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Novel green management strategies for fruit flies (Tephritidae: Diptera) infesting horticultural crops in India: a critical review

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Abstract

Fruit flies, in the family Tephritidae, are major pests of horticultural crops and of quarantine concern in India and globally due to their concealed feeding habits and invasive nature. In India, most problematic species belong to the genera *Bactrocera, Dacus*, and *Zeugodacus* within the subfamily Dacinae, and *Carpomya* within the subfamily Trypetinae. The economic impact of these pests extends beyond yield losses and increased management costs. They can also lead to the loss of export markets and increased expenses for the construction and maintenance of fruit treatment and management facilities. Approximately 40 species of Tephritidae have been intentionally or unintentionally introduced outside their natural ranges by humans. Notable examples include *Bactrocera dorsalis* (Hendel), *B. carambolae* Drew and Hancock, *B. latifrons* (Hendel), *Zeugodacus cucurbitae* (Coquillett), and *B. zonata* (Saunders), which have spread from the Oriental region to other parts of the world. Conversely, *B. oleae* (Rossi) was introduced from the Mediterranean region to India. Beyond their role as pests, some fruit flies are significant as biological control agents for invasive weeds. Over 20 species, primarily from the subfamily Tephritinae, have been used to manage invasive Asteraceae species.

Key words: Fruit flies, Horticultural crops, Tephritidae: Diptera, Diagnosis, Host plants, Biocontrol

Several species of *Urophora* were introduced to North America to control thistles and knapweeds (White and Elson-Harris, 1992). In India, introduction of *Cecidochares connexa* Macquart on Siam weed (*Chromolaena odorata*) and *Procedidochares utilis* Stone on *Eupatorium adenophorum* has been significant for biological control, causing stem galls (Bhumannavar *et al*., 2004; 2007; Ramani, 2004).The Tephritidae family, a significant group within the order Diptera (true flies), encompasses over 5,000 described species. These species are distributed across six subfamilies, 500 genera, and 40 tribes and subtribes (Korneyev, 1999; Norrbom *et al*., 1999; Freidberg, 2006).

In India, approximately 300 species from 84 genera and five subfamilies—Dacinae, Phytalmiinae, Tachiniscinae, Tephritinae, and Trypetinae—have been documented (Agarwal and Sueyoshi, 2005; David and Ramani, 2011; David *et al*., 2013; David and Hancock, 2013; David *et al*., 2014; David *et al*., 2017; David and Ramani, 2019; David *et al*., 2020, 2021, 2022, 2024).Tephritid fruit flies are distinguished by several morphological features. They possess well-developed frontal plates and frontal setae that are significantly longer than the surrounding setulae. A notable characteristic is the presence of a costal break before the apex of the subcostal vein, which is protected by two or three spines. The Sc vein is bent and joins the costa at nearly a right angle. The wing cell cup has an acute extension and may be either patterned or hyaline (Hardy, 1973; White and Elson-Harris, 1992; Korneyev, 1999b).These characteristics not only aid in the identification of tephritid flies but also highlight their ecological and economic importance, particularly in agriculture where many species are considered pests.

The Tephritidae family, encompassing over 5,000 species, is found in a variety of environments ranging from open savannahs to dense rainforests. These flies are widely distributed across tropical, subtropical, and temperate regions, with the notable exceptions of the Arctic and Antarctic (Kapoor *et al*., 1980; Norrbom *et al*., 1999; Agarwal and Sueyoshi, 2005).In India, fruit flies are prevalent across all geographic regions. The tribe Dacini, which includes the genera *Bactrocera*, *Zeugodacus*, and *Dacus*, is particularly widespread throughout the country. These genera are known for their significant impact on horticultural crops, making them a major concern for agricultural practices.

Additionally, introduction of certain Tephritidae species to non-native regions has further expanded their distribution. For example, *Bactrocera dorsalis* and *B. zonata* have been introduced from the Oriental region to other parts of the world, while *B. oleae* was brought from the Mediterranean region to India (Norrbom *et al*., 1999). In India, the subfamily Dacinae is the most prevalent, comprising nearly 42% of the country's Tephritidae fauna with 119 described species. The subfamily Tephritinae follows with 69 species, and Trypetinae with 65

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species. The tribe Acanthonevrini, within the subfamily Phytalmiinae, includes 18 species from 10 genera.

Only a single species from the subfamily Tachiniscinae has been reported in India (David and Hancock, 2013).The high diversity in the Oriental region, particularly in India, can be attributed to the varied climatic conditions and habitats that support a wide range of Tephritidae species. This diversity is crucial for understanding the ecological roles and economic impacts of these species, especially those that are pests of horticultural crops.

