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REVIEW ARTICLE

A comprehensive review of melon fruit fly, *Zeugodacus cucurbitae* Coquillett (Diptera: Tephritidae)

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Abstract

The melon fruit fly, *Zeugodacus cucurbitae* Coquillett is one the most devastating and polyphagous insect pests affecting cucurbitaceous vegetables and fruits across various regions worldwide. It primarily damages the economic part of the plant *i.e.,* the fruits, causing direct damage to the produce resulting in huge losses to the farmers. Moreover, the presence of immature fruit fly stages in harvested produce often leads to regulations. Among the four life stages of the fruit fly, three are concealed in nature (eggs in the superficial skin of the fruit, larvae in the flesh, and pupae in the soil),making its management challenging. The only stage visible in the crop habitat and availablefor intervention is the adult stage. In this paper, we have discussed the basic aspects of the melon fruit fly *viz.* distribution, biology, molecular and morphological identification, quarantine restriction and odour-based management available in trend and future prospects.

Keywords

host marking pheromone; male annihilation; male-sterile technique; melon fruit fly; species identification

Introduction

Fruit flies belong to the order Diptera, family Tephritidae and are recognized as one of the most important groups of insect pests infesting fruits and vegetables. Fruit flies infest 932 species of hostplants worldwide (1), and around 10% of the recognized species are insect pests of fruits and vegetables cultivated for commercial production (2). Among these, the melon fruit fly, *Zeugodacus cucurbitae* Coquillett, is the most catastrophic insect pest of several agricultural (Fig. 1) and horticultural crops (Fig. 2 & 3). The first record of melon fruit flies in India was reported by Froggatt in 1909. Weems and Heppner (3) stated that the melon fly was accidentally invaded to major parts of Asia, Oceania, North America, and Africa. *Z. cucurbitae* is widely distributed in temperate, tropical and sub-tropical regions of the world (4). The host range of melon fruit flies (Table 1) includes over 125 plant species (3), with the most preferred hosts being pumpkin, ridge gourd, snake gourd, bitter gourd, muskmelon, watermelon, guava, orange and mango, etc. Although primarily polyphagous, oligophagous populations have been found in Thailand, Malaysia and France (5). The geographical distribution of melon flies (Table 2) is extensive, ranging from rainforests (coolest weather) to open savannahs (sunny weather), showcasing the highly adaptable nature

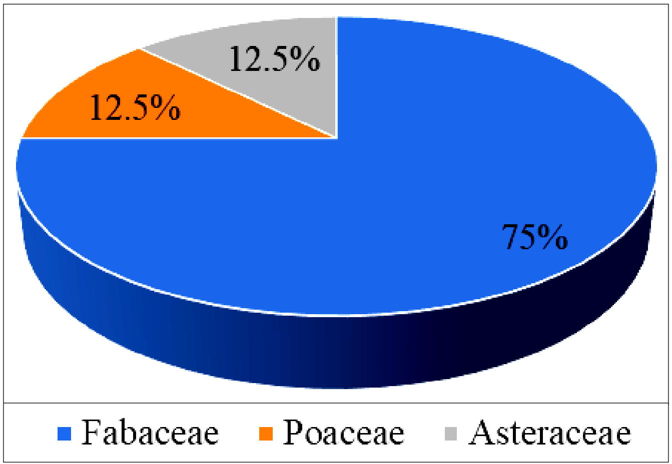


Fig. 1. Hosts of melon fruit fly – Field crops.

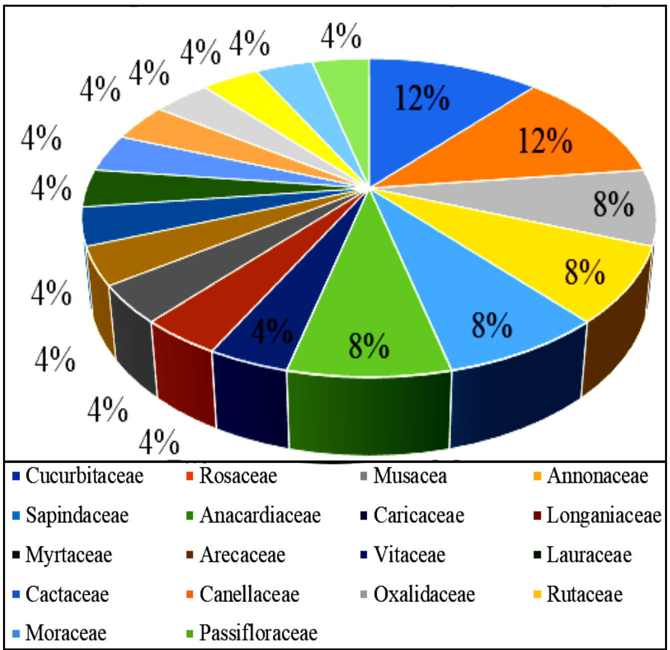


Fig. 2. Hosts of melon fruit fly – Fruit crops.

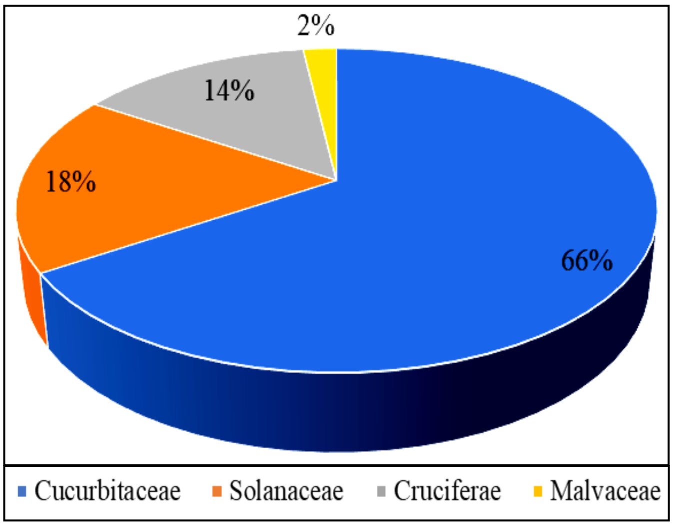


Fig. 3. Hosts of melon fruit fly – Vegetable crops.

in two extreme conditions, makes the management strategy harden with persistent survival percentage of melon flies. According to Atwal and Dhaliwal (6), fruitflies caused 50% of damage to cucurbits in India with losses ranging from 30% to 100% depending on environmental conditions and crop susceptibility (4).

