

Canola, corn, and vegetable oils as alternatives for wheat germ oil in fruit fly larval diets

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Abstract

Four wheat germ oil alternatives (corn oil, vegetable oil, canola oil with 10% vitamin E, and canola oil with 20% vitamin E), purchased from a local supermarket in Hawaii, were added to a fruit fly liquid larval diet as a replacement for wheat germ oil in the rearing of fruit fly larvae. The oils were tested on three species of fruit flies in Hawaii, *Ceratitis capitata* (TSL strain), *Bactrocera dorsalis*, and *Bactrocera cucurbitae*. They were evaluated for their efficacy in replacing WGO, based on: pupal recovery (%), larval duration (d), pupal weight (mg), adult emergence (%), adult fliers (%), mating (%), egg production per female per day, egg hatch (%), and peak egg period (d). Diets with WGO and without any oil were used as controls. The objective of the study was to select the most cost effective alternative oils with the best performance to replace the currently used WGO, which is pricey and hard to find. The results showed that there was no significant difference in performance among the tested oils in *B. cucurbitae* and *B. dorsalis* as regards the above mentioned parameters. Lower mating rate was observed in *B. cucurbitae* from those reared in vegetable oil and canola oil (10% vitamin E) diet. Lower egg production and egg hatch were obtained with *B. dorsalis* whose larvae were reared in vegetable and canola oil (both 10% and 20% vitamin E). Vegetable oil diet seemed to reduce pupal weight, shorten larval duration, and increase pupal recovery of *C. capitata*. The results suggest that WGO can be substituted with corn oil, vegetable oil, or canola oils for *B. cucurbitae*, while corn oil is a better alternative for *B. dorsalis*, and vegetable oil is best for *C. capitata*.

The sterile insect technique (SIT) was one of the first genetics approaches to pest control (Knipling 1955). It was originally developed to suppress new world screwworms and currently its use has been extended to many insects including fruit flies from the Tephritidae family. This technique requires that male fruit flies be exposed to gamma rays, which damage the chromosomes in the sperm to induce sexual sterility. The flies are then released into the target population. When the released sterile males

mate with wild females, the eggs of wild females are fertilized with sperms from irradiated males, cell division is disrupted, and the embryos die. If a sufficient number of sterile males are released into the wild over several generations, the reproductive success of the wild population can be progressively reduced and eliminated. In order to eradicate the flies, it is recommended to release them in a ratio of not less than 10 : 1 sterile to indigenous fruit flies (Knipling 1998; Robinson et al. 2002).

Because SIT relies upon efficient competition of released sterile males with wild males to mate with wild females, one of the most important components in the process of suppressing the fruit fly population is to have a well-established and cost effective rearing diet and methodology to mass rear healthy fruit flies. USDA-ARS recently developed a cost effective liquid diet for mass rearing fruit fly larvae to support the SIT Program (Chang et al. 2004, 2006, 2007). The quality of fruit flies from larvae reared with this liquid diet has been satisfactory. This liquid diet technology has been transferred to more than 36 interested groups with more than 26 species of fruit flies or other insects worldwide for evaluation, and has been demonstrated onsite in three medfly mass rearing facilities, including the world's largest El Pino medfly mass rearing facility in Guatemala and the facility in Valencia, Spain. Besides the promising results in the liquid diet implementation, one of the factors that hinder the implementation of liquid diet technology has been the lack of wheat germ oil WGO, due to either the high cost of the oil or its unavailability in a given locality.

Wheat germ oil is an indispensable ingredient in the liquid diet used to rear fruit fly larvae (Chang and Vargas 2007). This is because it provides nutrients and fatty acids that are essential for normal larval development and adult reproduction (Kahlon 1989). Wheat germ oil costs approximately \$96 per gallon (3.8 l). One gallon of WGO can be used to prepare 400 trays, according to the formulation of Chang et al. (2006, 2007). Therefore, WGO costs \$0.24 per tray to produce approximately 30 000 pupae. Other oils (such as corn oil, vegetable oil, and canola oil) cost approximately \$0.05 per tray. In addition, it is very difficult to obtain WGO in many countries. Our objective was to find more economical and readily available alternative oils that could effectively replace WGO as a fruit fly larval diet ingredient to rear quality fruit flies.