Biology and nature of damage

While fruit flies are commonly known as fruit feeders, only species within the subfamilies Dacinae (particularly the tribe Dacini) and Trypetinae are frugivorous. Other taxa within the Tephritidae family exhibit a diverse range of feeding habits, including bamboo shoot feeders, flower feeders, leaf miners, and gall makers. Female fruit flies possess an extendable ovipositor, which they use to deposit eggs between parts of the host flower, intact fruit, stem, or leaves. The life cycle includes three larval instars and a puparial stage.Larvae of fruit flies develop in seed-bearing plants, with approximately 35% of species attacking soft fruits. In addition to infesting soft fruits, around 40% of fruit fly larvae develop in Asteraceae flowers, while others are associated with flowers from various plant families or mine the leaves, stems, or root tissues (White and Elson-Harris, 1992). Some species also induce gall formation.

Fruit flies are synovigenic, meaning that female flies require a protein-rich diet to mature their eggs and commence oviposition after emergence. Most pestiferous species are multivoltine, producing 10–12 generations per year, with the exception of *Bactrocera minax*, which is univoltine. The damage caused by fruit flies is multifaceted. They not only directly damage the host plants but also facilitate the entry of secondary pathogens, exacerbating the economic losses.

Host plant associations of Tephritidae

Fruit flies exhibit a high degree of host specificity, with the exception of saprophytic and polyphagous taxa. Polyphagous species such as *Zeugodacus cucurbitae*, *Z. tau*, and various *Dacus* species are primarily associated with host plants in the family Cucurbitaceae. Among the pestiferous species, *Bactrocera minax* is highly host-specific to the Rutaceae family. In contrast, several monophagous species of *Dacus* are associated with the Asclepiadaceae family.Within the subfamily Dacinae, only the tribe Gastrozonini has adapted to bamboo as a host. Gastrozonini is considered a monophyletic tribe (Wang and Chen, 2002; Kovac *et al.*, 2006; De Meyer, 2006; Dohm *et al.*, 2014), with larvae primarily feeding on the shoot meristem or other soft tissues of living or dead bamboo shoots.Species in the subfamily Phytalmiinae are generally saprophagous. However, Hardy (1986) and Permkam and Hancock (1995) reported that species in the genera *Clusiosomina, Clusiosoma, Cheesmanomyia*, and *Rabaulia* infest fruits of *Ficus* species. Larvae of genera such as *Austronevra, Dacopsis, Diarrhegma, Diarrhegmoides, Lumirioxa*, and *Phytalmia* develop in decomposing tree trunks or rotting parts of trees (Hardy, 1986; Permkam and Hancock, 1995). Some species of *Afrocneros* and *Ocnerioxa* have been found under the bark of living trees (Munro, 1967), and *Termitorioxa termitoxena* (Bezzi) breeds in termite galleries within tree trunks (Hill, 1921).

The subfamily Trypetinae exhibits the most varied larval feeding habits. The tribe Adramini is primarily found in the Old World, with two species of *Euphranta* present in North America (Hardy, 1986; White and Elson-Harris, 1992; Hancock and Drew, 1994). One species, *E. toxoneura* (Loew), feeds on sawfly larvae within galls (Kopelke, 1984). According to White and Elson-Harris (1992), the tribe Carpomyini reproduces exclusively in fruits, with most species being highly host-specific.

FRUIT FLY PESTS IN INDIA

One of the problems faced by tephritiditologists in India and Asian countries is the proper identification of fruit fly species (Diptera: Tephritidae). Among the fruit flies, the genus *Bactrocera* and *Zeugodacus* are commonly encountered in parapheromone (methyl eugenol or cue lure) traps. Madhura and Verghese, 2004 present a key that would enable one to easily identify species that usually come into traps. This has quarantine implications also, as it helps to work out the spread or introduction of fruit flies to new areas.

Elucidation of genetic variation in geographical populations can be an important aspect to study the pest populations and their management. Within an ecosystem, the extent of genetic variation between geographical populations depends on several factors, including gene flow between populations, host range and time since separation.

Fruit fly systematics is one of the important fields of applied entomology. Despite the importance of the family, the higher classification of the Tephritidae is still in a fluid state. Years of work by many taxonomists using morphological characters had not yielded adequate resolution of higher classification within the family Tephritidae because of homoplasy of several morphological characters and difficulty involved in identification of immature stages. The first and foremost important step in pest management system is correct identification of the pest. *Bactrocera dorsalis* is a complex with high variability in morphology and behaviour with several cryptic species, yet undetermined by classical taxonomy.

Within an ecosystem, the extent of genetic variation between geographical populations depends on several factors, including gene flow between populations, host range, climatic factors, etc. The genomic DNA was extracted from male flies of *Bactrocera dorsalis* (Hendel) collected from different agro-ecological regions of Karnataka. The percent polymorphism varied from 33.33% to 100% with an average of 71.66%. The Jaccard's similarity coefficients ranged from zero to 0.91. UPGMA dendrogram generated by RAPD data indicated the segregation of populations into three clusters. Genetic diversity plays an important role in the survival and adaptability of a species; therefore, *B. dorsalis* populations of different agro-ecological regions have undergone changes probably to survive or the changes are consequent to interplay (Rashmi *et al.*, 2016).

