Out-of-Season Greenhouse Strawberry Production in Soilless Substrate[1]

FUMIOMI TAKEDA

Appalachian Fruit Research Station, United States Department of Agriculture, Agricultural Research Service, 45 Wiltshire Road, Kearneysville, WV 25430

Introduction

Hydroponic plant production has been practiced for several millennia and it permits crops to be grown where no suitable soil exists or where the soil is contaminated in some manner. In one of the seven wonders of the ancient world, the Hanging Gardens of Babylon, plants were grown in a steady stream of water (Jones, 1997; Stanley, 1998). Maximum yields are possible and this makes the system economically feasible in high-density and expensive land areas. In addition, more complete control of the environmental factors that affect plant growth and yield (root environment, fertigation, light, temperature, humidity, etc.) is possible. Future growth of hydroponic systems, and in general, controlled environment agriculture, will depend on the development of production systems that are competitive in costs and returns with open field agriculture (Jensen, 1999). Several disadvantages of controlled environment agriculture are high capital cost, a need for trained personnel with knowledge of plant nutrition, introduced pests may spread quickly, and a requirement for research and development to grow current cultivars under controlled environment.

Recently, plant production by hydroponics and other forms of soilless culture has increased tremendously. The world area of greenhouses is estimated to be 40,700 ha (101,750 acres) (Witter and Castilla, 1995) and greenhouse vegetable production alone accounts for over 24,000 ha (60,000 acres) worldwide (Jensen, 1999). The greenhouse industry, as a whole, still represents a minuscule part of total worldwide agricultural production, but the gross return to the local economy can be significant.

Protected Cultivation of Strawberries

In Japan and Korea, much of the strawberry acreage is under plastic houses. In Japan, about 8,000 ha (20,000 acres), representing 90% of the total strawberry production, is under protected cultivation. South Korea has about 7,500 ha (18,750 acres) in strawberries, much of it planted in soil under heated plastic houses (Kang and Oh, 1996). The Japanese have research projects to evaluate various soilless, bench-top strawberry growing systems and robotic fruit-harvesting systems to mitigate the lack of labor to perform intensive farming (Mochizuki, 1995; Takenaga, 1998; Yoshida, 1998). In northeastern China, "forcing" culture, plasticulture, and hydroponic methods of strawberry production are being adapted (Pritts *et al.*, 1998).

Greenhouse and tunnel strawberry production in western Europe, especially in the Netherlands and Belgium, is extensive (Lieten, 1993; Lieten and Baets, 1991). In these two countries, production of strawberries in peat substrate bags and pots now represents about 15% of the 3,000 ha (7,500 acres) strawberry industry. In some parts of Australia, limited amounts of strawberries are grown commercially in hydroponic systems and growers use PVC rain gutters in a linear or in an A-frame configuration (Donnan, 1997; Zorin *et al.*, 1997). Hydroponic strawberry production systems for space applications are being studied intensively by NASA scientists at Kennedy Space Center in Florida as well (Gary Stutte, personal communication).

[1] Received for publication January 12, 2000.

Rationale for Soilless Systems

In the United States, the impending loss of methyl bromide (MB) as a soil fumigant has underscored the need for economically acceptable alternative methods of growing strawberry plants for fruit production and nursery vegetative propagation material. To date, the strawberry industry has depended heavily on MB soil fumigation to control soilborne pathogens, insects, nematodes, and weeds. The loss of MB will lead to reduced yields under soil-based cropping systems in California and Florida (Larson and Shaw, 1995; Shaw and Larson, 1999). Many alternatives to MB including other fumigants, heat sterilization, and solar sterilization have been proposed (Himelrick and Dozier, 1991).

Another alternative strawberry production system is growing plants in soilless media that precludes the use of MB for preplant soil fumigation. Currently, I am aware of strawberry growers and hobbyists in over 30 states who have small (none more than 0.1 ha [0.25 acre]) hydroponic strawberry production enterprises (unpublished data). In the Middle Atlantic coast region, the use of soilless substrate coupled with greenhouse culture systems extends the harvest season and produces fruit during winter "off season" months when the value is highest (Takeda, 1999). Several years ago in Maryland, two greenhouse operators successfully marketed pot-grown 'Sweet Charlie' strawberry plants during the winter holiday season and Mother's Day (Stanley, 1998).

In the eastern United States, strawberries have been produced traditionally in perennial, matted-row culture system, typically established in the spring with dormant cold-stored plants (Galletta and Bringhurst, 1990). Now growers are interested in producing strawberries by using the annual plasticulture system (Poling, 1993). The annual plasticulture system relies on plant establishment in late summer and uses a cultivar developed in California. A few eastern cultivars, planted as dormant bare-roots, have performed well in plasticulture systems in colder areas (Nourse, 1999; O'Dell *et al.*, 1999). However, the performance of cold-stored, dormant transplants in plasticulture has not been entirely satisfactory. Also, a mechanical planter for planting dormant plants through the plastic needs to be developed (Nourse, 1999). Alternative transplant sources are fresh-dug, bare-root plants from nurseries in Canada or plug plants that are generated from harvested runner tips. The Canadian nursery industry supplies bare root plants to growers in the southeastern United States. However, the plants are available only from mid-September to mid-October, which is too late for planting in the mid-Atlantic coast region. Also, the Canadian nurseries are meeting the demand of Florida growers by propagating bare root plants of cultivars developed from breeding programs in California and Florida.