Materials and Methods

Insects

Newly collected eggs of three species of the fruit flies, *C. capitata* (Wiedemann) (TSL strain), *B. dorsalis* (Hendel), and *B. cucurbitae* (Coquillett) were provided by the Tropical Crop and Commodity Protection Research Unit of the USDA's Agricultural Research Service (ARS) and CDFA medfly rearing facility in Honolulu, Hawaii. The fruit fly colonies

were maintained at 25°C, 65% relative humidity (RH), and 12D : 12L for many generations.

Oils

The oils used were: WGO (KIC chemicals Inc. Aarmonc, NY; \$96/gal); Crisco corn oil (The J.M. Smucker Co., Orville, TN; \$20/gal); Crisco vegetable oil (J.M. Smucker; \$19/gal); Mazola canola oil/10% vitamin E (ACH Food Co., Inc., Memphis, TN; \$24.71/gal); and Crisco canola oil/20% vitamin E (J.M. Smucker; \$20/gal). All prices were determined using a Safeway supermarket in Honolulu, Hawaii. The nutritional data of all oils used in this study are listed in table 1.

Diet preparation

The diet formula and preparation method were slightly modified from Chang et al. (2004, 2007),

Table 1 Fatty acid composition of some common edible oils (% by weight of total fatty acids)

Nutrients (units)	Wheat germ oil	Corn oil	Vegetable oil	Canola oil
Proximates				
Energy (Kcal)	884.00	884.00	763.00	884.00
Energy (KJ)	3699.00	3699.00	3192.00	3699.00
Total lipid (fat) (g)	100.00	100.00	100.00	100.00
Choline, total (mg)	0.00	0.20	350.00	0.20
α -tocopherol (Vitamin E) (mg)	149.40	14.30	8.18	14.84
γ -tocopherol (mg)	0.00	0.00	0.00	35.37
δ -tocopherol (mg)	0.00	0.00	0.00	1.28
Vitamin K (μ g)	24.70	1.90	183.90	42.20
Lipids				
Total saturated fatty acids (g)	18.80	12.95	15.00	8.03
Palmitic acid (g)	16.60	10.58	11.98	5.08
Stearic acid (g)	0.50	1.85	2.92	2.03
Total monounsaturated fatty acids (g)	15.10	27.58	23.00	58.54
Oleic acid (g)	14.60	27.33	10.57	57.14
Total polyunsaturated fatty acids (g)	61.70	54.68	45.32	29.11
Linoleic acid (g)	54.80	53.23	40.18	22.98
Linolenic acid (g)	6.90	1.16	5.14	5.80
Total trans fatty acids (g)	0.00	0.29	0.00	0.33
Stigmasterol (mg)	0.00	0.00	0.00	9.00
Campesterol (mg)	0.00	0.00	0.00	233.00
β -sitosterol (mg)	0.00	0.00	0.00	419.00
Phytosterols (mg)	553.00	968.00	0.00	0.00

USDA National Nutrient Database for Standard Reference, Release 21 (2008)

consisting of brewer's yeast (LBI2240, 30.6 g, FNI LS65, 10.2 g) (Lallemand, Montreal, Canada), sugar (24.36 g), nipagen (0.4 g), sodium benzoate (0.4 g), streptomycin (0.3 g), citric acid (7.5 g), oil (2 ml, 1% of water volume), and water (200 ml). Dry diet ingredients were weighed and placed in a 200-ml plastic container with a lid. Water (150 ml) was added to the container with all other ingredients, except citric acid and oil. The container was then shaken to mix the dry ingredients with water. The mix was gently poured into a blender (Magic bullet), and 50 ml of water was used to rinse off all the ingredients in the container for further homogenization. After a 1–2 min blend, oil was added to the diet mixture, and the pH was adjusted to 3.5 with citric acid.

The diet mixture was then poured into a bento box (12.7 cm W × 17.78 cm L × 2.5 cm D) bedded with one piece of dry sponge cloth (10.16 × 15.24 cm²). The diet mixture was levelled with the thickness of sponge cloth (4 mm) to avoid overflooding. Another piece of wet sponge cloth (2 × 4 cm²) was seeded with 0.5 ml of eggs (<24 h old) and placed in the centre of the large, diet saturated, sponge cloth. The bento box was covered with a plastic lid and set inside a Rubbermaid plastic container (30.38 × 25.4 × 7.62 cm³) in a room maintained at 25°C, 65% RH, and 12D : 12L.

