623. American Peanut Research and Education Society, Yoakum, TX.

Diener, U.L., and N.D. Davis. 1977. Aflatoxin formation in peanuts by *Aspergillus flavus*. Bull. 493, Auburn University Agricultural Experiment Station, Auburn, AL.

Dorner, J.W., R.J. Cole, and L.G. Lomax. 1985. The toxicity of cyclopiazonic acid. *In* J. Lacey, ed., Trichothecenes and Other Mycotoxins, pp. 529-535. John Wiley and Sons, New York, NY.

Dorner, J.W., R.J. Cole, T.H. Sanders, and P.D. Blankenship. 1989. Interrelationship of kernel water activity, soil temperature, maturity and phytoalexin production in pre-harvest aflatoxin accumulation of drought-stressed peanuts. Mycopathalogia 105:117-128.

Holaday, C.E., and J.L. Pearson. 1974. Effects of genotype and production area on the fatty acid composition, total oil and total protein in peanuts. J. Food Sci. 39:1206-1209.

Jakkula, L.R., S.F. O'Keefe, D.A. Knauft, and K.J. Boote. 1997. Chemical characterization of a shriveled seed trait in peanut. Crop Sci. 37:1560-1567.

Kapur, A., J. Kaur, H.L. Sharma, and H. Singh. 1990. Preconditioning of peanut *(Arachis hypogaea)* seeds to release dormancy. Ann. Biol. Ludhiana 6:141-145.

Kleber, J.T., R. Crameri, U. Appenzeller, et al. 1999. Selective cloning of peanut allergens, including profilin and 2S albumins, by phage display technology. Int. Arch. Allergy Immun. 119:265-274.

Knauft, D.A., and D.W. Gorbet. 1989. Genetic diversity among peanut cultivars. Crop Sci. 29:1417-1422.

McIntosh, F.P., and J.I. Davidson. 1971. Effect of temperature on shelling runner- and spanish-type peanuts. Rep. 52-65, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Moseley, Y.C., H.B. Manbeck, G.L. Barnes, and G.L. Nelson. 1971. Controlled atmosphere for short duration storage of peanuts before drying. Trans. Amer. Soc. Agr. Eng. 14:206-210.

Olszewski, A., L. Pons, F. Moutete, et al. 1998. Isolation and characterization of proteic allergens in refined peanut oil. Clin. Exper. Allergy 28:850-859.

Sanders, T.H., P.B. Blankenship, J.R. Vercellotti, and K.L. Crippen. 1990. Interaction of curing temperature and inherent maturity distribution in descriptive flavor of commercial grade sizes of Florunner peanuts. Peanut Sci. 17:85-89.

Sanders, T.H., R.W. McMichael, and K.W. Hendrix. 2000. Occurrence of resveratrol in edible peanuts. J. Agric. Food Chem. 48:1243-1246.

Sanders, T.H., J.R. Verecellotti, P.B. Blankenship, et al. 1989. Interaction of maturity and curing temperature on descriptive flavor of peanuts. J. Food Sci. 54:1066-1069.

Singleton, J.A., and H.E. Pattee. 1989. Effect of chilling injury on windrowed peanuts. Peanut Sci. 16:51-54.

Singleton, J.A., and H.E. Pattee. 1991. Peanut moisture/size, relation to freeze damage and effect of drying temperature on volatiles. J. Food Sci. 56:579-581.

Slay, W.O., W.G. Ferguson, and J.A. Pomplin. 1985. Some effects of conventional and low-oxygen atmosphere storage and processing methods on Florunner peanut seed. Peanut Sci. 12:8-11.

Smith, J.S., P.D. Blankenship, and F.P. McIntosh. 1995. Advances in peanut handling, shelling and storage from farmer stock to processing. *In* H.E. Pattee and H.T. Stalker, eds., Advances in Peanut Science, pp. 500-527. American Peanut Research and Education Society, Stillwater, OK.

Smith, J.S., and J.I. Davidson. 1982. Psychometrics and kernel moisture content as related to peanut storage. Trans. Amer. Soc. Agric. Eng. 25:231-236.

Taylor, S.L. 1992. Chemistry and determination of food allergens. Food Tech. 46:146-152.

Whitehead, C.S., and R.M. Nelson. 1992. Ethylene sensitivity in germinating peanut seeds: the effect of short-chain fatty acids. J. Plant Physiol. 139:479-483.

Williams, E.J., and J.S. Drexler. 1981. A non-destructive method for determining peanut pod maturity. Peanut Sci. 8:134-141.

Wilson, D.A., and E. Jay. 1976. Effect of controlled atmosphere storage on aflatoxin production in high moisture peanuts (groundnuts). J. Stored Prod. Res. 12:97-100.

Pecan

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Scientific Name and Introduction

Carya illinoinsis L. is a member of the hickory family (Jugulaceae). The edible seed is surrounded by a shuck that opens (dehisces) when the seed is mature. Nuts are harvested in late fall and early winter by mechanically shaking the trees and gathering the nuts from the orchard floor. Nuts are covered by a shell that is divided into two relatively equal-sized halves. Pecans are native to the southern United States and Mexico and are classified for marketing either as seedling (primarily natives) or cultivars. Seedling pecans have typically thicker shells with smaller kernels, lower shellout percentage, and higher oil content than cultivars. The majority of commercial production is in cultivars such as 'Western,' 'Desirable,' 'Stuart,' 'Wichita,' and 'Pawnee.'