Fruitflies damage the economic parts of the crops by oviposition and larval feeding on ovaries and fruit pulp. Besides, these direct losses, indirect losses occur due to the rejection of export produce because of fruit fly maggots, as quarantine restrictions and eradication procedures are very strict nowadays. Fruit fly infestation may occur as pre-harvest in the field or as post-harvest during storage. India holds a great diversity of fruit flies, posing a severe threat to the export industry. These insects are omnipresent, polyphagous, and of great quarantine importance. In India, fruit flies are considered serious threats to horticulture,causing economic losses ranging from 2.5% to 100% depending upon the crop and season (7). In this paper, we have attempted to throw light on the information available on basic and applied aspects of the melon fruit fly and its management. This will provide a panoramic understanding of the insect and highlight future researchable issues and innovative management practices.

Biology

Egg

Research described the eggs of *Z. cucurbitae* as elongated, shiny, translucent, creamy white, cylindrical, slightly curved and tapering at one end (8, 9). The surface is sculptured with numerous longitudinal ridges and grooves.

Maggots

Maggots are apodous and pass through three larval instars to become adults. Research has described the first instar maggots as translucent and white, elongated, slightly flattened dorso-ventrally, and pointed at anterior ends, possessing mouth hooks at the anterior part of the body (10). Second instar maggots are ellipsoidal, creamy white color, slightly flattened dorsoventrally, slightly elongated, broad posteriorly, gradually tapered anteriorly and pointed at the head. In the thirdinstar, maggots are yellowish due to the accumulated food reserves and are opaquer than the earlier stages. A dark longitudinal line from the mouth toanus was observed, and black colored mouth hooks moved back and forth during feeding in the third instar.

Pre-pupa

The behaviour of matured maggots during the pre-pupal stage has been described (11). Maggots become quiescent, sluggish, stop feeding and remain stationary and assume. a spiral shape.

Pupa

The pupa is coarctate, with a hard wall called a puparium The anterior part of the pupa is narrower thanthe posterior portion. Freshly formed pupa is yellowish, later turning reddish brown to dark brown. A small black dot is present on the posterior end. Pupation occurs in soil (11).

Adult fruit flies

Adults are reddish-brown with lemon-yellow, curved vertical markings on the thorax and shading on the outer edges of the wings. Males are smaller than females, which can be distinguished by their tapering abdomen ending in a sharp ovipositor formedby the 7th to 11th abdominal segments. Adults measure 4 to 5 mm in length, with a wing expanse of 11 to 13mm in males and 14 to 16 mm in females (12).

Fecundity

The fecundity of melon fruit flies is up to 300 eggs per female. The mean single-generation time and the net reproductive rate are 71.7 days and 80.8 births per female,

Table 1. Hosts of melon fruit flies

S. No	Crops	Family	Reference
	Vegetables		
1	Snake gourd, Pointed gourd, Wild snake gourd, Ridge gourd, Bitter gourd, Bottle gourd, Cucumber, Chinese cucumber, Pumkin, Snap melon, Sponge melon, Ribbed guard, Ivy gourd.	Cucurbitaceae	Weems and Heppner (3)
2	Tomato, Eggplant	Solanaceae	
3	Cauliflower, Cantaloupe	Cruciferae	
4	Winter melon, Wild melon, Bitter cucumber, African melon, Maroon cucumber, Hedgehog cucumber, Hubbard squash, Crookneck pumpkin, Field pumpkin, Stuffing cucumber, Striped cucumber, Bitter melo, Chayote, Fluted pumpkin.	Cucurbitaceae	Eppo global database (62)
5	Scarlet eggplant, Forest bitter berry, African eggplant, Makoi	Solanaceae	
6	Wild cucurbits	Cucurbitaceae	
7	Squash melon	Cucurbitaceae	Narayanan and Batra (64)
8	Chilli	Solanaceae	
9	Bhendi	Malvaceae	
10	Broccoli, Kohl rabi, Kundru	Cruciferae	
11	Zingerone	Cruciferae	Tan et al. (65)
	Fruits		
12	Natal orange	Longaniaceae	Eppo global database (62)
13	Dragon Fruit	Cactaceae	
14	Ugandan greenheart	Canellaceae	
15	Cashew nut	Anacardiaceae	Vayssières et al. (66)
16	Fig	Moraceae	Weems and Heppner (3)
17	Grenadilla	Passifloraceae	
18	Orange	Rutaceae	
19	Papaya	Caricaceae	
20	Peach	Rosaceae	
21	Fig	Moraceae	Narayanan and Batra (64)
22	Guava	Myrtaceae	
23	Date palm	Arecaceae	
24	Apple, Strawberry	Rosaceae	
25	Galls grapevine	Vitaceae	
26	Avocado	Lauraceae	
27	Chinese banana, Blue field banana	Musacea	
28	Soar soup	*Annonaceae*	
29	Star fruit	Oxalidaceae	
30	Custard apple	Annonaceae	
31	Longan	Sapindaceae	Weems and heppner (3)
32	Litchi		Wen (67)
	Field Crops		
33	Sweet corn	Poaceae	White and Elson-Harris (68)
34	Sunflower	Asteraceae	
35	String bean	Fabaceae	Weems and Heppner (3)
36	Cowpea		
37	Common bean		Eppo global database (62)
38	Pigeon pea, Green gram, Hyacinth bean		Narayanan and Batra (64)

Table 2. Geographical distribution of melon fruit flies

S. No	Continent	Country	Reference
1	**Asia**	Afghanistan, Bangladesh, Brunei, Cambodia, Christmas Island, East Timor, India, Indonesia, Iran, Laos, Malaysia, Myanmar, China, Nepal, Oman, Pakistan, Philippines, Singapore, Sri Lanka, Taiwan, Thailand, United Arab Emirates, Vietnam, Egypt, Tanzania. Brunei Darussalam	Eppo global database (62)
2	**North America**	Hawaii	Weems and Heppner (3)
3	**Oceania**	Australia, Nauru, Papua New Guinea, Kiribati, Guam, Northern Mariana Island, Solomon Islands	Hu et al. (63)
4	**Africa**	Cameroon, Cote d'Ivoire, Gambia, Kenya, Reunion, Seychelles, Somalia, Benin, Burkina Faso, Guinea, Mali Niger, Nigeria, Senegal, Togo, Uganda.	Weems and Heppner (3)
		Burundi, Ethiopia, Ghana, Malawi Mauritius, Mozambique, Reunion, Seychelles, Sierra,Leone, Somalia, Sudan.	Eppo global database (62)

respectively, with 8 to 10 generations per year (3). Morphological identification (Table 3) and sexual dimorphism (Table 4) are similar to all the hosts of melon fruit flies.