Fruit fly evaluation parameters and data analysis

The quality of the fruit flies reared was evaluated by assessing: pupal recovery (%), larval duration (d), pupal weight (mg), adult emergence (%), adult flier (%), percent mating (%), egg production (no. eggs per female per day), egg hatch (%), and peak egg period (d).

Pupal recovery was calculated as a percentage of pupae collected from number of eggs hatched. As soon as fruit fly larvae start to jump out of the larval tray and into the vermiculite, the larval collection process began. The jumping usually occurred at 8 d for *B. dorsalis*, 10 d for *C. capitata*, and 5 d for *B. cucurbitae* after egg seeding. Larvae in the vermiculite were collected daily for six consecutive days. One or two days after each larval collection, the weight of four sets of 10 pupae from each treatment were measured, and the remainders were weighed daily to calculate pupal recovery, larval duration, and pupal weight.

Larval duration was calculated as the mean day of peak larval collection.

Pupal weight was calculated as the mean weight per pupa.

Adult emergence was calculated as percentage number of adults that emerged from the pupae. Four sets of 100 pupae from the largest larval collection were set up for adult emergence and flight tests, based on Boller's (1980) methods. The data were organized into four categories: (i) unemergence (did not emerge); (ii) partial emergence (portion of adult body stuck in puparium and cannot completely emerge); (iii) partial deformed wing (fly emerged with damaged or deformed wings); (iv) non-flier (fly looked normal, but could not fly out of a 20-cm long tube) and (v) fliers (fly looked normal and fly out of a 20-cm long tube). The percentage of adult fliers was calculated by dividing the total number of non-fliers by the total number of emerged flies, subtracted by the partially emerged flies and those with deformed wings, multiplied by 100. [Percent adult fliers = (100 × non-fliers)/(total emergence – partial emergence – deformed wings)].

Percent mating The adult flies were sexed on the first day of emergence they emerged as adults. Females and males were kept in different rooms and maintained at 25°C, 65% RH, and 12D : 12L. When they reached sexual maturity (6 days for *C. capitata* and 11 days for both *B. dorsalis* and *B. cucurbitae*), 100 of each sex were introduced into a Boller's plastic cage for a mating test. The test time varied depending on insect species. The mating test was carried out between 6 and 8 a.m. for *C. capitata*, 5–7 p.m. for *B. dorsalis*, and 7–9 p.m. for *B. cucurbitae*. Mating pairs were removed from the cage. Unmated female and male flies were counted. The percent mating was calculated as dividing two times of number of mating pairs by the sum of twice the number of mating pairs and the remainder females and males.

Fecundity was determined by counting the number of eggs produced per female per day. At least three sets of 20-g pupae (approximately 2000 flies) per treatment from the largest larval collection were set up for F₁ egg collection. Egg collection began once the flies reached sexually maturity and continued for a consecutive 7 days. The number of eggs was converted from collected egg volumes by multiplying 20 000 eggs for *C. capitata*, 15 000 eggs for *B. dorsalis*, and 12 000 eggs for *B. cucurbitae*. Egg peak period (d) was obtained from the day of the highest egg collection (Chang et al. 2006, 2007).

Fertility was determined by counting the number of eggs hatched from the F₁ eggs. Eggs collected from

the first day of egg were placed on three sets of four strips of 100 eggs each for each treatment to test for egg hatchability. The percent egg hatch was determined by subtracting the percentage of eggs that did not hatch from 100%. With the TSL strain, we evaluated the egg hatch from the first day through the seventh day to see whether the flies' fertility decreased as they aged. Moreover, the manager of USDA fruit fly mass rearing facility in Hawaii observed a decrease in egg hatch with ageing of flies (CL Chang, personal communication). Yeast : sugar (1 : 3) was used as adult diet for the fertility test.

All the data presented in this study were expressed as mean ± standard errors and were analyzed using PROC ANOVA in SAS version 9.2 (SAS Institute 2008). The Tukey test was used to determine differences among treatments. All experiments used three different batches of fruit flies; each batch had three sample replicates.

Results

Bactrocera cucurbitae

There were no significant differences in pupal recovery, larval duration, pupal weight, adult emergence, adult fliers, egg hatch, or peak egg period among five oil diets. Percent mating of adult flies from WGO, corn oil, or canola oil with 20% vitamin E was significantly higher than that from vegetable or canola oil with 10% vitamin E (F = 19.17; 5,17; P < 0.0001). Percent mating was the lowest for the adults that were reared in the no oil diet. In addition, larvae raised on the corn oil and canola oil (10% vitamin E) liquid diet produced significantly more eggs than those reared on the diet containing no oil or canola oil with 20% vitamin E (table 2). Furthermore, the results show that WGO can be substituted with corn oil, vegetable oil, or canola oils in the rearing of *B. cucurbitae*, with corn oil being the best replacement.