Quality Characteristics and Criteria

Pecan kernels should be yellow-golden to light-brown in color, be of roughly equal width from one end to the other, and be free of any shell or other foreign material as well as off odor or flavor. Water content should be <4% to prevent mold growth and retard rancidity development. Water content <2% increases brittleness that induces greater kernel breakage during handling and enhances cracking of the testa, which increases O_2 permeation of the nutmeat, favoring rancidity. Oil content of pecan kernels inversely affects shelf-life, and oil content varies from 55 to 75% (by weight) and is influenced by cultivar, geographic location, and year of production (Wells and McMeans 1978).

Horticultural Maturity Indices

Kernels are considered mature after oil accumulation is complete, which coincides with shuck split (Eddy and Storey 1988). Maturation of fruit within a tree occurs nonuniformly and can be influenced by cultivar and weather conditions.

Grades, Sizes, and Packaging

In-shell and shelled grades exist and are primarily determined by size, degree of kernel fill, color, and freedom from defects and foreign material. Grades for in-shell pecans include U.S. No. 1 and U.S. No. 2, based primarily on uniformity of shell color, absence of shell defects, kernel defects, and extraneous or foreign material. Sizes of in-shell pecans are based on number of nuts per 0.45 kg (1 lb) and include Oversize (≤55), Extra Large (56 to 63), Large (64 to 77), Medium (78 to 95), and Small (96 to 120). In-shell pecans are packaged in bags containing 36.4 to 54.5 kg (80 to 120 lb) or in palletized containers.

Grades for shelled pecans include U.S. No. 1 and U.S. Commercial for halves, halves and pieces, and pieces based primarily on testa color, degree of kernel fill, moisture content, freedom from shell or extraneous material, and freedom from damage. When the color of kernels in a lot conforms to the "light" or "light amber" classification, these color designations may be used to describe the lot in connection with the grade. Size classifications for halves are based on number of halves per 0.45 kg (1 lb) and include Mammoth (≤250), Junior mammoth (251 to 300), Jumbo (301 to 350), Extra large (351 to 450), Large (451 to 550), Medium (551 to 650), Small or Topper (651 to 750), and Midget (≥751). Size classification for pieces are based on the maximum and minimum round diameter in inches through which the pieces will or will not pass and include Mammoth (>1.3 cm, 1/2 in), Extra large (1.4 to 1.1 cm, 9/16 to 7/16 in), Halves and pieces (>0.8 cm, 5/16 in), Large (1.3 to 0.8 cm, 1/2 to 5/16 in), Medium (1.0 to 0.5 cm, 3/8 to 3/16 in), Small (0.6 to 0.3 cm, 1/4 to 1/8 in), Midget (0.5 to 0.2 cm, 3/16 to 1/16 in), and Granules (0.3 to 0.2 cm, 1/8 to 1/16 in). Shelled pecans are packaged in 13.6-kg (30-lb) grease-proof boxes, either loose or vacuum-sealed inside plastic bags.

Optimum Storage Conditions

Mechanically harvested in-shell pecans should be dried to 4.5% moisture prior to storage to preserve quality and prevent mold growth (Heaton et al. 1977). Pecan nutmeats contain 7 to 9% moisture after shelling and should be dried to 3 to 4% moisture to maintain quality. Drying temperatures greater than 38 °C (100 °F) should be avoided because they cause darkening of nutmeats. Recommended conditions for storage of pecans is <2 °C (36 °F) at 70% RH. Long-term storage should be near -18 °C (0 °F) with 70% RH. In-shell pecans can be stored for 6 mo at 22 °C (72 °F), 12 mo at 0 °C (32 °F), or 24 mo at -18 °C (0 °F); whereas shelled pecans can only be stored for 3 mo at 22 °C (72 °F), 9 mo at 0 °C (32 °F), or 18 mo at -18 °C (0 °F) (Woodroof and Heaton 1962).

Frozen pecans are brittle and should be handled with care to prevent excessive breakage. Pecans may be thawed and refrozen without damage, provided they are properly tempered. Tempering involves slowly raising the temperature of pecans at low RH and high airflow, with each 10 °C (18 ºF) increase in temperature occurring over 48 h. This can be accomplished by placing pecans from frozen storage sequentially into two rooms for several days each. The first room should be at 5 °C (41 °F) and the second room at 16 °C (61 °F) (Santerre 1994). Tempering prevents moisture condensation onto nutmeats during thawing that could induce a soggy texture and promote mold growth.

Modified Atmosphere Considerations

Shelf-life of pecans may be increased by storage in 2 to 3% O_2 in N_2, and less frequently in CO_2 as the balance gas. Storage at <2% O_2 for 52 days can cause a fruity flavor to develop (Santerre et al. 1990). O_2 transmission rates for packaging materials should be >0.08 mL per 100 cm per 24 h (Dull and Kays 1988). Vacuum packaging can offer a further benefit of protection from breakage.

Retail Outlet Display Considerations

Use of packaging to reduce O_2 concentration and prevent excessive light exposure is recommended for shelled pecans. In-shell pecans may be displayed in bulk containers. Exposure to moisture should be prevented.

Chilling Sensitivity

Pecans are not sensitive to chilling and are commonly stored at temperatures at or below freezing.

Ethylene Production and Sensitivity

Pecans produce very low amounts of ethylene. Prolonged exposure to ethylene may cause pecans to darken and shorten their shelf-life.