Increasingly, growers in the Middle Atlantic region, and other northern states, are interested in growing eastern cultivars that have increased cold hardiness and tolerance or resistance to major leaf-, root-, and fruit-rotting diseases in plasticulture (O'Dell *et al.*, 1999). However, one impediment to using the eastern cultivars in plasticulture is the lack of plug plants during the preferred mid-summer to late-summer planting period. Takeda *et al.* (2000) have demonstrated that a sufficient number of runner tips can be produced from mother plants growing in soilless culture system. By using this system, nurseries in the mid-Atlantic coast region can generate transplantable plug plants of eastern cultivars for grower fields within six months after plantlets are taken out of the sterile, *in vitro* environment and grown in the greenhouse to produce runners. When production of runner tips and plug plants in a protected environment is combined with a shorter propagation period, the potential of exposing plants to virus-transmitting insects is reduced significantly. Another advantage of this system is that phytosanitary concerns for soil fungal pathogens, nematodes, and insects encountered in field nurseries are minimized. The aim of this article was to review research conducted on soilless strawberry production systems in North America.

Strawberry Production in Soilless Systems

In North America, strawberry cultivation in greenhouses or under high tunnels still is limited. However, interest in soilless strawberry culture systems is increasing rapidly. In the major strawberry production areas of the central coast of California, the growers have the luxury of a maritime climate that provides an ideal environment for strawberry fruiting over many months. In contrast, growers in much of the remaining areas of the United States, excluding the Gulf Coast region, must deal with a continental climate of hot summer months and cold winter months, and they are unable to produce strawberries in the field on a year-round basis. Controlled environments offer growers an opportunity to produce strawberries year-round, and more specifically, during the off-season (November to January) when strawberries are not readily available and carry a high price (USDA, 1995).

Essentially, there are two hydroponic systems for growing strawberries, the "closed" and "open" systems. In a closed system, plants are grown in pipes, channels, or gutters, and the nutrient solution is recirculated. Closed systems can be operated either continuously (Durner, 1999; Takeda, 1999), with roots bathed in a thin film of nutrient solution, or intermittently, as "flood and drain" or "ebb-and-flow," when plants are grown in pots and roots are supported by a substrate with high water-holding capacity, as in bench-top production system (Pritts and Kelly, 1995). In an open or pass-through system, nutrient solution is applied, usually through a dripper, and it is not recirculated or recovered. The excess percolate from the growing substrate is discharged and run to waste.

The open system is preferred for growing cultivars susceptible to root-rot causing fungi like *Phytophthora cactorum* (Leb. & Cohn), *P. fragariae* (Hickman), and *Verticillium albo-atrum* (Reinke & Berth). However, with the ever-increasing environmental constraints, and in order to comply with the "zero discharge" of point-source pollutant mandated by the U.S. Clean Water Act of 1972, plans to prevent creation of waste must be developed. Dutch growers must change to closed, soilless systems to avoid discharge of fertilizers and to comply with instituted national environmental policy (Anon., 1989).

There are two examples of commercially available soilless strawberry growing systems. One is the Verti-Gro® (Tim Carpenter, Lady Lake, FL), in which square polystyrene pots with a plant at each corner of the pot are stacked as many as eight vertically, and the VerZontal™ growing system (Allen Williford, Andrews, NC), in which potted strawberry plants are grown in several tiers of PVC pipes. The advantages of these systems are the utilization of vertical space, increased plant density, and the option to operate in either the closed or open mode.

Greenhouse strawberry production research in the eastern United States has focused on growing strawberries for 'out-of-season' fruiting when locally produced berries are not available and shipments of fresh strawberries from California and Florida are low (Durner, 1999; Hamann and Poling, 1997; Pritts and Kelly, 1995; Takeda, 1999; Takeda *et al.,* 1997). Shipment of fresh strawberries from California to the market occurs from early spring to fall (Anon., 1996; USDA, 1995). Shipment of fresh strawberries from Florida peaks in February and March. During November and December, one chain of gourmet grocery stores on the East Coast displayed long-stemmed strawberries that were air-freighted from New Zealand and retailed for as much as \$30.78/kg (\$13.99 per lb) (T. Krantz, Sutton Place Gourmet, Inc., Rockville, MD, personal communication). During the 1998-1999 winter production cycle, we supplied three up-scale restaurants in the Eastern Panhandle of West Virginia with about 182 kg (400 lbs) of long-stem, greenhouse-grown strawberries ('Camarosa', 'Chandler', and 'Sweet Charlie') priced between \$6.60 and \$7.70/kg (\$3 and \$3.50 per lb) (Takeda, unpublished data). A Cornell University study reported on-campus sales of greenhouse strawberries at \$7.95/L (\$3.50 per pint) (Pritts and Kelly, 1995). These studies demonstrated that niche markets can be developed for highly flavored and attractive, "off-season" strawberries.

Cultural Systems

Dutch and Belgian growers have produced strawberries in soilless substrates using the production technologies developed at government-supported, glasshouse research and demonstration centers (e.g., Wilhelminadorp and Breda, the Netherlands, and Meerle and Tongeren, Belgium). These production research programs incorporate a broad range of cultural methods. These methods include heavy and light forcing techniques to extend the harvest season, peat in the bucket and peat/perlite mixture in bag growing systems, and the use of glasshouse-adapted 'Elsanta' strawberry. The other factors that have advanced their industry are the auction-house marketing system, and an established local infrastructure for plant materials, growing media, and soilless culture supplies.