Oriental fruit fly: *Bactrocera (Bactrocera) dorsalis* Hendel

Diagnosis: Adult: Face yellowish with two separate black spots. Medium sized flies with yellow lateral vittae on black/ reddish brown scutum. Wing with continuous costal band confluent with vein R_{2+3}. All femora yellow without any fuscous/black markings. Abdomen orange red with a prominent T shaped mark (White and Elson-Harris, 1992; Ramani, 1997).

Attractant: Methyl Eugenol

Host plants

Aegle marmelos (L.) Corr. (Bael), *Anacardium occidentale* L. (Cashew), *Artocarpus altilis* (Park.) (Bread fruit), *A.heterophyllus* Lamk.(Jack fruit), *Capsicum fruitescens* L.(Red pepper), *Carissa carandas* L. (Karanda), *Cerbera manghas* L.(Honde fruit), *Chrysophyllum cainitto* L.(Star apple), *Citrus aurantium* L.(Sour orange), *C. grandis* Osbeck. (Pomelo), *C. medica* L.(Citron), *C. nobilis* Lours (Orange), *C.reticulata* Blanco (Mandarin), *Coffea arabica* L. (Arabian coffee), *C. canephora* Pierre ex Froehner (Robusta coffee), *Cydonia oblonga* Mill.(Quince), *Diospyros* sp. (Persimmon), *Eriobotrya japonica* (Thunb.) (Loquat), *Ficus carica* L. (Fig), *F. mysorensis* Heyne, *Litchi chinensis* (Gaertn.) Sonn. (Litchi), *Malus pumila* Mill. (Apple), *Mangifera indica* L. (Mango), *Manilkara achras* (Mill.) (Sapodilla), *Mimusops elengi* L. (Spanish cherry), *Morus australis* Poir. (Common mulberry), *Musa paridisiaca* L. (Banana), *Persea americana* Mill. (Avocado), *Physalis peruviana* L.(Cape gooseberry), *Prunus armeniaca* L. (Apricot), *P avium* L. (Sweet cherry), *P. domestica* L. (Plum) , *P. persica* (L.) (Peach), *Psidium guajava* L. (Guava), *Punica granatum* L. (Pomegranate), *Pyrus communis* L.(Pear), *Rubus fruiticossus* L. (Black berry), *Santalum album* L. (White Sandalwood), *Solanum erianthum* D.Don., *Solanum indicum* L. (Indian night shade), *S. melongena* L. (Egg plant) , *S. torvum* Swartz, *Syzigium cumini* (L.) Skeels (Jamun), *Terminalia catappa* L. (Indian almond), *Zizyphus mauritiana* Lamk. (Jujube/ Ber) (White and Elson-Harris,1992; Kapoor, 1993; Ramani, 1997)

Distribution: Assam, Bihar, Delhi, Himachal Pradesh, Jammu & Kashmir, Kerala, Karnataka Maharashtra, Manipur, Orissa, Punjab, Rajasthan, Sikkim, Tamil Nadu, Uttar Pradesh, West Bengal (Bhat, 1989; Agarwal & Sueyoshi, 2005).

Biology and Ecology

The life cycle of *B. dorsalis* range from 21 to 26 days with an average of 23.5 days. Eggs are laid in clusters of 2 to 9 in half to overripe fruits by making punctures using telescopic ovipositor. Incubation period of eggs range from 24-48 hours with an average of 36 hours. Three larval instars are there, which take 2.16, 4.83 and 5.25 days respectively. Fully matured maggot drop to soil and pupation takes place in soil at a depth of two to ten centimeters with an average of 5.4 cm under field conditions (Belavadi, 1979).

Adults are synovigenic. They were observed to mate after feeding for a few days during evening hours of day. The mating usually starts at dusk and lasted from 35 minutes with an average 1 hour 10 minutes (Belavadi, 1979).

Bactrocera (Bactrocera) carambolae Drew & Hancock

Diagnosis: Face fulvous/ yellow with two oval black spots, scutum predominantly black with broad (>0.15mm) lateral postsutural vittae, fore femur with elongate black spot, mid and hind femur without spots/ markings, wing with costal band overlapping vein R_{2+3} and expanded slightly beyond the apex of $R_{2+3,}$ abdomen orange brown with a prominent T pattern and lateral transverse markings on tergites IV and V.