Respiration Rates

Pecans have a low respiration rate of <5 mg CO_2 kg^{-1} h^{-1} at 5 °C (41 °F), or about 2.5 mL CO_2 kg^{-1} h^{-1}. Heat production is about 1,100 BTU ton^{-1} day^{-1} or 305 kcal $tonne^{-1}$ day^{-1}.

Physiological Disorders

Wafering is characterized by asymmetric width of halves along the longitudinal axis. It is caused by poor kernel fill during development. This condition is most prevalent during a year in which the crop load on trees is excessive (Smith et al. 1993).

Stink bug and pecan weevil feeding during pecan development results in round or irregularly shaped black discoloration of the testa that is only evident after shelling. Pecan weevils lay eggs in developing pecans; larvae hatch soon after kernel maturity, consume the nutmeat, and exit the pecan leaving a small round hole in the shell. Pecans containing pecan weevil larvae can sometimes be identified by an oil-soaked or reddish appearance.

Opalescence, a condition characterized by an opaque or oil-stained appearance of all or a portion of the nutmeat, has been identified and attributed to breakdown of oil bodies and subsequent leakage of oil within the cotyledon. This leakage increases O_2 exposure of oil and decreases shelf-life by accelerating oxidative rancidity development.

Sticktights are nuts that fail to shed the shuck at harvest. Insufficient moisture in fall, or insect feeding on the shuck, may cause this condition because shuck splitting is an active process that requires the shucks to remain turgid and for abscission layers to form at the sutures and at the peduncle (Worley 1982). Early fall freeze or potassium insufficiency may also increase prevalence of sticktights. Kernels from sticktight pecans are often of lower quality due to premature death of the vascular system feeding the developing kernels.

Vivipary (sprouting of nuts on the tree) renders affected pecans unmarketable and may be reduced by late season irrigation (Stein et al. 1989) or by fruit thinning (Sparks et al. 1995).

Postharvest Pathology

The most common decay found in pecans is caused by molds, with *Penicillium* and *Aspergillus* most prevalent (Huang and Hanlin 1975). The intact shell provides some defense against mold. Some strains of *A. flavus* and *A. parasiticus* that have been isolated from pecans can produce aflatoxins, a heat-resistant carcinogenic and toxic byproduct. Storage at refrigerated or frozen temperatures prevents or slows mold growth. Reduction of nutmeat moisture content to <4.5% and storage at RH <70% provide a water activity of 0.65 to 0.70, which will not support growth of most molds.

E. coli is a common shell contaminant, especially for nuts harvested in orchards where animal grazing is practiced (Marcus and Amling 1973). Contamination of nutmeats may occur if shells are broken during harvest or if shells are not properly sanitized by addition of chlorine to heated soak-water just prior to cracking. Because of high amounts of organic material on the surface of pecan shells, chlorine should be monitored and replenished as needed to maintain the desired concentration.

Quarantine Issues

Pecan shucks, shells, and nuts in the shell, as well as containers, equipment, and vehicles used in association with them, must be free of pecan casebearer, pecan weevil, and hickory shuckworm prior to transportation into California.

Special Considerations

Pecans marketed in-shell should be cracked and sampled periodically to assess nutmeat quality. Pecan halves and pieces marketed in plastic bags should be handled with care to prevent excessive breakage and grade change. Since most bags for marketing shelled pecans are clear, care in prevention of exposure to direct sunlight or excessive UV radiation should be exercised to prevent darkening of the testa. Increased temperature during handling can also enhance darkening and promote development of rancid flavor. Pecans will absorb lipophilic volatiles in the environment that can introduce off flavors. Absorption of ammonia will cause darkening of nutmeats. Although frozen storage increases shelf-life, once out of storage pecans should be used quickly because of their short shelf-life at room temperature compared to never-frozen pecans.

References

Dull, G.G., and S.J. Kays. 1988. Quality and mechanical stability of pecan kernels with different packaging protocols. J. Food Sci. 53:565-567.

Eddy, M., and J.B. Storey. 1988. The influence of harvest date on oil and flavor development in Desirable and Whichita pecans. HortScience 23:782.

Heaton, E.K., A.L. Shewfelt, A.E. Badenhop, and L.R. Beuchat. 1977. Pecans: handling, storage, processing and utilization. Research Bull. 197, University of Georgia, Georgia Experiment Station, Athens, GA.

Huang, L.H., and R.T. Hanlin. 1975. Fungi occurring in freshly harvested and in-market pecans. Mycologia 67:689-700.

Marcus, K.A., and H.J. Amling. 1973. *Escherichia coli* field contamination of pecan nuts. Appl. Microbiol. 26:279-281.

Santerre, C.R. 1994. Pecan processing. *In* C.R. Santerre, ed., Pecan Technology, pp. 49-67. Chapman and Hall, New York, NY.

Santerre, C.R., A.J. Scouten and M.S. Chinnan. 1990. Room temperature of shelled pecans: control of oxygen. Proc. Southeastern Pecan Growers' Assoc. 83:113-121.

Sparks, D., W. Reid, I.E. Yates, et al. 1995. Fruiting stress induces shuck decline and premature germination in pecan. J. Amer. Soc. Hort. Sci. 120:43-53.

Smith, M.W., W. Reid, B. Carroll, and B. Cheary. 1993. Mechanical fruit thinning influences fruit quality, yield, return fruit set and cold injury of pecan. HortScience 28:1081-1084.