In contrast, hydroponic strawberry production in North America can still be considered to be at a research and development phase. Research has described numerous types of systems that differ in principle and in practice. Kempler *et al.* (1991) in British Columbia, Canada, evaluated the nutrient film technique (NFT) method for June-bearing (cvs. Hood, Rainier, and Totem), and day-neutral (cvs. Tellikum, Hecker, Burlington, Selva, Tribute, and Tristar) strawberries for summer production. In spring, bare-root, cold-stored plants were transplanted 15 cm (six-in) apart in sloped NFT troughs or in Rockwool® blocks positioned within the troughs. Nutrient solution was introduced at the high end of the troughs and allowed to flow by gravity the length of the troughs as a thin film of liquid and bathed the roots. The troughs were on an A-frame structure and spaced 30 cm (12 in) apart vertically. Each A-frame growing structure held 10 4.6-m long (15 ft) troughs that provided a plant density of 28 plants/m^2 (23 plants/yd^2). Because these plants were cold-stored, single-crowned, they developed only one or two flower clusters and subsequently developed runners when temperatures reached 35 °C (95 °F) and long photoperiod conditions. Kempler *et al.* (1991) found an interactive effect of cultivar and growing system on the yield components, but fruit production was low ($\leq$ 3 kg/m^2 [5 lb/yd^2]) and the berry size was small ($\geq$ 123 fruit/kg [56 fruit/lb]). Nonetheless, this study demonstrated the potential of growing strawberry cultivars developed in the Pacific Northwest in hydroponic systems.

Takeda and co-workers (Takeda, 1999; Takeda *et al.,* 1993, 1997) have evaluated the productivity of bare-root dormant, fresh-dug bare-root, and plug plants established in NFT system. On 1 Oct., plug transplants were set 30 cm (12 in) apart in 3.6 m (12 ft) long troughs suspended 1.2 m (4 ft) above the greenhouse floor and spaced 30 cm (12 in) apart linearly. The plants were fertigated in a closed system with nutrient solution made in a batch mode with Chem-Gro Strawberry Formula (5-15-25) (Hydro-Gardens, Inc., Colorado Springs, CO), or Peters Pro-Sol (8-16-38) (Scotts-Sierra Horticultural Products Co., Marietta, GA), supplemented with calcium nitrate and magnesium sulfate and delivered at a flow rate of 7.6 L (2.0 gal)/hr. Plug plants of 'Camarosa' and 'Chandler' strawberries have produced 910 g and 680 g/plant (2 and 1½ lb/plant) of marketable fruit, respectively, in a December to May time-frame. Problems may arise when small lettuce-type (10 cm, 4 in) channel gutters are used to grow a long-season crop such as strawberry. As the root mat size increases, the flow rate through the troughs diminishes. Plants at the upper end of the trough may diminish the oxygen and/or elemental content of the nutrient solution enough to affect plant growth and development at the lower end (Figure 1). Also, as the root mat thickens and become more dense, the flowing nutrient solution tends to move over the top and down the outer edge of the mat, reducing its contact with the entire root mass, and it will eventually lead to flooding and root death. For long-term strawberry crops in NFT, a channel width of at least 15 cm (6 in) is advised (D. Lankford, personal communication).

Strawberries also have been grown in vertical hydroponic systems to better utilize the vertical space in the greenhouse (Figure 2). Vertical polyethylene bags or PVC pipe columns filled with strawberry plants set in holes in the side (Resh, 1995; Stanley, 1995), and a column of interlocking square pots (Figure 3) (Durner, 1999; Takeda, 1999, Takeda *et al.,* 1997) are examples of vertical growing systems. Nutrient solution is applied at the top of the column, usually through a drip emitter, and the solution passes through the substrate and out the bottom. This system can be operated as an once-through or recirculating system. The composition of the nutrient solution can change as it passes through the column (Jones, 1997).

As with the A-frame system, plants grown in these high plant density systems neither grow uniformly nor produce similar yields (Durner, 1999; Takeda *et al.,* 1997). Irradiance (light intensity) markedly affects strawberry growth and development. High irradiance (PAR > 650 $\mu M/m^2/sec$) is necessary to increase leaf area and inflorescence number (Ceulemans *et al.,* 1986; Dennis *et al.,* 1970). During the winter months in the mid-Atlantic coast region (~39 °N latitude), sunlight is the determinant for greenhouse strawberry production. The total irradiance, duration of radiation, and the angle of the sun are much lower in winter compared with the remainder of the year. In areas where winters are characterized by heavy cloud cover or overcast days, supplemental lighting is essential for winter strawberry production. A vertical growing system causes environmental conditions in the lower sections of the towers to be sub-optimal (Table 1). The irradiance reaching the plants at the bottom of the towers was only 10% (< 100 $\mu M/m^2/sec$) of levels measured at the top. As a result, delayed growth occurred among the plants in the middle and bottom section of the column. Many plants did not develop an optimal number of branch crowns and subsequently produced less fruit compared with plants in the top section (Table 2). Similarly, Durner (1999) reported that fruit yield of 'Sweet Charlie' strawberry increased linearly with height in the column, probably because of increasing irradiance.