Identification of melon flies in quarantine

Molecular identification of melon fruit flies

Fruit flies damage several agricultural and horticultural crops and are categorized as importantquarantine insect pests. Précise morphological identification of fruit fly species is challenging due tothe presence of species complexes, the unidentifiability of immature stages (maggots) through morphological diagnostic features, and intraspecific variation. Hence, a fastand precise species segregation way is needed to verify and avert the launch of invasive fruit fly species in new terrains. For this persistence, DNA barcoding is a highly useful molecular toolfor identifying the fruit fly species. For this, the DNA sequence of a specific region of thegenome (most commonly the Mitochondrial cytochrome c oxidase subunit 1 gene [COI]) will beobtained from the fruit fly of our interest and it will be compared with a database of curatedsequences from positively identified reference specimens. COI, Nuclear Eukaryotic TranslationInitiation Factor 3 Subunit L (EIF3L), Nuclear Replication Protein A 32 Kda Subunit (RPA2), Nuclear Dolichyl-Diphosphooligosaccharide-Protein Glycosyltransferase Subunit 2 Isoform X2(DDOSTs2) and Nuclear Ribonuclease P Protein Subunit P29 (POP4) are the molecular diagnosticlocus for *Z. cucurbitae* (13).

DNA barcoding method is effective, time consuming, especially immature stages are easily morphologically indistinguishable and the accuracy level of identification is 100%. DNAbarcoding method increases the value of taxonomical identification of tephritid fruit fly species forquarantine purposes. DNA from specimens should be obtained through non-destructive practices, to preserve voucher specimens for further re-examination of morphological features (14). For adult fruit flies, the legs on one side of the body may be destructively sampled, while preserving other diagnostic features such as wings, thorax, and abdomen for future reference. In case of immature stages of fruit flies *i.e.,* maggots, their anterior and posterior parts are cut off to preserve the morphologically valuable mouthparts and spiracles (13). Lessnegative methods like Proteinase K digestion of interior tissues to retain the whole cuticle as an effective alternative (15).

A PCR–RFLP methodology has been developed to differentiate between the tephritid fruit fly species including *Z. cucurbitae* (16). This method amplifies the mitochondrial COI gene barcoding region in *Z. cucurbitae* specimens. The sequence analysis showed that the restriction enzyme RsaI differentiated among the target species, whether in the larval or adult stage. Therefore, they suggested that this method could be effectively utilized for decision-making at quarantine barriers and this method is particularly useful when only immature stages are present in the commodity. The sequence obtained from *Z. cucurbitae* is deposited at the GenBank database to test on different developmental stages of *Z. cucurbitae* and it showed 100% similarity with the database deposited at the gene bank. The same technique with DdeI or XmnI restriction enzymes is used to identify *Z. cucurbitae, B. zonata* and *Ceratitis capitata* (17).

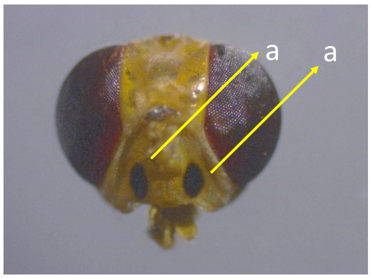
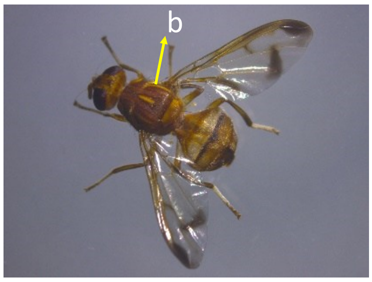
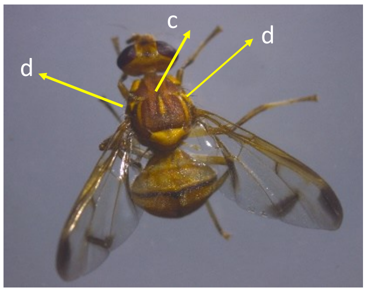
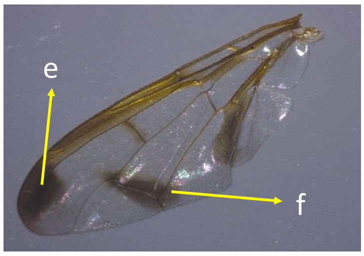
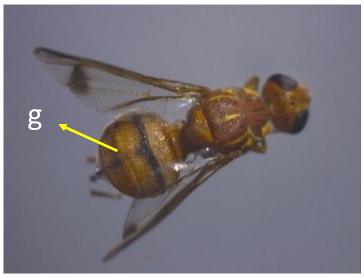
Taxonomic identification through cuticular hydrocarbon (CH) profiles

Cuticular hydrocarbon profiles being species-specific, are used to distinguish the species and sibling species taxonomically. The first effective use of CHs for the systematic identification of crypticspecies of *B. dorsalis* with the help of GC-MS based on the different chain lengths of CH was done by Goh et al (18). The CH is a taxonomic tool to identify the cryptic species of African fruit fly and cryptic species complex of *B. dorsalis, B. invadens*, *B. papaya, B. philippinensis* and *B. carambolae* (19).