Stein, L.A., G.R. McEachern, and J.B. Storey. 1989. Summer and fall moisture stress and irrigation scheduling influence pecan growth and production. HortScience 24:607-611.

Wells, J.M., and J.L. McMeans. 1978. Rancidity, iodine values and oil content of 21 pecan cultivars. Proc. Southeastern Pecan Growers' Assoc. 71:159-162.

Woodroof, J.G., and E.K. Heaton. 1962. Storage of pecans. Research Bull. 149, University of Georgia, Georgia Experiment Station, Athens, GA.

Worley, R.E. 1982. Tree yield and nut characteristics of pecan with irrigation under humid conditions. J. Amer. Soc. Hort. Sci. 107:30-34.

Pistachio

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Scientific Name and Introduction

Pistacia vera L. is the only species of the 11 in the genus *Pistacia* that produces edible nuts. It is a native of western Asia and Asia Minor, and wild representatives are still found in hot, dry locations in these areas. The pistachio was introduced to Europe at the beginning of the Christian Era. The USDA plant exploration service introduced the pistachio to the United States in 1890. It was introduced to California in 1904 at the Plant Introduction Station in Chico, CA (Hendricks and Ferguson 1995).

The pistachio tree is dioecious; thus orchard plantings must include the appropriate ratio of females and males (8:1 in older plantings, but up to 25:1 in more recently established orchards [Kallsen et al. 1995]). At present the California industry is dominated by one male cultivar ('Peters') and one female ('Kerman'), although other cultivars are being tested. The reliance on single cultivars poses the potential for catastrophic problems for the industry with pests and diseases, and efforts to evaluate existing alternative germplasm and develop new cultivars are underway (Parfitt 1995a,b). There are also a limited number of rootstocks in use. While the *Verticillium*-tolerant *Pistacia integerrima* is currently the dominant rootstock in use, *P. atlantica* × *P. integerrima* is increasingly being planted in California (Krueger and Ferguson 1995). An important problem for pistachio growers is the strong tendency toward alternate bearing.

Quality Characteristics and Criteria

In-shell and shelled pistachios are marketed extensively. An important aspect of quality of the in-shell product is a shell that is free of staining. This is not only for cosmetic reasons. Shell staining is also an indicator of development, pathogen, and insect problems prior to harvest. Kernel quality criteria include a firm, crisp texture (which is degraded by insufficient drying after harvest or storage at too high an RH), a sweet and oily flavor, and freedom from rancidity (Kader et al. 1982). Kernels are high in fat content (approximately 45% by weight) and crude protein (approximately 30%). Total levels of low-molecular-weight sugars are 3 to 4%, but reducing sugars (primarily glucose and fructose) make up only about 10% of the total sugar (Kader et al. 1982, Labavitch et al. 1982).

Horticultural Maturity Indices

The pistachio nut is a drupe; an exocarp and fleshy mesocarp surround the hard, but relatively thin, shell, which encloses the edible seed. Ideally the harvest is timed to the full accumulation of fat and sugar in the kernels. This is roughly coincident with the splitting of the shell. Shell split is not visible due to the fact that the fleshy mesocarp masks the shell in developing nuts. However, evidence of maturation can be seen in the color change of the hull (exocarp), which is green when the nut is not mature and then progresses through ivory to rose with full maturation. Activity in the abscission zones between the nuts and the rachis (assessed by a measurable decrease in "fruit removal force") also indicates maturation. When fully mature, the nut with its shell will be ejected from the hull when pressure is applied with the thumb and forefinger at the hull's distal end (Ferguson et al. 1995). Nuts at full maturity, as judged by the preceding criteria, will have full accumulation of fat and simple sugars (Labavitch et al. 1982).

Harvest should not be delayed past full maturation of the crop because this will increase losses to navel orangeworm (*Amyelois transitella* Walker), birds, and fungi (particularly *Aspergillus flavus*), as well as late season weather (rain and wind). Furthermore, delayed harvest can lead to shell staining because of breakdown of the phenolic-compound-rich hull tissues. When harvested the nuts are split and moisture content is high (40 to 50%). Trees are shaken (by hand for young trees, mechanically for mature trees) and the nuts are caught on tarps or a catching frame and transferred to bins in order to eliminate problems caused by contact with the soil.

Delays between harvest and further processing should be minimized because they only exacerbate problems caused by hull breakdown or contamination of hull tissues. Problems caused by unavoidable delays in hulling and drying (below) can be reduced by cold storage of bins at 0 ºC (32 ºF) and <70% RH without increasing shell staining (Kader et al. 1980, Thompson 1997). At the processor, the bins of nuts are dumped, and debris is removed by passage over an air leg. Hulls are removed, blanks are removed in a float tank, and the in-shell nuts are dried to 5 to 7% moisture. Most large handlers now use a two-stage process: Nuts are dried in a column dryer to 12 to 13% moisture with forced hot air at 82 ºC (180 ºF) before the drying is completed more slowly (24 to 48 h) with air heated to no more than 49 ºC (120 ºF) (Ferguson et al. 1995).

Grades, Sizes, and Packaging

In-shell and shelled grades exist and are determined primarily by kernel size, degree of dryness, absence of foreign material, and freedom from defects caused by insects and mold. For the in-shell product, additional grading criteria include absence of shell pieces and free kernels, shells without stains and adhering hull material, and absence of unsplit shells and blanks. A complete description of U.S. quality standards, grades, and sizes for pistachios in the shell can be found at http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5050502.