Bench-top production of strawberries in containers has been evaluated. The Dutch and Belgians have considerable acreage under bucket and peat bag culture. In such systems, when the containers are elevated above the ground, the space can be used more effectively resulting in greater plant densities and increased harvest efficiency than when plants are grown in field soil. European producers have used drip emitters to deliver water and nutrients to plants in containers. For several growing seasons, Pritts and Kelly (1995) used "ebb-and-flow" benches to grow potted strawberry plants. The substrate contained equal parts of vermiculite, sphagnum peat moss, and perlite to allow for drainage. Although this was a closed, recirculating system, root diseases did not develop.

Takeda and colleagues have experimented with pot culture. Plug plants of 'Camarosa' and 'Chandler' strawberry were transplanted on 5 Nov. into round, 7.6 L (two-gallon) pots (5 plants/pot) and square, 2.8 L (3-quart) "Verti-Gro" pots (4 plants/pot), filled with a peat-based substrate (Sunshine Mix #4, SUNGRO Horticulture Inc., Bellevue, WA) and placed on benches at the density of 4.3 pots/m^2 (3.6 pots/yd^2). Flowers were deblossomed until 22 Dec. Ripe fruit were harvested from 10 Feb. to 29 May. The two cultivars produced about 510 gm/plant (1.1 lbs) of fruit, of which only 14% were cull fruit (< 10 g or diseased berries), in both pot types. Over a 7-month growing cycle the larger pots yielded 14.3 kg/m^2 (23.4 lb/yd^2). Fruit size of marketable berries averaged > 30 g/fruit (< 15 fruit/lb) in February and about 18 g/fruit (25 fruit/lb) from March to May. Although pots used in this study provided a rooting vessel of different volume and dimensions, yields were similar.

Little good information is available on the substrate volume required by strawberry plants and the relationships that exist between rooting habit, rooting media, and container environment and volume (Jones, 1997). More studies are needed with the growing systems to determine the substrate volume required to obtain maximum plant performance. However, the containers and strawberry plants must be spaced to allow sufficient light penetration into the plant canopy and permit efficient harvesting.

Enhancing Winter Fruit Production

Several approaches have been taken to maximize greenhouse space utilization and optimize fruit production in the development of "off-season" greenhouse strawberry production in North America. Strategies to enhance fruiting in early winter include use of plants from plug propagation (Hamann and Poling, 1997; Takeda *et al.,* 1997), evaluation of daylength-sensitive and -insensitive cultivars (Hamann and Poling, 1997; Pritts and Kelley, 1995; Takeda, 1999); and photoperiod and low-temperature preconditioning treatments (Durner, 1999; Hamann and Poling, 1997; Takeda, 1999).

'Selva' plug plants derived from second-order and third-order daughter plant cuttings produced similar yields over a three-month fruiting period from August to October, but in the first month, secondary plants had substantially greater fruit production than plugs derived from third-order runner plantlets (Hamann and Poling, 1997). The difference was due to a delay in reproductive maturity of plants derived from third-order daughter plantlets. Hamann and Poling (1997) also reported that plug plants transplanted earlier into a fruit production environment grew more and developed a greater number of branch crowns. June-propagated plug plants of 'Selva' produced more than 256 g (0.5 lb) of marketable fruit from August to October under controlled-environment conditions. To achieve greater yields early in the season, preconditioning treatments must minimize situations that lead to plant stress such as root-bound conditions that can develop with extended periods in small container cells.

Plug plants have outperformed fresh-dug, bare-root plants in greenhouse trials. Takeda *et al.* (1997) determined the productivity of 'Camarosa', 'Chandler', and 'Sweet Charlie' in an NFT production system. Runner tips were set in cell packs in late August to produce plug plants. On 1 Oct., fresh-dug plants from a nursery in Canada and locally produced plug plants were transplanted into NFT troughs. Overhead microsprinklers were operated intermittently for the first 10 days. In all three cultivars, the plug plants flowered earlier and produced more fruit during the first month of harvest (December) than the fresh-dug plants. Greater yields from plug plants were a result of a greater number of fruits (13.5%) and not larger fruits (1.9%). Of the three cultivars, 'Sweet Charlie' was the earliest to produce fruit, followed by 'Camarosa' and 'Chandler'. During the major harvest period starting in March, 'Camarosa' outperformed the other two cultivars by 30% (316 g [11 oz]/plant vs. 245 g [9 oz]/plant).

Photoperiod and low-temperature conditioning of strawberry plants induces precocity. Facultative short-day cultivars such as 'Sweet Charlie' and 'Chandler' require daylengths less than 14 hours and/or temperatures less than 15 °C (59 °F) for flower induction (Darrow, 1936; Guttridge, 1985). Durner *et al.* (1987) reported on the interactive effect of chilling and photoperiod on flowering and fruiting to determine the optimum digging date for cultivars utilized in Florida winter production. Chilling enhanced early-season yields if it was accumulated before the optimum photoperiod date. If plants were dug after the optimum date, early yield decreased. Fourteen days of short-day conditioning treatment (16 h dark) in early September advanced the first harvest date of 'Camarosa' strawberry by three weeks (Table 3). By April, however, plants grown without the dark treatment were 32% larger, both in terms of biomass and branch crown numbers, and they produced more fruit. Durner (1999) advanced fruit production in 'Sweet Charlie' by treating plants with two weeks of 9-h short days and one week of chilling (12 °C; 54 °F) during the nyctoperiod in mid-September. Yield in December was less than 20 g (< 0.75 oz) per plant for both conditioned and control plants, but conditioned plants produced more fruit compared with control plants in January and February. In this study, most of the harvest was not realized in time for the targeted winter holiday market.