Quarantine

Importing and exporting are primary ways insect pests spread through the transport of infested plant material to non-infested areas. Before importing vegetables and fruits, commodities should be compulsorily treated to kill the fruit fly larvae and infested commodities with melon flies. Fruit flies are controlled at quarantine stations through vapor heat treatments for 30 min at 46°C and with fruit flesh temperature at a minimum of 45°C. After treatment, melons are cooled at ambient air temperature until their core temperature falls below 30°C (20). Cold storage of fruits is done at 1.1°C or below for 14 continuous days to kill the egg or larva in the host itself (21). Fumigation of methyl bromide at concentrations of 16 to 32 g/m^3 for 2 h exposure period brought complete mortality of all the immature stages (22). Radiation treatment at 116 Gy prevented the emergence of adults (23). Countries that have eradicated the melon flies are given in Table 5.

Table 3. Morphological Identification of melon fruit fly species

Body part	Identification feature	Photo
Head	**a**) Presence of two dark color oval shaped facial spots above the mouthparts.	
Thorax	**b**)Scutum is red-brown or golden in color with or without dark markings.	
	c) One narrow medial vitae. **d**) Two lateral yellow post sutural vittae.	
Wing	**e**) Brown costal band expanding into a semicircular spot in wing apex. **f**) Transverse brown bands on dm-cu.	
Abdomen	**g**) Reddish brown and longitudinal medial line in terga 3-5.	

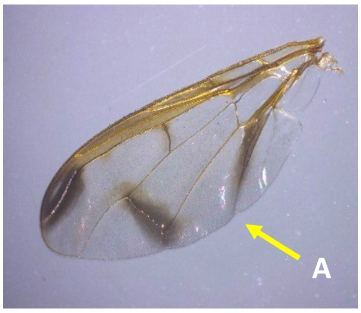
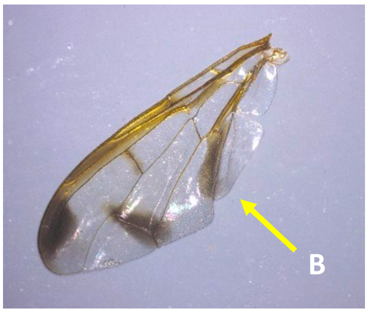
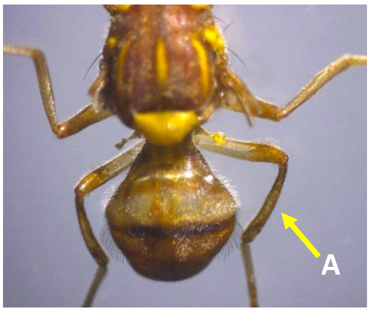
Odour-based management of melon fruit flies

Male annihilation technique (MAT)

Mass trapping of male fruit flies using attractants, known as MAT, is a pivotal method for suppressing, or eradicating tephritid fruit flies. Cue-lure and methyl-eugenol are widely used as parapheromones to attract and kill the fruit flies through MAT and are recommended for area-wide management of fruit flies (11). Methyl eugenol possesses both olfactory and phagostimulatory properties, attracting fruit flies from as far as 800 m away (24). The use of Methyl eugenol reduced the pesticide use by up to 75–95% (25) but it attracts only males. One way to increase theeffectiveness of methyl eugenol is by combine it with fruit juice to also attract female fruit flies. Combining methyl eugenol and star fruit extract has been found to be effective in trapping fruit flies (26). When 5 or 6 mL of methyl eugenol was applied through cotton wicks placedin delta traps, it was found to be effective in trapping male fruit flies. Field longevity was 4–8 weeks and replacement should be done at every 6-week intervals (27).

Cue-lure and its diacetyl derivative Raspberry ketone (RK) are specific attractants to melon flies. Cue-lure combined with mashed sweet gourd in a bitter gourd ecosystem attracted and killed 40–65% of fruit flies, resulting in 2–4 times higher yields compared to untreated plots (28). A bait mixture of ethanol, carbaryl, and cue-lure in the

Table 4. Sexual dimorphic morphological traits in melon fruit fly

S. No	Sexual dimorphism	Female	Male
1	**Female:** White color pupa. **Male:** Brown color pupa (69)		
2	**Female:** Protruding ovipositor present. **Male:** Protruding ovipositor absent (70)		
3	**Female:** Regular wing outline with only slight depression at a certain position (A). **Male:** A distinct depression exists at the lower edge of the male wing (B) (70).		
4	**Female:** Four abdominal rectangular brownish-black patches are present on the ventral side of the abdomen. **Male:** Three round brownish patches are present on the ventral side of the abdomen (70)		
5	**Female:** Pecten hairs are Absent. **Male:** Pecten hairs are Present (A) (70).		

ratio of 8:2:1 effectively trapped melon flies (29). Several commercial attractants such as Cue-lure (95%) + naled (5%), Cue-lure (85%) + diazinon (15%), cue-lure (85%) + flycide (15%), Eugelure (20%), Eugelure (8%), are available in the market and have been proven efficient in controlling the insect (27). Cue-lure B1 (Ethylcis-5-Iodo-trans-2-methylcyclohexane-1- carboxylate) exhibited 4 to 9 times more potential than Trimedlure in attracting melon flies (30). Various mixtures of methyl-eugenol and cue-lure have been tested and found that traps baited with a 10:90 ratio of cue-lure to methyl-eugenol were more effective in monitoring and managing *Z. cucurbitae* in guava and vegetable crops (31).

Table 5. List of Melon fruit fly restricted areas in World

S. No	Continent	Country	Eradicated Year
1	**Africa**	Tunisia	2012
		Morocco	2018
2	**North America**	Los Angeles	1985
		Kern	2010
		San Diego	1974
		Mexico	2018
		Paraguay	1992
		USA	1994
		Uruguay	1992
3	**Asia**	East Timor	2017
		Japan	2016
		Bahrain	2003
		Iran	2018
		Kazakhstan	2017
		Korea, Republic	2018
4	**Europe**	Netherland	2023
		Slovenia	2017
		Azerbaijan	2007
		Türkiye	2016
		Georgia	2018
		Moldova	2017
		Switzerland	2019
		United Kingdom	2020
5	**Oceania**	New Zealand	2000

Pheromone nanogels

Parapheromones are species-specific and factors such as auto-oxidation, photo-oxidation, isomerization, volatility, etc. makes them unstable and these need further refinement for field studies (32). By the use of supramolecular self-assembly principles and nanotechnology, parapheromones are processed and immobilized in a nanogel with increased shelf-life. They are called as pheromone nanogels and show high residual action, and outstanding effectiveness in open-field conditions even throughout adverse climatic conditions. These are eco-friendly also. Pheromone nanogels are successfully used to control *B. dorsalis* and are expected to control other species of fruit flies also in the future (33).