Ceratitis capitata (TSL strain)

Pupal recoveries from corn oil, vegetable oil, and canola oils were either significantly higher than or equal to those from both WGO and no oil diets (table 3). Duration of the larval stage was shortened and pupal weight was lower with vegetable oil diet. Adult emergence from vegetable oil diet was higher than those reared in a WGO diet. Adult fliers, mating rate, egg hatch and peak egg period among larvae reared in oil supplemented diets were the same (table 3). Egg hatch did not show significant

Table 2 Comparison of four oil alternatives to wheat germ oil and no oil supplements in liquid larval diet for *Bactrocera cucurbitae*

Parameters	No oil	Wheat germ	Corn	Vegetable	Canola (10E)	Canola (20E)	Significance
Pupal recovery (%)	22.85 ± 1.29 b	36.61 ± 3.07 a	32.41 ± 3.48 a	35.25 ± 2.51 a	32.86 ± 1.80 a	34.12 ± 1.69 a	F = 4.05; d.f. = 5, 17; P = 0.0219
Larval duration (d)	8.30 ± 0.33 a	6.98 ± 0.03 b	7.20 ± 0.10 b	7.21 ± 0.07 b	7.28 ± 0.12 b	7.25 ± 0.10 b	F = 8.6; d.f. = 5, 17; P = 0.0012
Pupal weight (mg)	11.94 ± 0.10 a	10.78 ± 0.23 b	10.11 ± 0.04 b	10.40 ± 0.17 b	10.58 ± 0.23 b	10.08 ± 0.15 b	F = 16.31; d.f. = 5, 17; P < 0.0001
Adult emergence (%)	90.50 ± 0.00 a	91.17 ± 2.65 a	91.67 ± 1.72 a	93.58 ± 1.71 a	93.00 ± 2.78 a	93.83 ± 1.72 a	F = 0.30; d.f. = 5, 17; P = 0.9039
Adult fliers (%)	99.20 ± 0.81 a	97.07 ± 0.31 a	96.22 ± 1.07 a	95.46 ± 1.01 a	96.10 ± 1.02 a	95.08 ± 1.97 a	F = 1.68; d.f. = 5, 17; P = 0.2145
Mating (%)	63.03 ± 3.70 c	85.10 ± 1.65 a	87.78 ± 0.46 a	75.09 ± 2.36 b	76.25 ± 0.88 b	86.83 ± 1.71 a	F = 21.04; d.f. = 5, 17; P < 0.0001
No. egg/female/day	6.46 ± 1.19 a	9.89 ± 1.85 a	10.20 ± 0.51 a	6.87 ± 0.91 a	9.80 ± 1.04 a	5.82 ± 2.08 a	F = 2.10; d.f. = 5, 17; P = 0.1353
Peak egg time	14.40 ± 0.13 a	13.85 ± 0.09 a	13.87 ± 0.13 a	14.30 ± 0.09 a	13.82 ± 0.08 a	14.25 ± 0.31 a	F = 2.63; d.f. = 5, 17; P = 0.0792
Egg hatch (%)	34.00 ± 10.16 b	83.75 ± 1.70 a	76.92 ± 4.12 a	72.58 ± 5.33 a	78.08 ± 4.18 a	69.58 ± 4.26 a	F = 10.27; d.f. = 5, 17; P = 0.0005

Within a row, Mean values with the same letters are not significant different. PROC ANOVA, Tukey test.

Table 3 Comparison of four oil alternatives to wheat germ oil and no oil supplements in liquid larval diet for *Ceratitis capitata* (TSL strain)