Shell staining is usually caused by dehiscence of the hull along its suture at the same time as the shell within is splitting. This premature hull dehiscence increases "early" problems with insects and molds (Doster and Michailaides 1999). Pearson (1996) and Pearson and Slaughter (1996) described testing of a machine vision system that might prove useful in sorting of nuts in processing streams to reduce the incidence of staining in the marketed product. The simultaneous splitting of shell and hull is generally caused by too tight an adherence of the hull to the shell. The absence of a tissue gap between the two pericarp-derived parts of the nut makes it impossible for the shell to split without triggering hull split. This often leads to shells with adhering hull material (Pearson et al. 1996), considered a defect.

Optimum Storage Conditions

Once they have been dried (see above), nuts can be held at 20 ºC (68 ºF) and 65 to 70% RH for up to a year (Ferguson et al. 1995). Pistachios are considerably less prone to rancidification (precipitated by oxidation of polyunsaturated fatty acids) than are almonds and, particularly, pecans and walnuts. These commodities are also high in fat content, but walnut and pecan oils have a much higher content of polyunsaturated fatty acids than pistachio oil.

Controlled Atmosphere Considerations

While relatively stable when stored in air at 20 ºC (68 ºF), storage under high CO_2 (Maskan and Karatus 1998), reduced O_2 (<0.5%), and lower temperature (0 to 10 ºC) further improve flavor stability with the added benefit of providing insect control. Vacuum packaging or N_2 flushing of packages also provides benefits.

Chilling Sensitivity

Pistachios are not sensitive to chilling and can be stored at or below freezing.

Ethylene Production and Sensitivity

Pistachio production of ethylene is very low. There are no documented responses to ethylene that might affect nut quality.

Respiration Rates

The low water content of properly stored, dried pistachios makes them relatively inert metabolically. Respiratory rates are very low.

Physiological Disorders

Rancidification and shell staining have been discussed in previous sections.

Developmental and physiological problems that occur before full maturity can have particularly important consequences for nut quality. Because nuts are only useful when they have split, failure of hull split as nuts reach full maturity can cause substantial yield losses. While splitting is maturation-dependant, it will be reduced by water stress late in the growing season (mid-August through September) and failure to maintain adequate boron (120 ppm [mg kg^{-1}] leaf dry weight). Early in postharvest drying, the split on partially split nuts tends to widen (Freeman and Ferguson 1995).

Blank nuts result when the embryo fails to develop. This can be caused by promotion of shell development from ovary tissues without successful fertilization. Blank development also occurs later in the season and has been explained as the result of the inability of the tree to provide sufficient assimilate to complete development of its entire crop. Inadequate boron and water stress are also indicated as causes of blank formation (Freeman and Ferguson 1995).

Pistachios are strongly alternate-bearing and failure of hull split and blank formation are correlated with “on” and “off” crop years. Studies indicate that blanking tends to be much higher in “off” years and nonsplit nuts are much more common in “on” years. Of course, crop load is much higher in “on” years, and this has a large effect on assimilate partitioning.

Insect Problems

Several insects that are field pests of pistachios are able to cause superficial damage (“epicarp lesion”) to developing nuts. If insects are able to probe deeply or introduce fungal pathogens, these pests can cause damage to the kernels. The navel orangeworm (*Amyelois transitella* Walker), a primary field pest, is the major insect problem after harvest. Methyl bromide fumigation has been used to control navel orangeworm in harvested pistachios (Hartsell et al. 1986), but this fumigant is being phased out. Laboratory tests of navel orangeworm survival during pistachio processing indicate that very few of the insects survive nut-drying (Johnson et al. 1996). Projections indicate that survival of navel orangeworms is insufficient to be a problem in stored nuts, particularly because reinoculation of nuts due to insect reproduction within the dried, stored nuts is likely to be virtually nonexistent (Johnson et al. 1996).

Postharvest Pathology

Several fungi are capable of infecting growing pistachio nuts and causing damage to hulls and kernels. Infection is often facilitated by early splitting of hulls, which leads to infestations by a number of hemipteran insects that feed on the nuts and serve as nonspecific vectors for diseases. *Alternaria* and *Cladosporium* species are also colonizers of early split nuts. Late season rains will promote activity of *Botryosphaeria dothidea* on pistachio hulls and kernels (Michailides et al. 1995). Because mold counts on nuts going into storage can be high (Heperkan et al. 1994), it is important that proper storage conditions (especially low RH and absence of standing water) be maintained to avoid serious problems.

The greatest postharvest disease threats are from *Aspergillus flavus* and *A. parasiticus*. The danger is particularly serious because these fungi can produce aflatoxin. As with many disease problems of pistachio, vectoring by insects attracted to early split nuts (such as navel orangeworm) is an important contributing factor. In Doster and Michaelides’ (1994) study of *Aspergillus* molds in California pistachios, early split nuts had over 99% of the aflatoxin detected and navel-orangeworm-infected nuts had substantially more infection by several *Aspergillus* species, as well as over 84% of the aflatoxin detected. The close association of contamination with early split nuts suggests that the potential aflatoxin problem can be reduced by following procedures for reducing early splitting or sorting out nuts with shells stained because of early splitting (discussed above and Michaelides et al. 1995). In theory, nuts with aflatoxin contamination could be sorted out based on aflatoxin fluorescence; however, Steiner et al. (1992) concluded that this approach may have limited value because of limited sensitivity of detection and inconsistent presentation of fluorescence in contaminated nuts. Further complicating the detection problem is the fact that substantial contamination in a large sample of nuts may be due to the initial contamination and spread by only a few individual nuts.