Temperature sensitive nano cue-lure

The speed and time of the release of cue-lure are not controllable and hence, most of the cue-lure will be wasted reducing its effectiveness and increasing the cultivation costs. To prolong the releasing time of cue-lure in field conditions, a temperature-sensitive cue-lure nano-controlled release agent was developed, this can regulate the release rate by adjusting to changes in environmental temperature. Here cue-lure as pro drug, MWCNTs-COOH as the carrier and PNIPAM hydrogen gel as switch (controlled release). It demonstrates effective temperature-sensitive controlled release properties and maintained excellent stability when exposed to high temperatures of 60°C for a week, and 73% to 75% trapping was observed (34).

Food based fruit fly baits

As female fruit flies are the key factors in the reproduction of this insect, developing female-focused trapping systems would be more logical, appropriate, and advantageous. In this regard,several low-cost and easily available natural sources like grapes, banana, fishmeal, molasses, snake gourd, red pumpkin, crucifers, ocimum, etc. have been tested in mixture withyeast, acetic acid or ammonium acetate (5%) and black jaggery in snake gourd field to capture both sexes of fruit flies (35). They found that, banana and grapes efficiently trapped melon fruit flies with the maximum cost-benefit ratios of 1.82 and 1.74 respectively. Bharathi et al. (36) found that the melon fruit flies were particularly attracted to banana, followed by soybean hydrolysate when compared to beef extract, fish meal, dog biscuits and bread. Food based attractants of fruit flies are protein hydrolysate, brewer's yeast, torula yeast, GF -120, ammonium acetate, trimethylamine and biolure (37). Additional food bait combinations are listed in Table 6.

Protein based fruit fly baits

Protein baits play a major role in attracting the female fruit flies of various species. Female and male fruit flies need protein sources for sexual maturity and egg development. Exploiting the need for proteins in adult female fruit flies, protein bait traps with a liquid solution containing protein and fermenting sugar can be used for mass trapping and killing of females (38). Protein baits combined with a killing agent (*i.e.* malathion, fipronil, acephate, flubendiamide, spinosad and thiodicarb @ 0.01–0.05%) is a commonly used and effective attract-and-kill strategy for managing fruit fly populations, specifically targeting females (39). Protinex bait attracts more female fliesthan the males in snake gourd and bitter gourd ecosystems (40, 41). The attraction of protein hydrolysate increased effectiveness at the concentrations in the range of 0.5–10% (42). Response of *Z. cucurbitae* towards the protein bait traps increased with the increasein pH of the bait (43). Other protein baits effective in trapping melon flies are given in Table 7.

Bait sprays

Bait sprays are the most common management method for fruit flies in field conditions. A bait spray contains an attractant and a killing agent to attract flies and simultaneously kill them before their oviposition or sexual maturity. Oviposition may occur after the ingestion of poison bait also, but the fecundity of the female is reduced. The bait sprays using GF-120 (fruit fly bait with 0.02% spinosad) became the main method for the widespread control and reduction of tephritid fruit fly populations in the Hawaiian Islands (25). When bait-spraying was done on border crops such as

Table 6. Combination of Food baits recommended to control melon fruit fly

S. No	Food bait	Reference
1.	Proteinex powder + guava + casein + yeast + ammonium acetate (5%)	
2.	Fruit fly diet + sugar + banana	Ravikumar (71)
3.	Banana / jaggery (10g) + water (1lit) +malathion (2ml)	
4.	Ammonium acetate + extracts of redpumpkin and snake gourd	Mangan and Thomas (72)
5.	Banana + grapes + molasses + fishmeal +red pumpkin + snake gourd + ocimum + crucifers + yeast+ black jaggery+ ammonium acetate (5%)	Sowmiya et al. (35)
6.	Fruit pulp + dichlorvos / Spinosad	Yugendra et al. (73)
7.	Torula yeast + Borax	Thomas et al. (74)
8.	Overripe banana (1kg) + furadon (10 g) +citric acid (1g)	Satpathy et al. (75)
9.	Banana+jaggery+carbofuran+red banana + boiled jaggery + carbofuran	Jiji et al. (76)
10.	Banana + soybean hydrolysate	Bharathi et al. (36)
11.	Juices of Pineapple/guava/banana/grapes + Spinosad	Balagawi et al. (77)
12.	Banana (30g) + food grade alcohol (3ml)	Pujar et al. (78)
13.	Grapes + yeast + black jaggery +acetic acid	Sowmiya et al. (35)
14.	Pinnacle (420g / litre) + Thai brewery waste(33ml/litre)	Chinajariyawong et al. (79)
15.	Guava + musk melon + yeast (0.3g) + food grade alcohol (10ml) + cane sugar (3g) +protinex (3g)	Abinaya et al. (80)
16.	Mango, guava, banana and papaya +soybean powder + yeast + jaggery (1:1:1) + ammonium acetate (5%)	Devi et al. (81)
17.	Tomato / banana/ bitter gourd / pineapple / guava + jaggery (10%) +yeast (0.5%) + borax (2%) + malathion (0.001%)	Sruthi et al. (43)

Table 7. List of Protein baits recommended to control melon fruit fly

S. No	Protein Bait	Reference
1.	Protein hydrolysate (10%)	Gopaul and Price (82)
2.	Yeast autolysate (5%)	Seewooruthun et al. (83)
3.	Soybean hydrolysate (12.5%)	Bharathi et al. (36)
4.	Soybean + sugar + banana (1:1:1)	Rajitha (84)
5.	Protein hydrolysate (3%) + malathion (0.1%)	Patel and Patel (85)
6.	Protein hydrolysate + water (1:50)	Tamori and Iraha (86)
7.	GF-120 (40-80 ppm) + Spinosad	Prokopy et al. (44)
8.	Proteinex powder + mango / guava / banana / papaya + yeast + jaggery (1:1:1) +ammonium acetate (5%)	Devi et al. (81)

sorghum, it was observed that the main crop *i.e.,* cucumber was protected from the melon fly in Hawaii (44). Thus, melon fruit fly also controlled through spraying of protein bait with spinosad on the border crop *O.sanctum* around bitter gourd as the main crop (45). In addition, the spot spraying technique of bait spray required less insecticide and was less harmful to beneficial insects.