The large, multiple-crown plants, referred by the Dutch growers as cold-stored, "waiting-bed" plants, may be used for winter fruit production. These plants typically have, at the time of transplanting, a crown diameter greater than 19 mm (¾-in) and several inflorescences and flowers initiated. From such plants, as many as 50 fruits can be harvested within a 3-month period from the transplant date. Although the importance of reserve storage capacity, measured as crown number × crown diameter, on yield potential has been emphasized (Galletta and Bringhurst, 1990), the ideal crown number or size to achieve high marketable yield must be determined for each cultivar (Popenoe and Swartz, 1985). In a study on "waiting-bed" plant performance for winter production in Spain, Lopez-Galarza *et al.* (1997) found that crown number did not affect the productivity of 'Oso Grande' strawberry, but it did in the case of 'Chandler' and 'Pajaro' strawberries. With an increase in crown number fruit size declined in 'Oso Grande' strawberry, but not in 'Chandler' or 'Pajaro' strawberries.

Pest and Disease Management

Pest problems can be minimized in the controlled, stable environment of a greenhouse. One advantage of greenhouse production is the absence of weeds. However, precautions must be taken to ensure plants are free of pests before establishment in the greenhouse, and measures must be taken to exclude pests from the greenhouse by screen barriers and good phytosanitary practices. Plants may be dipped into an insecticide-fungicide solution before planting, and isolate the foliar portion of the plant from the substrate by using plastic barrier. Even under best of situations, pest problems can develop. In research at Cornell University (Pritts and Kelly, 1995) and at Appalachian Fruit Research Station (Takeda, 1999; Takeda *et al.*, 1997) problems developed with two-spotted spider mites (*Tetranychus urticae* Koch), flower thrips (*Frankliniella* spp. Perg), and powdery mildew (*Sphaerotheca macularis* Wallr.:Fr). Insect pests and fungal diseases can proliferate under favorable greenhouse conditions.

Currently, no pesticide is registered for greenhouse strawberry production, and biological control agents (predators) have been the method of choice for control of two-spotted spider mites, thrips, aphids, and fungus gnats. The recommendation is to release predators or natural enemies such as *Phytoseiulus persimilis* Athias-Henriot for two-spotted spider mite control at regular intervals and not wait until an outbreak occurs. Therefore, scouting for pests is a critical component of greenhouse strawberry production because a complete eradication or immediate reduction of the target pest population is not possible when biological control is practiced. For example, predatory mites

(*Amblyseius cucumeris* Oudemans) were released at weekly intervals into a greenhouse that was infested heavily with flower thrips as monitored with blue and yellow sticky cards. Over one month elapsed before thrips counts declined to an acceptable level (Figure 4), and flower thrips feeding damage was tolerable.

Powdery mildew is a particularly severe problem on strawberry plants grown in greenhouses and in tunnel production (Maas, 1998). Severe infections can occur especially under conditions of low irradiance, high humidity, and low temperature. Strawberry cultivars differ widely in their resistance to powdery mildew (Nelson *et al.*, 1996). We have observed more powdery mildew on leaves and fruit of greenhouse-grown 'Sweet Charlie' and 'Allstar' compared with 'Camarosa' and 'Chandler' strawberry. Experimental biofungicides have been used to control powdery mildew. Weekly foliar applications of a strain of yeast *Ampelomyces quisqualis* Ces. (isolate M-10, Ecogen Inc., Langhorne, PA) and an in-house yeast isolate obtained from Dr. Samir Droby of The Volcani Center, Bet Dagan, Israel, to the strawberry plant have provided powdery mildew control as good as sulfur treatments (Takeda, unpublished data).

Beneficial bacteria have been studied widely for use in agriculture. These studies have involved nitrogen fixation, phosphate-solubilization, and production of antibiotics and plant growth regulators. During the 1970s, specific rhizosphere bacteria applied to seeds were reported to colonize roots and promote plant growth. Mechanistic studies indicated that plant-growth-promoting rhizobacteria (PGPR) promote plant growth directly by production of plant growth regulators or stimulating nutrient uptake or indirectly by production of siderophores or antibiotics to protect plants from soilborne pathogens or deleterious rhizobacteria (Hallmann *et al.,* 1997). Investigations on mechanisms of biological control by PGPR have reported that some PGPR strains protect plants from pathogens by inducing systemic resistance or stimulating the natural plant disease resistance process in some plant-pathogen systems (Wei *et al.,* 1991). Recently Benhamou *et al.* (1998) demonstrated that root colonization by *Bacillus subtilis* Meyer & Guttheil (strain SE34), in combination with chitosan, triggered a series of plant defense reactions in tomato plants.

We determined the effects of PGPR on fruit production and powdery mildew infection in greenhouse-grown 'Camarosa' and 'Sweet Charlie' strawberries colonized with a strain of *B. subtilis*. In both cultivars, root treatment with PGPR during the plug production phase increased fruit yield by more than 20% over control plants (Table 4). However, PGPR treatment had no effect in reducing the incidence of powdery mildew infection of the fruit of 'Camarosa' or 'Sweet Charlie' strawberry.