Attractant: Methyl Eugenol

Host plants: It is known to breed on 75 host plants belonging to 26 families. Ranganath and Veenakumari (1995, 1999) recorded its severe incidence in *Syzygium* spp. in Andamans**;** List of host plants: *Alangium griffithii* (Alangiaceae), *Bouea oppositifolia Mangifera indica* (Anacardiaceae), *Annona montana, Annona muricata, Rollinia pulchrinervis*, *Uvaria grandiflora* (Annonaceae), *Thevetia peruviana* (Apocyanaceae), *Argena pinnata* (Arecaceae), *Garcinia atroviridis, Garcinia cowa,* *Garcinia griffithii, Garcinia mangostana* (Clusiaceae), *Terminalia catappa, Terminalia catappa, Terminalia manii, Terminalia procera* (Combretaceae), *Baccaurea motleyana, Drypetes longifolia* (Euphorbiaceae), *Persea americana* (Lauraceae), *Fagraea ceilanica* (Loganiaceae), *Aglaia dookoo, Lansium domesticum, Sandoricum koetjape* (Meliaceae), *Artocarpus altilis, Artocarpus comeziana, Artocarpus elastia, Artocarpus heterophyllus, Artocarpus integer, Artocarpus lakoocha, Artocarpus odoratissimus, Artocarpus rigidus* var. *asperulus, Ficus grossularioides, Ficus hispida, Pouroma paefolia* (Moraceae), *Knema angustifolia* (Myristaceae), *Eugenia uniflora, Psidium cattleianum, Psidium guajava, Rhodomyrtus tomentosa, Syzygium aqueum, Syzygium grande, Syzygium jambos, Syzygium malaccense, Syzygium samarangense* (Myrtaceae), *Ochanostachys amentosa* (Olacaceae), *Averrhoa bilimbi, Averrhoa carambola* (Oxalidaceae), *Xanthophyllum amoenum* (Polygalaceae), *Punica grandum* (Punicaceae), *Ziziphus jujuba* (Rhamnaceae), *Pellacalyx saccardianus, Rhizophora* sp. (Rhizophoraceae), *Citrofortunella mitis, Citrus aurantifolia, Citrus limon, Citrus madurensis, Citrus paradisi, Citrus reticulata, Fortunella margarita, Fortunella polyandia, Paramignya andamanica, Tetractomia majus, Triphasia trifoloia* (Rutaceae), *Lepisanthes alata* (Sapindaceae), *Chrysophyllum cainito, Manilkara littoralis, Manilkara zapota, Mimusops elengi, Planchonella longipetiolatum, Pouteria campechiana* (Sapotaceae), *Irvingia malayana* (Simaroubaceae), *Capsicum annum, Lycopersicon esculentum, Solanum ferox* (Solanaceae), *Symplocos cochinchinensis* (Symplocaceae) (Allwood *et al.*, 1999)

Distribution: Peninsular Malaysia, Malaysia, Indonesia, Singapore, Thailand, Borneo, India (Andaman Islands); French Guiana, Surinam, Vietnam (Drew & Hancock, 1994; Drew and Romig, 2016), Bangladesh (Leblanc *et al.*, 2019). It was originally described from Malaysia in 1994 by Drew and Hancock. Ranganath and Veenakumari (1995, 1999) reported the occurrence of *B. carambolae* in Andaman Islands, India. Hence this pest cannot be considered as an invasive species to India, as it has been already reported from Andaman Islands. Even though it has been recorded from Andaman Islands, so far, no *B. carambolae* were encountered in mainland India.

Guava fruit fly: *Bactrocera (Bactrocera) correcta* (Bezzi)

Diagnosis: Adults are medium-sized with scutum black in colour with broad lateral vittae (>0.15 mm). Wing with a costal band discontinuous beyond vein R_1, sometimes faint with a narrow apical spot. Abdomen reddish brown with a prominent T shaped mark. This species is characterized by the presence of facial spots coalescing to form a transverse line (White and Elson-Harris, 1992, Ramani, 1997).

Attractant: Methyl Eugenol

Host plants

Carrisa carandas L.,*Casimiroa edulis* Llave & Lex, *Eugenia uniflora* L., *Mangifera indica* L , *Malphigia glabra* L., *Prunus armeniaca* L. *Santalum album* L., *Vitis vinifera* L., *Zizyphus mauritiana* Lam. (Kapoor,1993; Ramani, 1997).

Distribution: Bihar, Gujarat, Haryana, Himachal Pradesh, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Punjab, Tamil Nadu (Bhat, 1989; Agarwal & Sueyoshi, 2005).

Peach fruit fly: *Bactrocera (Bactrocera) zonata* (Saunders)

Diagnosis: Pale orange brown to red species with lateral postsutural yellow vittae on scutum, circular to oval facial spots, anterior supra-alar setae, prescutellar setae, 2 scutellar setae present. Wing with discontinuous costal band to form a spot apically. Abdomen reddish brown with pecten on third tergum of males (Ramani, 1997; White and Elson-Harris, 1992)

Attractant: Methyl Eugenol

Host plants: *Aegle marmelos* (L.) Corr. Serr., *Anona squamosa* L.,*Careya arborea* Roxb., *Casimiroa edulis* Llave & Lex, *Citrus aurantium* L., *C.grandis* Osbeck., *C.limon* (L.) Burman f., *C.medica* L., *C.nobilis* Lours, *C.reticulata* Blanco., *C.sinensis* (L.), *Cucumis melo* L., *Diospyros blancoi* A.DC, *Ficus carica* L., *Lagenaria siceraria* (Mol.) Standl., *Luffa acutangula*L(Roxb.), *Luffa aegyptica* Mill., *Lycopersicum esculentum*(L.) Karst., *Malphigia glabra* L., *Mangifera indica* L. , *Prunus persica* (L.) Batsch., *Psidium guajava* L., *Punica granatum* L. , *Pyrus communis* L., *Solanum melongena* L., *Syzigium cumini* (L.) Skeels., *S. jambos* (L.) Alston., *Terminalia catappa* L., *Zizyphus mauritiana* Lamk.(Kapoor, 1993; Ramani, 1997).