Electroantenogram Detection (EAD) active compounds fruit flies

Host plant odors are the major cues for insects in identifying the food, mate and locations of feeding, mating and oviposition. These odors play a significant role in the interactions between insects and plants. Host plant odours are a mixture of several volatile compounds that can be present in the air up to certain distances around the host plant. Insects identify and perceive these odours through their antennae, enabling them to locate the host. The olfactory system of insects can perceive, identify, and discriminate among a wide array of volatile signaling molecules of various chemical groups including acids, alcohols, esters and aromatics (46). The antenna is the key part of the insect in identifying these host plant odors. Therefore, identifying the attractive volatile compounds in hosts of fruit flies through electroantennogram studies and exploitation of these in their trapping system is a very useful technique in fruit fly management. The EAD active odorous compounds identified through GC–MS in the extracts of various hosts of *Zeugodacus* sp. are listed in Table 8.

Identification of host plant volatile compounds in monitoring and management of melon fruit flies

The screening of antennal responses of four important tephritid fruit flies including *Z. cucurbitae* to volatile compounds from five commercially available protein-based baits has been done using GC-EAD (47). Thirteen antennal active compounds were identified and they were reconstituted in synthetic blends for each species and these species-based blends were found to be attractive to that particular species of tephritids. Njuguna et al. (48) experimented on the attraction of melon fruit flies to the volatiles collected from tomato and cucumber. Through GC-MS analysis, 21 and 34 compounds were identified respectively and among them, 13 were the shared compounds in both cucumber and tomato. Responses of male and female melon fruit flies were analyzed in GC-EAD and found

Table 8. List of EAD active compounds recommended to control melon fruit fly.

S.No	EAD active compound	Host/ Bait	Part of host	Reference
	Fruits & Vegetables			
1	(E)- Caryophyllene	Tomato	Fruit	Njuguna et al. (48)
2	1-Hexanol	Cucumber		
3	A-Phellandrene, a-ocimene, β-ocimene, β-phellandrene			
4	α - pinene, 1- octen - 3 ol, p cymene, p - ethyl benzaldehyde, methyl salicylate, p-cymen-7-ol	Ridge gourd		Shivaramu et al. (87)
5	β - cis ocimene, ethyl benzaldehyde, ethanone - 1-(4 - ethyl phenyl), p - diace-			Subhash et al. (88)
6	(Z)-6-nonenal	Ah Cheng pumpkin		Shen and Chuang (89)
	Food bait			
7	2 - heptanone, α - pinene, a- ocimene, a - phellandrene, pentanol, 1, 3 pentadiene, 1, p-cymene, mycene, limonene, benzothiazole	Food bait	Guava(30g) + Cane Sugar (3g) + Yeast (0.3g) + Food Grade Alco-	Paripoorani et al. (90)
	Bacteria			
8	3, methyl 1, butanol, 3, hydroxy 2, butanone, 2, phenyl ethanol, 2, methyl 1, butanol	Bacteria	*Klebsiella oxytoca, Citrobac-*	Hadapad et al. (91)

that antennae of both sexes detected 10 EAD active compounds consistently. Biasazin et al. (47) also collected volatiles from brewer's yeast, baker's yeast, torula yeast, GF120 and an amed protein baits. GC-MS and GC-EAD analysis revealed that 14 active compounds elicited antennal responses in fruit flies *i.e., B.zonata, B.dorsalis, Z.cucurbitae* and *C.capitata*.

31 EAD active compounds were identified from fresh and aged puréed cucumbers which were detected by female melon fruit flies through GC-EAD analysis (49). With these compounds, they prepared several synthetic blends among which, a nine-component blend attracted a significant number of female fruit flies in outdoor rotating olfactometer experiments. They also opined that female-attracting lures are advantageous over others which attract only males, because the removal of females in the field has a very remarkable effect on the reduction of fruit fly population. They also suggested that their synthetic