Quarantine Issues

Insect infestation is a potentially important problem, as are the fungal infections that often accompany insect damage. Fumigation with methyl bromide or phosphine has been used for disinfestation, but the former is being curtailed and insect resistance to phosphine has been reported (Zettler et al. 1990). New fumigants are being developed and tests of efficacy, including effects on flavor, are being performed (E.J. Mitcham, Univ. of California, Davis, 2002, personal communication). Thus far, the newer fumigants are not registered for pistachio nuts.

References

Doster, M.A., and T.J. Michailides. 1994. *Aspergillus* molds and aflatoxins in pistachio nuts in California. Phytopathology 84:583-590.

Doster, M.A., and T.J. Michailides. 1999. Relationship between shell discoloration of pistachio nuts and incidence of fungal decay and insect infestation. Plant Dis. 83:259-264.

Ferguson, L., A. Kader, and J.Thompson. 1995. Harvesting, transporting, processing and grading. *In* L. Ferguson, ed., Pistachio Production, pp. 110-114. University of California, Pomology Department, Center for Fruit and Nut Crop Research and Information, Davis, CA.

Freeman, M., and L. Ferguson. 1995. Factors affecting splitting and blanking. *In* L. Ferguson, ed., Pistachio Production, pp. 106-109. University of California, Pomology Department, Center for Fruit and Nut Crop Research and Information, Davis, CA.

Hartsell, P.L., H.D. Nelson, J.C. Tebbets, and P.V. Vail. 1986. Methyl bromide fumigation treatments for pistachio nuts to decrease residues and control navel orangeworm *(Amyelois transitella)* (Lepidoptera: Pyralidae). J. Econ. Entomol. 79:1299-1302.

Hendricks, L., and L. Ferguson. 1995. The pistachio tree. *In* L. Ferguson, ed., Pistachio Production, pp. 7-9. University of California, Pomology Department, Center for Fruit and Nut Crop Research and Information, Davis, CA.

Heperkan, D., N. Aran, and M. Ayfer. 1994. Mycoflora and aflatoxin contamination in shelled pistachio nuts. J. Sci. Food Agric. 66:273-278.

Johnson, J.A., R.F. Gill, K.A. Valero, and S.A. May. 1996. Survival of navel orangeworm (Lepidoptera: Pyralidae) during pistachio processing. J. Econ. Entomol. 89:197-203.

Kader, A.A., C.M. Heintz, J.M. Labavitch, and H.L. Rae. 1982. Studies related to the description and evaluation of pistachio nut quality. J. Amer. Soc. Hort. Sci. 107:812-816.

Kader, A.A., J.M. Labavitch, F.G. Mitchell, and N.F. Sommer. 1980. Quality and safety of pistachio nuts as influenced by postharvest handling procedures. *In* Pistachio Association Annual Report, pp. 44-52.

Kallsen, C., G.S. Sibbett, and C. Fanucchi. 1995. Planning and designing the orchard. *In* L. Ferguson, ed., Pistachio Production, pp. 36-40. University of California, Pomology Department, Center for Fruit and Nut Crop Research and Information, Davis, CA.

Krueger, B., and L. Ferguson. 1995. Pistachio rootstocks. *In* L. Ferguson, ed., Pistachio Production, pp. 41-42. Center for Fruit and Nut Crop Research and Information, University of California, Pomology Department, Davis, CA.

Labavitch, J.M., C.M. Heintz, H.L. Rae, and A.A. Kader. 1982. Physiological and compositional changes associated with maturation of 'Kerman' pistachio nuts. J. Amer. Soc. Hort. Sci. 107:688-692.

Maskan, M., and S. Karatas. 1998. Fatty acid oxidation of pistachio nuts stored under various atmospheric conditions and different temperatures. J. Sci. Food Agric. 77:334-340.

Michailides, T., D.P. Morgan, and M.A. Doster. 1995. Foliar and fruit fungal diseases. *In* L. Ferguson, ed., Pistachio Production, pp. 148-159. University of California, Center for Fruit and Nut Crop Research and Information, Davis, CA.

Parfitt, D. 1995a. Genetic improvement. *In* L. Ferguson, ed., Pistachio Production, pp. 47-53. University of California, Pomology Department, Center for Fruit and Nut Crop Research and Information, Davis, CA.

Parfitt, D. 1995b. Pistachio cultivars. *In* L. Ferguson, ed., Pistachio Production, pp. 43-46. University of California, Pomology Department, Center for Fruit and Nut Crop Research and Information, Davis, CA.

Pearson, T. 1996. Machine vision system for automated detection of stained pistachio nuts. Lebensm.-Wiss. u.-Technol. 29:203-209.

Pearson, T., and D.C. Slaughter. 1996. Machine vision detection of early split pistachio nuts. Trans. Am. Soc. Agric. Eng. 39:1203-1207.

Pearson, T., D.C. Slaughter, and H.E. Studer. 1996. Hull adhesion characteristics of early-split and normal pistachio nuts. Appl. Eng. Agric. 12:219-221.

Steiner, W.E., K. Brunschweiler, E. Leimbacher, and R. Schneider. 1992. Aflatoxins and fluorescence in brazil nuts and pistachio nuts. J. Agric. Food Chem. 40:2453-2457.