Another strategy to mitigate pest and disease problems in short-day cultivars is to bring plants into the greenhouse at one-month intervals and remove them after one cycle of fruiting and not retain them in the greenhouse for the entire 6- to 8-month production period. By using staggered planting dates for 'Jewel' strawberry, Pritts and Kelly (1995) achieved yields of 12 kg/m^2 (22 lbs/yd^2) over an 8-month period.

Conclusion

A successful greenhouse management system maximizes profitability and must have the essential features of low energy input, minimal maintenance, high yields of high-quality fruit in "off-season," high plant density, and minimal or no pesticide applications. The hydroponic technique for strawberry production has a high initial construction cost and requires knowledge regarding plant growth and nutrition. Also, currently available strawberry cultivars need further research and development for adaptation to controlled growing conditions, especially for attaining greater yields in November and December.

The future of hydroponic/soilless strawberry production in North America will depend on the development of production systems and introduction of cultivars that will make this unique system competitive in terms of monetary return in comparison with open-field strawberry production. Protected cultivation systems will provide opportunities to extend strawberry production to areas traditionally considered unsuitable for open-field strawberry culture. Although various methods of solution delivery, plant support media, and the composition and management of the nutrient solution are workable, more research is needed to develop environmentally and economically sustainable strawberry production systems.

Literature Cited

Anonymous. 1989. National Environmental Policy Plan., SDU Uigeverij, The Hague, The Netherlands. 258 pp.

Anonymous. 1996. 1996 Annual Report of the Processing Strawberry Advisory Board of California, Watsonville, CA. 19 pp.

Benhamou, N., R. R. Belanger, and T. Paulitz. 1998. Induction of resistance against *Fusarium* wilt of tomato by combination of chitosan with an endophytic bacterial strain: ultrastructure and cytochemistry of the host response. Planta 204:153-1168.

Ceulemans, R., W. Baets, M. Vandergruggen, and I. Impens. 1986. Effects of supplemental irradiation with HID lamps and NFT gutter size on gas exchange, plant morphology, and yield of strawberry plants. Scientia Horticulturae 28:71-83.

Darrow, G. M. 1936. Interrelation of temperature and photoperiodism in the production of fruit buds and runners in the strawberry. Proc. Amer. Soc. Hort. Sci. 34:360-363.

Dennis, F. G., J. Kipecki, and C. Kiang. 1970. Effects of photoperiod and other factors upon flowering and runner development of three strawberry cultivars. J. Amer. Soc. Hort. Sci. 95:750-754.

Donnan, R. 1997. Hydroponic strawberries—the Australian experience. Practical Hydroponics & Greenhouse 34:54-63 (May/June 1997).

Durner, E. F. 1999. Winter greenhouse strawberry production using conditioned plug plants. HortScience 34: 615-616.

Durner, E. F., E. B. Poling, and E. A. Albregts. 1987. Early season yield responses of selected strawberry cultivars to photoperiod and chilling in a Florida winter production system. J. Amer. Soc. Hort. Sci. 112: 53-56.

Galletta, G. J. and R. S. Bringhurst. 1990. Strawberry management. pp. 83-156. In G. J. Galletta and D. C. Himelrick (eds.). Small Fruit Crop Management. Prentice-Hall Press, Englewood, NJ.

Guttridge, C. G. 1985. *Fragaria×ananassa*. p. 16-33. In A. H. Halevy (ed.). CRC Handbook of Flowering. Vol. III. CRC Press. Boca Raton, FL.

Hallmann, J., A. Quadt-Hallmann, W. F. Mahaffee, and J. W. Kloepper. 1997. Bacterial endophytes in agricultural crops. Can. J. Microbiol. 43:895-914.

Hamann, K. K. and E. B. Poling. 1997. The influence of runner order, night temperature and chilling cycles on the earliness of ' Selva' plug plant fruit production. Acta Horticulturae 439:597-603.

Himelrick, D. C. and W. A. Dozier, Jr. 1991. Soil fumigation and soil solarization in strawberry production. Adv. Strawberry Production 10:12-29.

Jensen, M. H. 1999. Hydroponics worldwide. Acta. Horticulturae 481:719-729.

Jones, J. B., Jr. 1997. Hydroponics: A Practical Guide for the Soilless Grower. St. Lucie Press. Boca Raton, FL.

Kang, S. Y. and S. H. Oh. 1996. The present and future of strawberry production in Korea. Proc. 1996 Japan Strawberry Seminar. 5:30-37. (In Japanese with English summary).

Kempler, C., E. van Zinderen Bakker, K. Shaw, and A. Newnham. 1991. An evaluation of the nutrient film technique for growing strawberries in greenhouse environment. The 21st Century Gardener 5(6):28-38.

Larson, K. D. and D. V. Shaw. 1995. Relative performance of strawberry genotypes on fumigated and nonfumigated soils. J. Amer. Soc. Hort. Sci. 120: 274-277.

Lieten, F. 1993. Methods and strategies of strawberry forcing in central Europe: Historical perspectives and recent developments. Acta Horticulturae 348:158-170.

Lieten, F. and W. Baets. 1991. Greenhouse strawberry culture in peat bags. Adv. Strawberry Production 10:56-57.

Lopez-Galarza, S., J. V. Maroto, A. San Bautista, and J. Alagarda. 1997. Performance of waiting-bed strawberry plants with different number of crowns in winter plantings. Acta Horticulturae 439(1):439-448.

Maas, J. L. (ed.). 1998. Compendium of Strawberry Diseases, Second Ed. APS Press, St. Paul, MN.