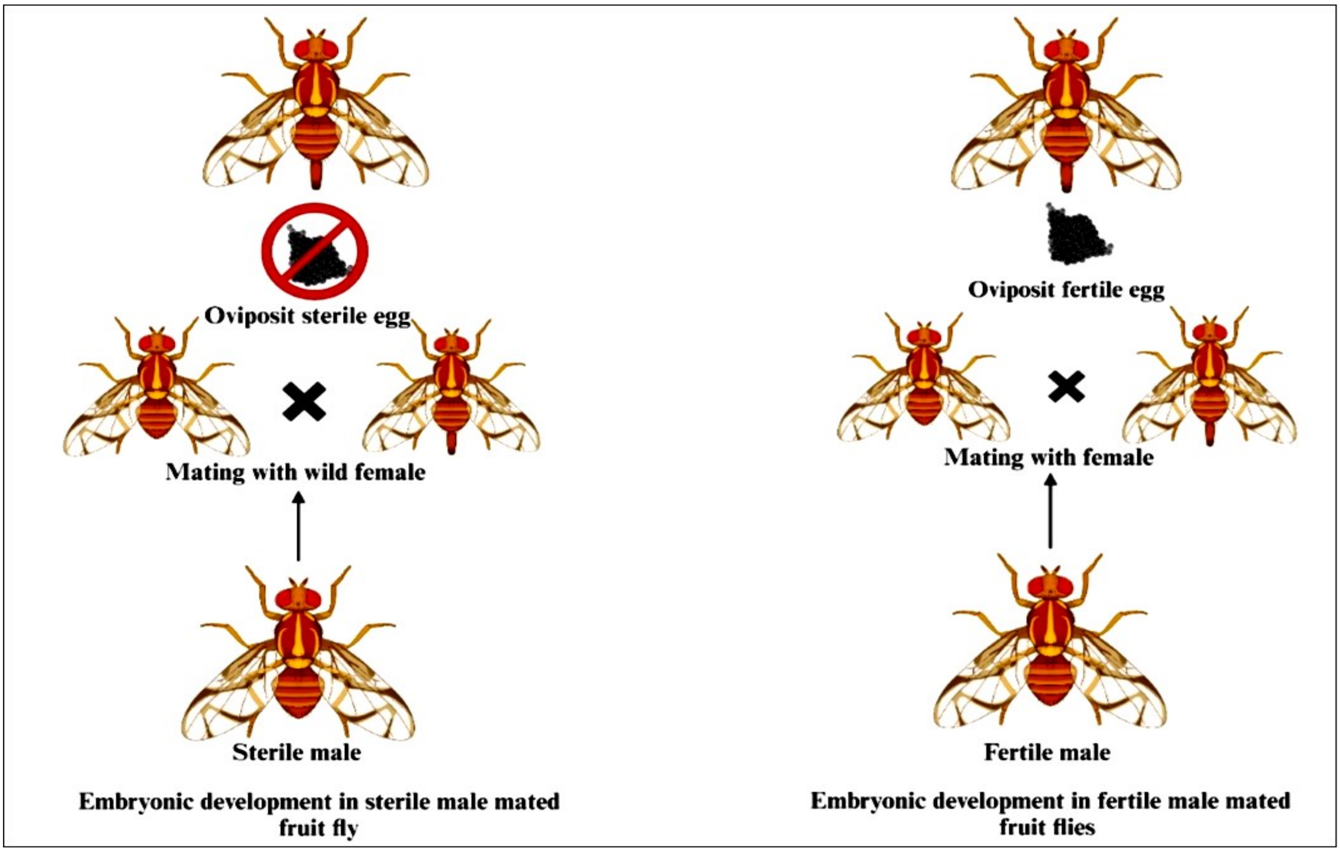


Fig. 4. Difference in embryonic development between sterile & fertile male mated fruit flies.

lure is long-lasting, adaptable to use with a dry trap and captured fewer non-target species than food-type attractants. Biasazin et al. (47) attempted to formulate Tephritid fruit fly-specific species-based blends using the antennal active odorous compounds identified from protein-based baits. A 13-compound blend that elicited antennal responses in all the tephritid fruit flies *i.e., Z.cucurbitae, B.dorsalis, B.zonata* and *C.capitata,* was created, along with other four blends, cucublend, dorsablend, zonablend, capiblend formulated based on the specific responses of each fruit fly species accordingly.

Male-sterile technique

The Male-sterile technique is a control method where sterile males are released into fields to mate with wild females. These females either do not oviposit or sterileeggs, causing the next generation to be arrested, thus reducing fruit fly infestations (Fig. 4). The sterile insect technique (SIT) has been used effectively to control Mediterranean fruit flies in Southern Mexico, *C. capitata* in Chile during 1995 (50), *B. dorsalis* in Okinawa and neighboring islands in the Ryukyu Archipelago, Japan. From 1972 to 1993 in Okinawa, Japan melon flies were completely eradicated through the Male-sterile technique by releasing 50000 million sterile flies in open field conditions and mated with wild female flies (51).

Semiochemicals in the management of fruit flies

Push-pull strategy : Host Marking Pheromones **(**HMP) are chemicals used by fruit flies to mark the oviposited hosts to avoid further oviposition on the host by other insects so that the immature stages of insects are equally distanced from proper food sources without competing with others and completely developed. HMPs are considered effective tools for controlling tephritid pests. Katsoyannos and Boller (52) was suggested to use HMPs to prevent fruit flies from laying eggs. They sprayed raw HMP extract from the fecal matter of a cherry fruit fly, *Rhagoletis cerasi* in cherry orchards which reduced its infestation by up to 90%. Aluja and Boller (53) tested the synthetic HMP of *R. cerasi* in cherry fields and this was the first application of a "push-pull strategy" (Fig. 5) in fruit flies. In the push-pull strategy, insects are repelled (push) away from the host by using stimuli to mask the host. Simultaneously, they are attracted (pull) away from the host towards the attractive traps. It was achieved by treating one-half of the tree with the synthetic HMP of *R.cerasi* and the other part of the tree was equipped with several olfactory and visual traps, the flies repelled by the synthetic HMP and were trapped in traps and this gave 90% reduction in cherry fruit fly infestation. Similarly, pheromone extract from fecal matter of medfly gave 84% reduced infestation on coffee plants (54).