Thompson, J.F. 1997. Maintaining quality of bulk-handled, unhulled pistachio nuts. Appl. Eng. Agric. 13:65-70.

Zettler, J.L., W.R. Halliday, and F.H. Arthur. 1990. Phosphine resistance in insects infesting stored peanuts in the southeastern United States. J. Econ. Entomol. 82:1508-1511.

Walnut

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Scientific Name and Introduction

Persian (English) walnut (*Juglans regia* and a few related species) is a member of the family Juglandaceae and is by far the most important commercial walnut. The genus *Juglans* contains three other groups (butternut, east asian species, and black walnut species) that produce edible kernels. Persian walnuts evolved in central and eastern Asia and were introduced into California in the late 1700s. About 95% of U.S. production is in California. The most important cultivars are 'Hartley,' followed by 'Chandler,' 'Serr,' and 'Vina.' Recent cultivars such as 'Tulare' and 'Howard' will become more important.

Nuts are mechanically shaken from trees during an extended harvest period from late August to early November. The edible kernel is surrounded by a husk that dehisces as the kernel nears maturity. The husk, which should be well split and relatively dry at harvest, is generally lost when the nuts fall to the ground. Harvested nuts (the shell and kernel) may be 35% or more water. Nuts are quickly swept from the orchard floor to avoid damage to the fragile nut and are then dehydrated in forced-air dryers to 8% water content. The temperature of the drying air is kept low, <43 °C (110 °F), to avoid damage leading to kernel rancidity.

Quality Characteristics and Criteria

The primary quality criterion is a high oil content (55 to 65% dry weight) and lack of off flavors caused by oxidation of polyunsaturated fatty acids. Thus, an important criterion is maintaining kernel water content below 4%. Not only does this retard the progression of events that lead to rancidity, it also prevents mold growth and maintains the kernel's crispness. If water content drops too low, however, damage to the kernel's covering can enhance O_2 penetration and rancidity.

The skin covering the kernel contains chemicals that protect fatty acids in the kernel from becoming rancid. Light-colored kernels earn a higher price because the light color indicates that the kernel still has a relatively long shelf-life. An important criterion for evaluating new varieties is yield of light-colored kernels (Hendricks et al. 1998). Retention of light color is influenced by the integrity of the seal between the two halves of the shell, because the shell is an important barrier to O_2 entry. Shell strength and seal integrity are also important in protecting kernels from insect damage and fungi infections that often follow insect damage. Two-thirds of the California production is sold as shelled products (see Siebert 1998); therefore, additional characteristics of processing quality are ease of shelling and yield of intact kernel halves.

Horticultural Maturity Indices

Kernels are considered mature when oil accumulation is complete. This is generally indicated by browning of the internal packing tissue. However, harvest should not begin until the husk is well split and separated from the shell. In the hottest growing regions of California, kernels may be mature 3 weeks prior to husk "maturation" (dehiscence). Low temperatures and high RH, as occurs in some growing regions and can occur at night, advance dehiscence. Ethephon applications are used to advance the harvest and make nut maturation more uniform throughout the tree/orchard (Olson et al. 1998).

Grades, Sizes, and Packaging

In-shell and shelled grades exist and are primarily determined by size, degree of kernel fill, color, and freedom from defects and foreign material. Freedom from off flavors (rancidity) is important. Shelled kernels held for a long period are particularly susceptible. A complete description of Federal quality standards can be found at http://www.ams.usda.gov/AMSv1.0/ams.fetchTemplateData.do?template=TemplateN&page=FreshNutandSpecCropStandards.

In-shell walnut kernels derive protection against oxidative changes from the intact shell and kernel skin. Packaging should be moisture-proof. Shelled products should be packaged in airtight, moisture-proof, opaque or foil packages to maximize shelf-life. Unroasted kernels are less likely to take up moisture than roasted kernels. FDA-approved antioxidants such as butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) can be applied to the kernels in vegetable oil to enhance stability. Edible coatings may be used as O_2 barriers to retard kernel rancidity (Maté et al. 1996).

Optimum Storage Conditions

Low water content and high fat content of the kernel make it relatively stable metabolically and able to tolerate low temperatures. The primary objectives of storage are to maintain the low water content attained after preliminary drying (to suppress enzyme activity, retain texture, and reduce microbial activity) and to limit exposure to O_2 (to minimize rancidity). The optimum temperature range for storage is 0 to 10 °C (32 to 50 °F), with the lower temperature being better. Within this temperature range, a 50 to 65% RH will maintain walnuts at 4% moisture (Beuchat 1978). Lopez et al. (1998) modeled sorption of walnut kernels and concluded that optimum stability and texture were retained in a storage environment of 10 °C (50 °F) and 60% RH in air.

Controlled Atmosphere Considerations

Shelf-life can be extended by storage in <1% O_2. O_2 <0.5% (balance N_2) or CO_2 >80% in air can be effective in insect control.

Chilling Sensitivity

Walnuts are not sensitive to chilling. They may be stored at or below freezing.

Ethylene Production and Sensitivity

Walnuts produce very low levels of ethylene. There are no documented responses of walnut to ethylene that might affect quality.

Respiration Rates

The low water content of properly stored walnuts makes them relatively inert metabolically. Respiration rates are very low.

Physiological Disorders

The most serious postharvest physiological disorder that affects walnut quality is oil rancidity. The problem appears to be caused by poor seed storage conditions: elevated temperature and RH and failure to use CA with reduced O_2 concentration.