Distribution: Andhra Pradesh, Assam, Bihar, Delhi, Gujarat, Haryana, Himachal Pradesh, Punjab, Karnataka, Kerala, Madhya Pradesh, Maharashtra , Tamil Nadu, Uttaranchal, Uttar Pradesh, West Bengal (Agarwal & Sueyoshi, 2005).

Zeugodacus (Hemigymnodacus) diversus Coquillett

Morphology: Adult: Small to medium sized fly, with greenish black body with both lateral and medial vittae on the thorax. Wings with costal band confluent with $R_{2+3.}$ Males lack pecten on 3rd abdominal tergite. Sexual dimorphism is seen in this species. Face of male entirely yellow, without facial spots, face of female with a transverse black line above the mouth opening (Ramani, 1997; White and Elson-Harris, 1992).

Attractant: Methyl Eugenol

Host plants: *Benincasa hispida* (Thunb.) Cogn., *Luffa aegyptica* Mill. , *Citrus aurantium* L., *C.grandis* Osbeck., *Coccinia grandis* L. Voigt., *Cucurbita maxima* Duch. , *Cucurbita pepo* L.,*Lageneria siceraria*(Mol.) Standl.,*Musa paradisica* L., *Psidium guajava* L., *Syzygium cumini*(L.) Skeels.,*S.malaccense* (L.) Merr. & Perr., *Solanum erianthum* D.Don., *Mangifera indica* L., *Myristica beddomei* King, *M.fragrans* Houtt., *Citrus aurantium* L. (Kapoor,1993)

Distribution: Andhra Pradesh, Bihar, Himachal Pradesh, Karnataka Maharashtra, Meghalaya, Punjab,Tamil Nadu, Uttaranchal, Uttar Pradesh, West Bengal (Bhat, 1989; Agarwal & Sueyoshi, 2005).

Nature of damage: The female flies lay eggs at the base of the flower and flower buds, nearer to the ovary. In opened flowers, the flies may lay eggs directly into the ovary. The larvae on hatching feed on the reproductive organs of flower. The affected flowers become unfit for pollination or fruit setting and subsequently drop off and rot (Gavigowda, 1976).

Melon fly: *Zeugodacus* (*Zeugodacus*) *cucurbitae* (Coquillett)

Diagnosis: A predominantly orange-brown species with separate black spots on fulvous face. Scutum with yellow medial and lateral postsutural vittae, wing is characterized by the presence of broad costal band expanded into an apical spot, with radial medial band and subapical band.

Attractant: Cuelure

Host plants

It is a highly polyphagous pest with wide host range. *Benincasa hispida* (Thunb.) Cogn., *Capsicum fruitescens* L., *Careya arborea* Roxb., *Coccinia grandis* L. Voigt,*Cucumis melo* L., *C. sativus* L., *Momordica charantia* L.,*Momordica dioica* Roxb.ex Wild, *Mukia maderaspatana* (L.) M. Roem., *Trichosanthes cucumerina* L., *T.dioica* (L.), *Luffa* spp, *Citrus* spp, *Psidium guajava* L., *Carica papaya* L. (Kapoor,1993; Ramani, 1997) are list of few host plants infested by *Z. cucurbitae*.

Distribution: Widespread in India (Agarwal & Sueyoshi, 2005).

Biology and ecology

The adult female inserts their eggs singly or in clusters of 4-10 beneath the skin of suitable hosts, especially in tender vegetables. Incubation period ranges from 27-28 hours during August and 31-38 hours during May (Back & Pemberton, 1914). Narayanan and Batra (1960) reported 24 hours and 6-9 days as duration of eggs in summer and winter, respectively. There are three larval instars, which span for 1.2, 1.58 and 2.25 days respectively and the total larval duration is 5-6 days at mean temperature of 25.72^{0}C. However, the larval duration varies with the host plant and season. Puparium is formed out of the third larval skin; pupation takes place in soil and the pupal period ranges from 8 to 10 days. Adult life may vary based upon the nutrition, if given water only, life is prolonged to 3 days, with sucrose, the flies survived for 17 days, with sucrose and water, up to 32 days (Gavigowda, 1976).