Parameters	No oil	Wheat germ	Corn	Vegetable	Canola (10E)	Canola (20E)	Significance
Pupal recovery (%)	9.43 ± 1.40 c	20.05 ± 2.80 bc	30.80 ± 3.54 ab	44.26 ± 4.03 a	38.71 ± 3.76 a	38.88 ± 2.87 a	F = 16.60; d.f. = 5, 17; P < 0.0001
Larval duration (d)	15.14 ± 0.22 a	3.99 ± 0.28 ab	13.39 ± 0.21 b	12.99 ± 0.24 b	13.29 ± 0.20 b	13.59 ± 0.46 b	F = 7.29; d.f. = 5, 17; P = 0.0024
Pupal weight (mg)	11.35 ± 0.46 a	11.18 ± 0.33 a	10.68 ± 0.25 ab	9.76 ± 0.03 b	9.98 ± 0.13 ab	10.39 ± 0.33 ab	F = 4.77; d.f. = 5, 17; P = 0.0125
Adult emergence (%)	86.25 ± 1.38 b	86.25 ± 1.03 b	88.25 ± 1.70 ab	92.00 ± 1.47 ab	92.75 ± 0.25 a	89.25 ± 1.44 ab	F = 4.58; d.f. = 5, 17; P = 0.0072
Adult fliers (%)	82.11 ± 4.74 ab	87.96 ± 1.67 a	91.64 ± 1.84 a	95.79 ± 1.88 a	92.62 ± 1.88 a	91.14 ± 3.32 a	F = 2.84; d.f. = 5, 17; P = 0.0464
Mating (%)	47.29 ± 2.40 b	82.68 ± 2.59 a	83.45 ± 3.72 a	88.48 ± 2.30 a	78.07 ± 5.17 a	91.69 ± 0.51 a	F = 26.41; d.f. = 5, 17; P < 0.0001
No. of egg/female/day	5.00 ± 2.05 b	12.83 ± 0.71 a	8.87 ± 1.33 ab	10.92 ± 1.21 ab	5.01 ± 2.06 b	7.83 ± 0.65 ab	F = 4.71; d.f. = 5, 17; P = 0.013
Peak egg time	8.82 ± 0.18 b	8.82 ± 0.05 b	8.91 ± 0.20 b	9.25 ± 0.06 ab	9.58 ± 0.11 a	9.58 ± 0.21 a	F = 5.74; d.f. = 5, 17; P = 0.0062
Egg hatch (%)	78.92 ± 3.03 b	87.50 ± 0.76 a	85.92 ± 1.71 a	87.08 ± 1.02 a	82.42 ± 2.38 ab	85.58 ± 0.94 a	F = 3.21; d.f. = 5, 17; P = 0.0452

Within a row, Mean values with the same letters are not significant different. Proc ANOVA, Tukey test.

changes from day 1 to day 7 on all treatments except on canola oil (10% vitamin E) (data not shown; for +WGO, F = 0.40, P = 0.8716; -WGO, F = 2.31, P = 0.0717; corn oil, F = 1.15, P = 0.3707; vegetable oil, F = 0.67, P = 0.6768; canola oil (10%), F = 3.64, P = 0.0123; canola oil (20%), F = 1.37, P = 0.2727; All d.f. = 6, 27). This result confirmed that the egg hatch from adults that reared in WGO diet as larvae are consistent with ageing at least for 7 days. Fewer eggs were produced from adults reared on the diet supplemented with canola oil (10% vitamin E) than those were produced from adults reared on WGO. Therefore, all tested oils except canola oil can be substituted for WGO when rearing *C. capitata* on a liquid diet. However, vegetable oil may be the best of all the substitute oils.

Bactrocera dorsalis

There were no significant differences in pupal recovery, larval duration, pupal weight, adult emergence, and adult fliers among the five oil treatments (table 4). Egg production was the same for adults from diets supplemented with WGO and corn oil, which was significantly higher than the vegetable oil and the canola oil treatments. Egg hatch of WGO and corn oil reared adults were similar, but were significantly higher than that of the vegetable oil reared adults. There was no difference in egg hatch between corn oil and canola oil treatments. There was no significant difference among the five oil treatment in peak egg period and mating. Therefore, corn oil is a better alternative to WGO than vegetable or canola oils for *B. dorsalis* (table 4).

Chang and Vargas (2007) have shown that diet with WGO was generally perform significantly better than those without any oil. Similar results were obtain in this study. Therefore, we will ignore the discussion related to diet without any oil.