Implications on biological control **:** HMP can also attract

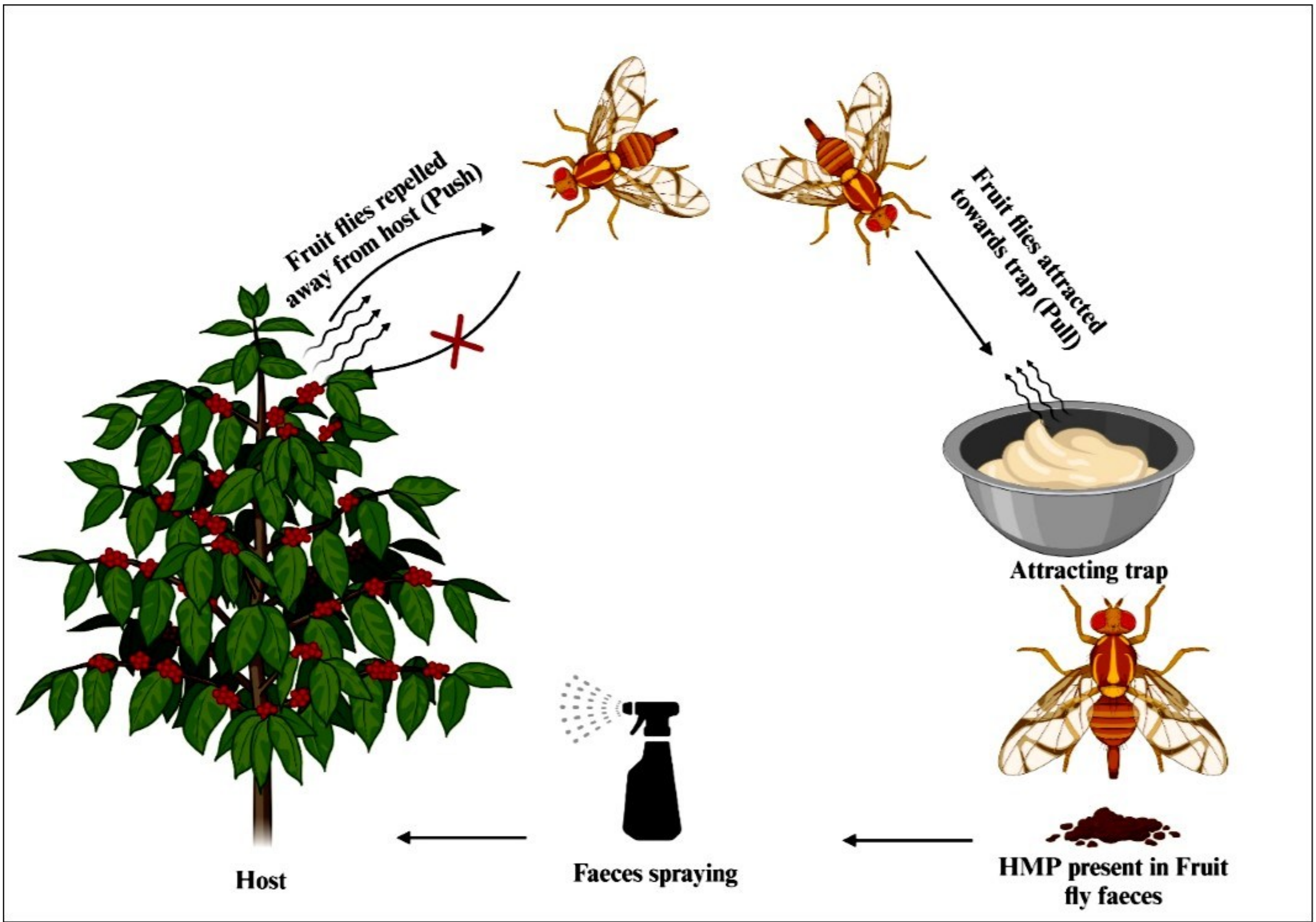


Fig. 5. Push – Pull strategy.

parasitoids. This interspecific interaction between the parasitoid and immature stages of fruit flies destroys the immature stages in the fruit itself without development. With this action, HMP enhances the activity of biological control. During mass culturing of braconid wasp, *F.arisanus,* HMP was incorporated in its artificial diet so that, it clearly distinguished HMP among the plant volatiles and an increase in its searching efficiency towards the HMP on infested fruit and control the population was observed (55).

Combination of Semiochemical and Sterile Insect Technique

The integration of semiochemicals enhances the efficacy of SIT and MAT in controlling fruit fly populations. In the case of semiochemical-based SIT, immature stages of sterilized males are fed with an artificial diet incorporated with parapheromones of males until sexually mature (56). It helps to increase the mating efficiency, survival and dispersal capacity of male flies (57). Khan et al. (58) demonstrated this approach by feeding immature *Bactrocera tryoni* males with an artificial diet incorporated with a raspberry ketone (RK). After reaching sexual maturity, these males were released to mate with wild females in the field. With this, the attraction of male flies to attractants used in MAT was reduced and it also increased the survival of male flies which caused a reduction in the next generation population by increasing the mating efficiency of male flies.

Artificial Olfaction and Pheromone-Based Nanosensors

Biosensors make signals to fruit flies at minimum concentration and maximum distance by using biological and artificial components. Odour-based pheromones from flies are isolated, purified and made stable in changing temperature and pH and these pheromone-based biosensors are used to monitor early infestation to take timely control measures (59). For instance, a pheromone biosensor for *B. dorsalis* was developed using odor detection systems, where proteins were immobilized proteins onto interdigitated electrodes with a nitrocellulose membrane. It is tested on *Beta vulgaris* and found that benzaldehyde is emitted from that plant. It is used to determine the population of insects through chemical signals released by the insect (60). For the management of olive fruit flies, a β-cyclodextrinylated based biosensor was developed from the sex pheromone of female (61).

Conclusion

In this review, we discussed novel management practices of cucurbit fruit flies, focusing on odour-based techniques and the importance of molecular identification to prevent the spread of cryptic species into new areas. Molecular methods such as DNA barcoding and PCR-RFLP are critical for accurate species identification and quarantine applications**.** The role of male annihilation techniques using parapheromones for area-wide management of fruit flies. As parapheromones are unstable in field conditions, their processing in to environment friendly pheromone nanogels with good residual activity and efficacy is a breakthrough in the successful management of fruit flies. Temperature sensitive nano cue-lures were also developed for controlled release of the active ingredient to enhance their performance. Several food and protein based baits were also tested widely, this approach is based on the need of both female and male fruit flies for protein sources for the sexual maturity and egg development. Bait sprays are effective in field conditions as they bring fly mortality before maturing sexually and laying eggs. Identification of EAD active odorous compounds through GC–MS are widely done. After their identification, several synthetic and species-specific blends are being prepared for the successful trapping of fruit flies. The male sterile technique restricts the further generations. Using host marking pheromones in preventing egg laying by fruit flies also enhances the level of biological control. Pheromone-based biosensors are also used to monitor fruit fly infestations for timely control.

Future prospect

Laboratory studies have shown that fruit flies are strongly attracted to certain host plants like cucumber, snake gourd, ridge gourd, musk melon, and white pumpkin, likely due to specific odorant compounds. Identifying these compounds via Electroantennographic Detection allows us to create synthetic blends. By optimizing ratios and concentrations, we can surpass the attractiveness of natural derivatives. Factors like trap color, shape, and height further influence capture rates. Combining synthetic blends with aesthetically pleasing traps enhances trapping efficacy. Integrating technologies like Intelligent, Electronic, and Automatic traps offers real-time monitoring and population control, applicable across pest management practices. Bridging gaps in chemical ecology and technological integration promises cost-effective pest control, narrowing the margin between production costs and returns.

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Authors' contributions

AR conceptualized and formulated the project. ZK, VC, SM, SG and MLM wrote various chapters of the review paper, reviewed and edited.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no competing interests.

Ethical issues: None

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