Insect Problems

Insect damage can contribute to handling and quality problems. The major insect pest is the codling moth *(Cydia pomonella)*. While nuts attacked in mid season are likely to be rejected, minor early codling moth damage can lead to more serious infestation with navel orangeworm (*Amyelosis transitella* [Walker]), and this is more difficult to detect if the nut is not shelled. The walnut husk fly *(Rhagoletis completa)* is a serious pest in mid to late season. Larval feeding damages the husk tissues, leading to staining of the shell and failure of the husk to split. This reduces the harvest yield and nuts that remain in the orchard serve as a reservoir of insects to threaten the next crop cycle (van Steenwyk and Barnett 1998).
In all cases, insect damage will tend to increase problems with pathogen infection.

Postharvest Pathology

Most infections with pathogens are initiated in the orchard and transferred to the postharvest environment. In-shell product is protected unless the shell has been broken or penetrated by insects. The most serious pathogens are fungi such as *Aspergillus flavus* and *A. parasiticus*, which can produce aflatoxins that are both toxic and carcinogenic. It is important that damaged kernels be discarded prior to storage and that the low temperature and RH conditions discussed above be maintained in order to reduce the chance for mold growth. Toxin-producing *Penicillium* sp. have also been found on walnuts.

Quarantine Issues

Insect infestation is a potentially important problem, as are the fungal infections that often accompany insect damage. Fumigation with methyl bromide or phosphine has been used for disinfestation, but the former is being restricted and insect resistance to phosphine has been reported (Zettler et al. 1990). Johnson et al. (1998) have recommended an initial disinfestation treatment of 0.4% O_2 for 6 days followed by a combination of "protective" treatments that includes 10 °C (50 °F) storage in 5% O_2 and application of the indianmeal moth granulosis virus for control of navel orangeworm and indianmeal moth (*Plodia interpunctella* Hübner). Vail et al. (1991) have reported that these same walnut storage pests are susceptible to the *Bacillus thuringiensis* insecticidal crystal protein. Researchers have successfully introduced the gene for the *Bt* protein into walnut embryos and demonstrated its efficacy in suppressing larval development (Dandekar et al. 1998).

Special Considerations

This presentation of quality maintenance guidelines for walnuts has introduced some discussion of changes of the fundamental character of the nut that may be brought about by the use of genetic engineering. The anticipated changes in nut quality and stability could have important effects on the potential for use of walnuts in a variety of food products. However, it is not certain that the work will be successful or that engineered products will be acceptable, particularly since an important part of the crop is destined for export. Whether or not new walnuts are introduced, it is certain that the most important aspects of postharvest quality will be based on rapid harvest with minimal exposure to field heat, forced-air drying at relatively low temperature, and cold storage at an RH designed to maintain low nut moisture in a reduced O_2 atmosphere.

References

Beuchat, L.R. 1978. Relationship of water activity to moisture content in tree nuts. J. Food Sci. 43:754-755,758.

Dandekar, A.M., G.H. McGranahan, P.V. Vail, et al. 1998. High levels of expression of full-length *cryIA(c)* gene from *Bacillus thuringiensis* in transegnic somatic embryos. Plant Sci. 131:181-193.

Hendricks, L.C., W.C. Coates. R.B. Elkins, et al. 1998. Selection of varieties. *In* D.E. Ramos, ed., Walnut Production Manual, pp. 84-89. Pub. no. 3373, University of California, Division of Agriculture and Natural Resources, Davis, CA.

Johnson, J.A., P.V. Vail, E.L. Soderstrom, et al. 1998. Integration of nonchemical, postharvest treatments for control of navel orangeworm (Lepidoptera: Pyralidae) and indianmeal moth (Lepidoptera: Pyralidae) in walnuts. J. Econ. Ent. 91:1437-1444.

Lopez, A., M.T. Pique, A. Romero, and N. Aleta. 1998. Modelling of walnut sorption isotherms. Ital. J. Food Sci. 10:67-74.

Maté, J.I., M.E. Saltveit, and J.M. Krochta. 1996. Peanut and walnut rancidity: effects of oxygen concentration and RH. J. Food Sci. 61:465-468,472.

Olson, W.H., J.M. Labavitch, G.C. Martin, and R.H. Beede. 1998. Maturation, harvesting and nut quality. *In* D.E. Ramos, ed., Walnut Production Manual, pp. 273-276. Pub. no. 3373, University of California, Division of Agriculture and Natural Resources, Davis. CA.

Seibert, J.B. 1998. Marketing California walnuts. *In* D.E. Ramos, ed., Walnut Production Manual, pp. 23-30. Pub. no. 3373, University of California, Division of Agriculture and Natural Resources, Davis, CA.

Vail, P.V., J.S. Tebbets, D.F. Hoffmann, and A.M. Dandekar. 1991. Responses of production and storage walnut pests to *Bacillus thuringiensis* insecticidal crystal protein fragments. Biol. Control 1:329-333.

van Steenwyk, R.A., and W.W. Barnett. 1998. Insect and mite pests. *In* D.E. Ramos, ed., Walnut Production Manual, pp. 247-253. Pub. no. 3373, University of California, Division of Agriculture and Natural Resources.

Zettler, J.L., W.R. Halliday, and F.H. Arthur. 1990. Phosphine resistance in insects infesting stored peanuts in the southeastern United States. J. Econ. Ent. 82:1508-1511.