Discussion

Some parameters showed the same results in the three species. In particular, some were more sensitive to differences in the type of oil used. Those sensitive parameters were related to reproduction and larval survival. For *B. cucurbitae*, the lack of significant difference in pupal recovery, larval duration, pupal weight, adult emergence, and adult fliers indicates that the larvae will develop normally as long as there are saturated or unsaturated fatty acids/fats in their diet. However, they

Table 4 Comparison of four oil alternatives to wheat germ oil and no oil supplements in liquid larval diet for *Bactrocera dorsalis*

Parameters	No oil	Wheat germ	Corn	Vegetable	Canola (10E)	Canola (20E)	Significance
Pupal recovery (%)	42.92 ± 5.74 b	75.16 ± 1.02 a	72.03 ± 4.78 a	66.56 ± 3.82 a	75.97 ± 1.54 a	66.94 ± 10.63 a	F = 4.82; d.f. = 5, 17; P = 0.0119
Larval duration (d)	10.17 ± 0.27 a	8.77 ± 0.07 b	9.04 ± 0.22 b	9.32 ± 0.07 b	9.34 ± 0.01 b	9.21 ± 0.17 b	F = 8.14; d.f. = 5, 17; P = 0.0015
Pupal weight (mg)	13.14 ± 0.17 a	11.35 ± 0.09 b	11.56 ± 0.06 b	11.66 ± 0.12 b	11.29 ± 0.11 b	11.25 ± 0.08 b	F = 42.89; d.f. = 5, 17; P < 0.0001
Adult emergence (%)	96.75 ± 0.63 a	96.25 ± 1.80 a	99.75 ± 0.25 a	98.50 ± 0.29 a	99.00 ± 0.41 a	98.25 ± 0.48 a	F = 2.58; d.f. = 5, 17; P = 0.0628
Adult fliers (%)	87.30 ± 3.52 a	83.54 ± 5.17 a	95.45 ± 1.47 a	94.06 ± 1.37 a	94.76 ± 1.38 a	94.67 ± 1.40 a	F = 3.16; d.f. = 5, 17; P = 0.0322
Mating (%)	86.07 ± 1.78 a	93.84 ± 1.97 a	84.01 ± 2.10 a	86.35 ± 4.58 a	90.49 ± 1.70 a	85.01 ± 1.95 a	F = 21.04; d.f. = 5, 17; P < 0.0001
No. egg/female/day	0.93 ± 0.58 c	39.84 ± 6.65 a	34.57 ± 3.58 a	8.67 ± 3.34 bc	17.10 ± 1.28 b	21.08 ± 5.58 b	F = 13.12; d.f. = 5, 17; P = 0.0002
Peak egg time	13.17 ± 0.30 a	12.42 ± 0.04 b	12.57 ± 0.09 ab	12.51 ± 0.01 ab	12.42 ± 0.07 b	12.72 ± 0.17 ab	F = 3.57; d.f. = 5, 17; P = 0.0330
Egg hatch (%)	34.92 ± 2.30 d	89.17 ± 0.33 a	75.17 ± 2.95 a	52.83 ± 6.42 bc	80.08 ± 1.33 b	74.08 ± 3.76 b	F = 33.77; d.f. = 5, 17; P < 0.0001

Within a row, Mean values with the same letters are not significant different. Proc ANOVA, Tukey test.

may not reproduce normally. The percent mating from those adults reared on diets with WGO, corn oil, and canola oil (20% vitamin E) were the same, although there are differences for those reared on vegetable oil and those reared on canola oil with 10% vitamin E (table 2). This is probably due to the low percentage of vitamin E in both oils. We speculate that vitamin E may be responsible for mating results in *B. cucurbitae*. This result may concur with the finding that vitamin E is a special 'fertility vitamin' (Jager, 1973). Egg production from flies reared on corn oil, vegetable oil, and canola oil was not significantly different from those reared in WGO, although canola oil (20% vitamin E) was significantly different from those reared in corn oil (table 2). This may be because canola oil (20% vitamin E) has a low polyunsaturated acid content (22.98%) and a higher monounsaturated acid content (58.54%) than corn oil. These results suggest that the high concentration of oleic acid in liquid diet has a lipid-lowering effect that may be necessary for successful fruit fly reproduction (Fujiwara et al. 2005).

For *C. capitata*, pupal recoveries from the larvae reared in diet with vegetable oil and those reared in canola oils (both 10% and 20% vitamin E) were higher than those reared in diet supplemented with WGO. Vegetable oil and canola oils may be better than WGO as a diet supplement for *C. capitata*. This also may be due to the fact that vegetable and canola oils have a higher vitamin K content, because the sole job of the latter in the body is to make the proteins that regulate the flow of calcium in and out of tissues. Vitamin K makes it possible for the body to convert the amino acid glutamic acid into gamma-carboxyglutamic acid (<http://www.the-vitamin-and-supplement-guide.com/vitaminkinformation.html>).