***Dacus* (*Didacus*) *ciliatus* Loew**

Integrated pest management

Fruit flies, specifically *Bactrocera* spp and *Zeugodacus cucurbitae*, pose significant threats to various fruit crops such as mango, guava, custard apple, dragon fruit, sapota, and others. *Zeugodacus cucurbitae* is particularly problematic for cucurbitaceous crops and tomatoes. Effective management strategies for fruit flies, particularly *Bactrocera* spp. and *Zeugodacus cucurbitae*, involve an integrated approach combining several methods. Key strategies include field sanitation to remove infested fruits and reduce breeding sites, and the use of protein bait sprays and pheromone traps (e.g., methyl eugenol for *Bactrocera* spp. and cue-lure for *Z. cucurbitae*) to attract and kill adult flies (Sivinski *et al.*, 2018). Additionally, bagging fruits can physically prevent oviposition, while early harvesting can reduce the window of vulnerability.

Verghese and Rashmi 2022 Evaluated the potential of Plant Health Clinics (PHCs) as a model for disseminating biocontrol products to farmers. The study finds that PHCs can effectively bridge the gap between research and practice, facilitating the adoption of biocontrol methods and enhancing pest management in horticultural crops.

Plant Health Clinics (PHCs) are pivotal in the implementation of Integrated Pest Management (IPM) strategies, especially in horticultural crops. Here's how they contribute:

- **Diagnosis and advisory services**: PHCs provide accurate diagnosis of pest and disease problems in crops. By identifying the specific pests or pathogens affecting the plants, they can recommend targeted and effective IPM strategies. This helps in reducing the indiscriminate use of pesticides and promotes the use of environmentally friendly control methods.

- **Promotion of biocontrol products**: PHCs play a crucial role in promoting the use of biocontrol agents and products. They educate farmers about the benefits of using natural predators, parasitoids, and microbial pesticides, which are integral components of IPM. This not only helps in managing pest populations sustainably but also reduces the reliance on chemical pesticides.
- **Training and capacity building**: PHCs conduct regular training programs and workshops for farmers, extension workers, and other stakeholders. These programs focus on the principles and practices of IPM, including the use of cultural, biological, and mechanical control methods. By building the capacity of farmers, PHCs ensure that IPM practices are effectively implemented at the field level.
- **Monitoring and surveillance**: PHCs are involved in the regular monitoring and surveillance of pest populations. They collect data on pest incidence and severity, which helps in predicting pest outbreaks and implementing timely control measures. This proactive approach is essential for the success of IPM programs.
- **Extension and Outreach**: PHCs serve as a bridge between research institutions and farmers. They disseminate the latest research findings and IPM technologies to the farming community. This ensures that farmers have access to up-to-date information and can adopt the best practices for pest management.
- **Customized Solutions**: PHCs provide customized pest management solutions based on the specific needs and conditions of individual farms. This personalized approach ensures that IPM strategies are tailored to the local agro-ecological conditions, making them more effective and sustainable (Verghese *et al*., 2021).

In summary, Plant Health Clinics are instrumental in promoting sustainable pest management practices through the implementation of IPM. They provide essential services that help farmers manage pests effectively while minimizing the environmental impact and ensuring food safety (Verghese and Rashmi, 2022).

Integrated Pest Management Strategies

Integrated Pest Management (IPM) strategies are crucial for managing fruit flies, particularly *Bactrocera* spp. and *Zeugodacus cucurbitae*. These strategies include cultural practices such as field sanitation, which involves removing infested fruits to reduce breeding sites. Protein bait sprays and pheromone traps, such as methyl eugenol for *Bactrocera* spp. and cue-lure for *Z. cucurbitae*, are effective in attracting and killing adult flies (Vargas *et al*., 2015). Additionally, bagging fruits and early harvesting can prevent oviposition and reduce the window of vulnerability (Dhillon *et al*., 2005).

Biological control

Biological control agents play a significant role in managing fruit fly populations. Parasitoids and entomopathogenic fungi are commonly used to target various life stages of the flies. For instance, augmentative releases of parasitoids like *Fopius arisanus* have shown promising results in controlling *Bactrocera* spp. (Sivinski *et al*., 2018). The use of entomopathogenic fungi, such as *Metarhizium anisopliae*, has also been effective in reducing fruit fly populations (Nair *et al*., 2022).

Chemical control

Chemical control methods, including the use of selective insecticides, are often integrated with other management strategies to enhance effectiveness. Reduced-risk insecticides, such as Spinosad and neem-based products, are preferred due to their lower environmental impact and safety for non-target organisms (Dhillon *et al*., 2005). These insecticides can be used in bait sprays or as part of a broader IPM program to manage fruit fly populations effectively (Verghese *et al*., 2002).

Host plant resistance

The development and use of resistant cultivars is another important strategy in managing fruit flies. Resistant cultivars can significantly reduce the incidence of fruit fly infestations. Research has shown that certain cultivars of cucurbits exhibit resistance to *Z. cucurbitae*, thereby reducing the need for chemical interventions (Nair *et al*., 2022). This approach not only helps in managing fruit fly populations but also promotes sustainable agricultural practices.