Mochizuki, T. 1995. Past and present strawberry breeding programs in Japan. Adv. Strawberry Res. 14:9-17.

Nelson, M. D., W. D. Gubler, and D. V. Shaw. 1996. Relative resistance of 47 strawberry cultivars to powdery mildew in California greenhouse and field environments. Plant Dis. 80:326-328.

Nourse, T. 1999. Adapting the plasticulture system to northern conditions using dormant plants. Proc. 1999 Southeast Strawberry Expo. pp. 14-16.

O'Dell, C., J. Williams, and R. Harris. 1999. Progress report with eastern strawberry varieties for colder areas. Proc. 1999 Southeast Strawberry Expo. pp. 17-19.

Poling, E. B. 1993. Strawberry plasticulture in North Carolina: II. Preplant, planting, and postplanting considerations for growing 'Chandler' strawberry on black mulch. HortTechnology 3:383-393.

Popenoe, J. and H. J. Swartz. 1985. Yield component comparison of strawberry plants grown in various cultural systems. Adv. Strawberry Production 4:10-14.

Pritts, M. P. and M. J. Kelley. 1995. Strawberry production in greenhouses. Misc. Publ., Dept. Fruit and Vegetable Science, Cornell Univ., Ithaca, NY.

Pritts, M. P., J. J. Zhang, C. Finn, and J. Gao. 1998. The strawberry industry in China. Adv. Strawberry Res. 17:1-6.

Resh, H. M. 1995. Hydroponic Food Production, Second Ed. Woodbridge Press Publishing Co., Santa Barbara, CA.

Shaw, D. V. and K. D. Larson. 1999. A meta-analysis of strawberry yield response to preplant soil fumigation with combinations of methyl bromide-chloropicrin and four alternative systems. HortScience 34:839-845.

Stanley, D. 1995. Trading wastewater for crops. Agricultural Research. 43(2):10-11 (February 1995).

Stanley, D. 1998. Hydroponic strawberries avoid soil pests. Agricultural Research. 46(11):10-11 (November 1998).

Takeda, F. 1999. Strawberry production in soilless culture systems. Acta Horticulturae 481:289-295.

Takeda, F., P. R. Adler, and D. M. Glenn. 1993. Growing greenhouse strawberries with aquaculture effluent. Acta Horticulturae 348:264-267.

Takeda, F., P. R. Adler, and D. M. Glenn. 1997. Strawberry production linked to aquaculture wastewater treatment. Acta Horticulturae 439:673-677.

Takeda, F., S. Hokanson, and J. Enns. 2000. Hydroponic strawberry runner-tip production. Proc. 2000 Mid-Atlantic Fruit and Vegetable Convention. pp. 103-105.

Takenaga, H. 1998. Strawberry harvesting robot for greenhouse. Proc. Japan Strawberry Seminar. 7:6-11 (in Japanese).

U.S. Department of Agriculture. 1995. Monthly wholesale prices for fresh strawberries in New York. 1980-1993. Agr. Mktg. Serv., USDA.

Wei, G., J. W. Kloepper, and S. Tuzun. 1991. Induction of systemic resistance of cucumber to *Colletotrichum orbiculare* by select strains of plant growth-promoting rhizobacteria. Phytopathology 81:1508-1512.

Witter, S. H. and N. Castilla. 1995. Protected cultivation of horticultural crops worldwide. HortTechnology 5:6-23.

Yoshida, Y. 1998. "Rakuchin," a new type of strawberry substrate culture of Kagawa. Proc. Japan Strawberry Seminar. 7:7-12 (in Japanese with English summary).

Zorin, M., N. Greer, M. Herrington, D. Hutton, and L. Ullio. 1997. Australia—Strawberry industry and research. Acta Horticulturae 439:377-383.

Figure 1. Strawberry production in a hydroponic system using NFT troughs and a nonrecirculating nutrient delivery system. Note the development of chlorosis (iron deficiency) in the young leaves of plants in the tail section (foreground) fertigated with a dilute aquaculture effluent delivered at a 6 L/hr (1.6 gal/hr) flow rate to a 3.5 m (12 ft) long trough with 10 plants. (Source: Agricultural Research/February 1995)

Table 1. Amount of incident photosynthetically active radiation (PAR) at several tower locations during the day. PAR measurements were collected and averaged from five columns from 8:00 a.m. to 6:00 p.m. The PAR sensor was positioned over a plant in the northeast (NE) and southwest (SW) quadrant of the top, middle, and buttom pots. Means within columns were separated by Duncan's new multiple range test (p = 0.05). (Source: F. Takeda)

		PAR (μM•m^{-2}•sec) Time of day (HR)				
Location	Quadrant	800	1000	1200	1400	1800
TOP	NE	275 a	721 a	840 a	701 a	434 a
	SW	279 a	685 a	964 a	604 a	438 a
MIDDLE	NE	88 b	108 bc	93 bc	60 c	115 bc
	SW	83 b	185 b	264 b	352 b	200 b
BOTTOM	NE	37 c	62 c	70 c	33 c	35 c
	SW	38 c	72 c	244 bc	256 b	164 b

ZMean of 5 readings.