Larval duration and pupal weight from vegetable oil diet was shortened and reduced significantly. Adult emergence and peak egg time was increased and enlengthened, adult fliers, mating rate, and egg hatch were the same for adult flies reared on vegetable and canola oils as for those raised on the WGO diets. This concurred with the results of *B. cucurbitae*. However, significantly lower egg production was obtained from adult flies reared on canola oils (10% and 20% vitamin E) compared to those reared on diet with WGO, which indicates that lower polyunsaturated fat and higher monounsaturated fat may cause lower egg production for *C. capitata*. This result also suggests that high oleic acid may cause a lipid-lowering effect that decreases egg production (Fujiwara et al. 2005).

For *B. dorsalis*, there were no significant differences among diets in pupal recovery, larval duration, pupal weight, mating rate/percentage, and peak egg-ing period. Once again, this concurred with our findings for *B. cucurbitae* and *C. capitata*. However, egg production from flies reared on vegetable oil or canola oils was significantly lower than that from those reared on corn oil and WGO. This may be explained by the fact that corn oil and WGO possess higher polyunsaturated fat than vegetable oil and canola oils. Egg hatch from vegetable oil and canola oils was also significantly lower than those from WGO diet. However, adult emergence from corn oil and canola oil (10% vitamin E) were significantly higher than the WGO diet although they are all in high 90%. Adult fliers from corn oil diet, vegetable oil diet, and canola oil diet were all higher than that from WGO diet.

In conclusion, all tested fruit flies including *B. cucurbitae*, *B. dorsalis*, and *C. capitata*, can develop normally as long as there are some essential saturated and unsaturated fatty acids in the diet, although with some of them such as vegetable oil and canola oil (10% vitamin E) may not reproduce or exhibit normal sexual behaviour. Interestingly, the impact of lack of oil in reproduction was more evident in both *Bactrocera* species than in the medfly. In this study, the results suggest that WGO can be substituted with corn oil, vegetable oil, or canola oils for *B. cucurbitae*, while corn oil is a better alternative for *B. dorsalis* and vegetable oil is the best substitute for WGO for *C. capitata*. Further detailed study on how saturated and unsaturated fatty acids affect fruit fly performance is needed.

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References

- Chang CL, Vargas RI, 2007. Wheat germ oil and its effects on a liquid larval rearing diet for oriental fruit flies (Diptera: Tephritidae). *J. Econ. Entomol.* 100, 322–326.
- Chang CL, Caceres C, Jang EB, 2004. A novel liquid larval diet and its rearing system for Melon fly, *Bactrocera cucurbitae* (Coquillett) (Diptera: Tephritidae). *Ann. Entomol. Soc. Am.* 97, 524–528.
- Chang CL, Vargas RI, Jang EB, Caceres C, Cho IK, 2006. Development and assessment of a liquid larval diet for *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae). *Ann. Entomol. Soc. Am.* 99, 1191–1198.
- Chang CL, Caceres C, Ekesi S, 2007. Life history parameters of *Ceratitidis capitata* (Diptera: Tephritidae) reared on liquid diets. *Ann. Entomol. Soc. Am.* 100, 900–906.
- Fujiwara Y, Satsuka A, Tsutsumi C, Kaneko K, Yasuda F, Matsumoto A, Fushimi N, Seyama Y, 2005. Effect of a diet high in oleic acid on plasma lipids in Guinea pigs and humans. *J. Home Econ. Jpn.* 56, 171–179.
- Jager FC, 1973. Linoleic acid intake and vitamin E requirement. Ph.D. thesis. Agricultural University, Wageningen.
- Kahlon TS, 1989. Nutritional implications and uses of wheat and oat kernel oil. *Cereal Foods World*, 3, 872–875.
- Knipling EF, 1955. Possibilities of insect control or eradication through the use of sexually sterile males. *J. Econ. Entomol.* 48, 902–904.
- Knipling EF, 1998. Role of parasitoid augmentation and sterile insect techniques in areawide management of agricultural insect pests. *J. Agri. Entomol.* 15, 273–301.
- Robinson AS, Cayol JP, Hendrichs J, 2002. Recent findings on medfly sexual behavior implications for SIT. *Fla. Entomol.* 85, 171–181.
- SAS Institute 2008. SAS user's guide, version 9.2. SAS Institute, Cary, NC.