Phytophagous insects use chemical cues emanating from plants to orient to their food hosts while plants ward off herbivory again through use of chemicals. This interplay between chemicals is an interesting area of chemical ecology. Secondary metabolites that occur constituently in plants act as chemical barriers to insects and many protect plants against attack by a wide range of potential pests (Verghese *et al*., 2012)

The changing cycles of tannin according to varieties and time is an index of infestation of fruits. The defensive mechanism exhibited by the tannins in resistant varieties is evident from the results and confirmed through regression. The signal start by Langra and EC 95862 via., tannins may therefore deter females from ovipositing. If commercial varieties like Alphonso and Banganpalli have to be made resistant to fruit flies the peels need to be augmented with tannins with modern breeding tools or gene transfers. From the knowledge of the present studies, semiochemical lures, attractants and repellents can be developed for tephritids and future research should not only continue the mix of basic and applied research on fruit flies but also explore multimodal communication systems such as sound, vision and gustation in order to improve the application of chemical ecology to solve real-world pest problems (Rashmi *et al.*, 2020).

A push-pull strategy for the management of the Oriental fruit fly, *Bactrocera dorsalis (*Hendel) in mango explores the effectiveness of a push-pull strategy in managing *Bactrocera dorsalis*. The study shows that combining repellent plants (push) with attractant-baited traps (pull) significantly reduces fruit fly infestations in mango orchards, offering an environmentally friendly and sustainable pest management approach (Verghese *et al.*, 2020).

The effectiveness of a push-pull strategy to manage the Oriental fruit fly, *Bactrocera dorsalis*, in mango orchards. The push component involves the application of azadirachtin, a neem-based pesticide, on mango trees during the fruiting stage to repel female fruit flies. The pull component uses methyl eugenol traps to attract and capture male fruit flies. The combined approach significantly reduces fruit fly infestations, offering an environmentally friendly and sustainable pest management solution (Verghese *et al.*, 2020).

Sterile Insect Technique (SIT)

The Sterile Insect Technique (SIT) is a widely used method in wide-area management programs. This technique involves the mass-rearing and sterilization of male fruit flies, which are then released into the wild. When these sterile males mate with wild females, no offspring are produced, leading to a gradual reduction in the fruit fly population. The SIT has been successfully implemented in various regions, including Hawaii and the Mediterranean, to control *Bactrocera* spp. populations (Vargas *et al.*, 2015; Dhillon *et al.*, 2005). The Sterile Insect Technique (SIT) is an effective, species specific and environment friendly approach to achieve area-wide management of insect pests and has been successfully applied against several species of fruit flies like *Ceratitis capitata* Wied, *Anastrepha ludens* Loew and *Bactrocera* spp. in different countries. It involves releasing a large number of specially reared and sterilized male insects into the target area where they mate with wild females of same species resulting in failure of off-spring production thus gradually bringing down the pest population.

The SIT was conceived by Knipling in 1955 and was used to successfully eradicate the NewWorld Screwworm, *Cochliomyia hominivorax* Coquerel, a cattle pest, from North and Central America. This can be used in a wide range of situations either for prevention of establishment of new pests or to suppress or eradicate the existing pests. Use of SIT resulted in an enormous growth in the export of fresh fruits and vegetables in Mexico, Chile, South Africa, USA etc. (Rami Reddy and Rashmi, 2016).

Area-Wide Integrated Pest Management (AW-IPM)

Area-Wide Integrated Pest Management (AW-IPM) programs combine multiple control strategies over large geographic areas to manage fruit fly populations effectively. These programs often include the use of SIT, biological control agents, bait sprays, and cultural practices. For example, the Hawaii Area-Wide IPM program (HAWPM) integrated these methods over a 10-year period, significantly reducing fruit fly populations and damage (Vargas *et al.*, 2015). Similarly, the Regional Fruit Fly Project in the Pacific targeted *Bactrocera* fruit flies in Pacific Island Countries and Territories, demonstrating the effectiveness of AW-IPM strategies (Vargas *et al.*, 2015).

The localized eradication of the mango stone weevil, *Sternochetus mangiferae*, a significant pest in mango production by implementation of targeted control measures, following IPM including the use of strategic pesticide applications, to effectively reduce weevil populations in specific regions. The results demonstrated that these localized interventions significantly mitigated weevil infestations, thereby protecting mango yields and improving fruit quality. The findings underscored the importance of adopting precise and region-specific pest management strategies to enhance the sustainability and productivity of mango orchards in India (Verghese *et al.*, 2023).

Use of entomopathogenic fungi

Entomopathogenic fungi, such as *Metarhizium anisopliae* and *Beauveria bassiana*, have been explored as biological control agents in wide-area management programs. These fungi infect and kill fruit flies, providing a natural and environmentally friendly control method. Studies have shown that these fungi can be effectively integrated into AW-IPM programs to suppress fruit fly populations (Gutiérrez, 2010).