Table 2. Earliness to fruiting and productivity of strawberry plants in a tower system. (Source: F. Takeda)

Cultivar	Location	First harvest date	Yield (g/plant)
Chandler	Top	12 Dec	282 ± 49Z
	Middle	29 Dec	164 ± 55
	Bottom	19 Jan	138 ± 45
Sweet Charlie	Top	7 Dec	181 ± 53
	Middle	14 Dec	188 ± 59
	Bottom	5 Jan	131 ± 26

ZMean ± std. error.

Table 3. Effect of 14 days of short photoperiod (9-hr days) preconditioning in September on first harvest date, crown number, and crown dry weight in April in 'Camarosa' and 'Chandler' strawberry plants. Plug plants were transferred to a production greenhouse in early December. (Source: F. Takeda)

			Crown	
Conditioning treatment	Cultivar	First harvest date	Number	Dry weight (g)
Natural	Camarosa	23 Feb	8.3	5.4
	Chandler	20 Feb	6.1	3.8
9-hour day	Camarosa	6 Feb	6.3	4.1
	Chandler	20 Feb	6.9	4.1

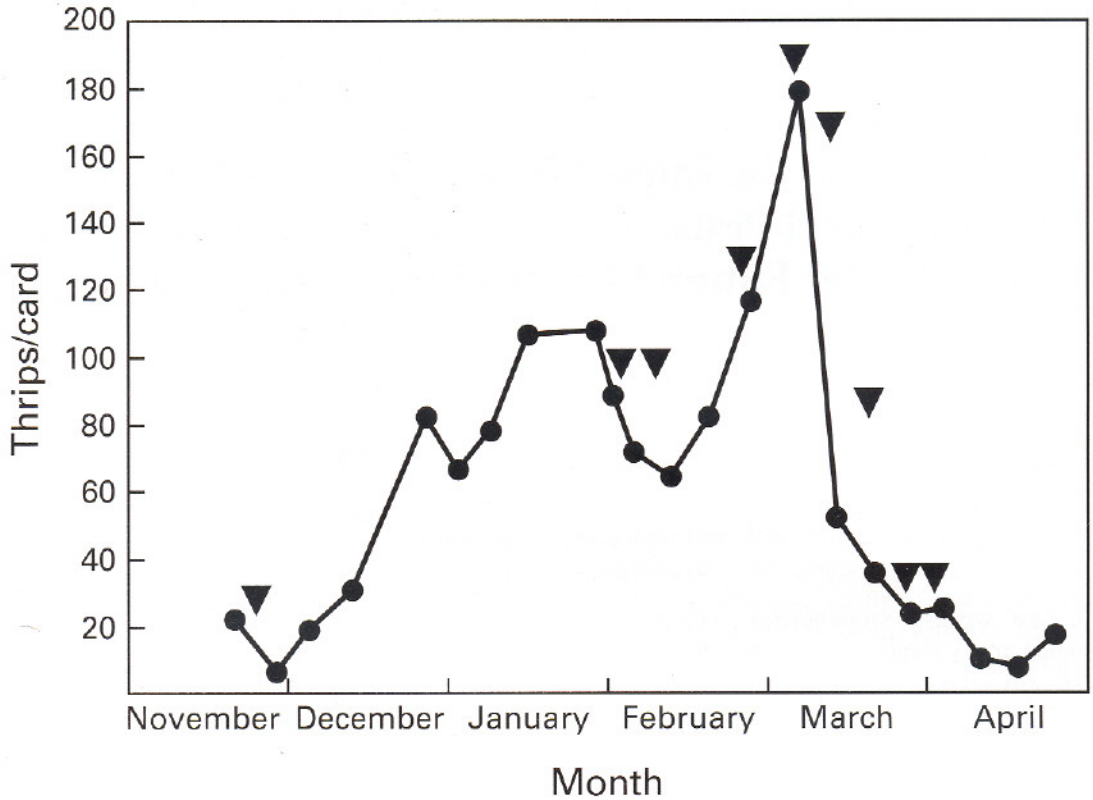

Figure 4. Weekly thrips counts on blue and yellow sticky cards. Strawberry plants ('Camarosa' and 'Chandler') were grown in NFT troughs in a 186 m^2 (2,000 ft^2) greenhouse from October to May. Points on the line represent average counts of thrips from eight cards. The symbol (▼) indicates the dates of predatory mite (*Amblyseius cucumeris*) release.

Table 4. Influence of cultivar and plant growth promoting rhizobacteria (PGPR) on the yield per section (8 plants) of strawberry plants grown in winter greenhouse pot culture during 1998-1999. The PGPR treatment was made by sticking runner tips into cell packs containing a peat substrate that was inoculated with PGPR strain LS213. All values are in grams (Source: F. Takeda)

	Total yield	Marketable yield	Diseased fruit	Misshapen fruit	Yield of berries < 10 g
Cultivar					
Camarosa	1354.8 b[z]	1065.4	155.4 b	48.4	85.6 b
Sweet Charlie	1936.7 a	1208.1	445.1 a	45.3	238.2 a
PGPR treatment					
Control	1446.3 b	939.9 b	296.6	46.2	163.6
LS213	1795.3 a	1284.3 a	303.0	47.4	160.6
Pr > F					
Cultivar	0.0011	0.2168	0.0001	0.7262	0.0035
PGPR	0.0197	0.0100	0.8806	0.9502	0.9415
Cultivar × PGPR	0.5370	0.9715	0.2931	0.2126	0.7258

[z]Letters within main effects represent mean separations by Duncan's new multiple range test (p = 0.05).