Geographical Information Systems (GIS)

Geographical Information Systems (GIS) are increasingly being used in wide-area management programs to monitor and manage fruit fly populations. GIS technology allows for the mapping and analysis of fruit fly distribution and population dynamics, enabling more targeted and efficient control measures. This technology has been particularly useful in large-scale eradication programs, such as those implemented in Australia and the United States (Dhillon *et al.*, 2005).

Previously, the Indian Institute of Horticultural Research (IIHR) in Bangalore developed cost-effective integrated pest management (IPM) strategies (Verghese *et al.*, 2002). However, there is now an urgent need to phase out traps using insecticide-laced plywood or other substrates due to concerns about high residuals, environmental pollution, and impacts on non-target organisms, especially ants. The strategy of male annihilation for fruit flies is no longer effective in most fruit ecosystems, debunking the myth that "more flies in traps mean more control." This approach remains somewhat valid in vegetable ecosystems where fruit fly densities are typically low. Parapheromone lures should be reserved for fruit fly surveillance and diversity assessment, as sticky traps are unsuitable for identification in diversity studies. Young males do not respond well to Methyl eugenol (ME) combined with insecticides, making male annihilation unsatisfactory. Frank Milburn Howlett (1877-1920): Discoverer of the pied piper's lure for the fruit flies (Tephritidae: Diptera)" by Verghese *et al.* (2013) provides a historical account of Frank Milburn Howlett's groundbreaking discovery of methyl eugenol as an attractant for male tephritid fruit flies.

The IPM of fruit flies has been significantly improved by Rashvee International Phytosanitary and Research Services (RIPRS), recognized by the Government of India and DPPQ. Under a BIRAC, DBT program, an insecticide-free liquid lure fruit fly trap, ovipositional deterrence spray, and phagostimulant baits were developed. These innovations align with updated export protocols and Good Agricultural Practices. The key components of Integrated Fruit Fly Management are as follows:

Sanitation: Collect fallen fruits into small manure pits (3ft x 3ft x 3ft), wet them, and close the pits after harvest. This practice, recommended at one pit per tree, attracts older females and prevents pupation and subsequent adult emergence by collecting infested fruits with maggots.

Non-insecticidal liquid lure: Introduce a climate-resilient, anti-evaporant liquid lure (Rashvee fruit fly liquid lure) instead of plywood or other substrate traps. Use 5ml of the lure per 100ml of water in disposable water bottles. These traps, designed to withstand high wind, rainfall, and temperature, should be used at a minimum of 8-10 traps per acre for mango and 15 traps per acre for cucurbits. For fruit crops, use the Rashvee fruit fly liquid ME lure. Fasten traps on lower branches, between 2 meters in height, at least marble-sized fruits, or 30 days prior to harvest.

Trap superiority: The liquid traps have been found superior to commercial traps in attracting diverse species of fruit flies, as studied by ICAR-NBAIR.

Placement geometry: Follow the RIPRS placement geometry for optimal results.

Female fruit fly deterrence: Based on trap surveillance data, further control can be achieved by applying 2-3 pre-harvest sprays of 1ml Azadirachtin 10000 ppm synergized with 1ml Rashvee Herbal Liquid Soap as an adjuvant, 30 days prior to harvest, to deter oviposition.

High trap catches: If trap catches are high (15 per day), a single spray of 0.37 ml/litre Spinosad 20 days prior to harvest is recommended.

Phagostimulant Bait: Rashvee Phagostimulant Bait, splashed at the base of the tree, attracts and kills both male and female fruit flies.

Bait preparation: Prepare the bait by mixing 20 litres of water with 1 kg of phagostimulant bait, leaving it overnight covered. The next day, add 40 ml of Decamethrin, stir well, and splash it at the base of the tree using an old brush. This can be done 10 days before harvest and repeated 5 days before harvest.

Post-harvest technology encompasses a range of techniques and practices aimed at preserving the quality and extending the shelf life of agricultural products from the moment of harvest until they reach the consumer. It plays a crucial role in reducing food loss, ensuring food security, and enhancing the economic value of crops by maintaining their quality and safety.

Key methods include Hot Water Treatment (HWT), where mangoes are immersed in hot water to kill pests without damaging the fruit, and Vapor Heat Treatment (VHT), which uses hot, humid air to achieve similar results. Cold Treatment involves storing mangoes at low temperatures to control pests and extend shelf life. Irradiation exposes mangoes to ionizing radiation to sterilize pests, ensuring the fruit meets international quarantine standards. Edible Coatings, such as chitosan or aloe vera, form a protective barrier on the fruit, reducing moisture loss and delaying ripening. Modified Atmosphere Packaging (MAP) alters the atmospheric composition around the fruit to slow down respiration and ripening processes. These technologies are crucial for maintaining the quality, safety, and marketability of mangoes, ensuring they meet both domestic and international standards (Verghese & Rashmi, 2014).

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