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Tephritid fruit flies in Himachal Pradesh: diversity and management

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Abstract

Fruit flies belong to family Tephritidae and are most devastating pests of agriculture causing extensive damage directly or indirectly. In Himachal Pradesh, tephritid fauna include several economically important species of fruit flies, which have their own economical impact on the production of fruits and vegetable. Management of fruit flies to minimize losses can be done effectively after understanding their host range, population dynamics and seasonal abundance. Effort has been made in the present manuscript to highlight the status of fruit flies in Himachal Pradesh, their host range, population dynamics, economic losses, new vistas of management, trade restrictions, as well as post-harvest losses. The dynamics of population fluctuations, seasonal abundance, and multivoltinism have also been discussed in brief to understand their influence on management strategies. Effective management practices especially the male annihilation technique (MAT) and the role of endosymbionts as potential future management options solutions has been discussed.

Keywords: Endosymbionts, host range, multivoltinism, population dynamics, seasonal abundance, Tephritidae

Fruits and vegetables are attacked by a variety of insect pests, of which tephritid fruit flies are of utmost economic importance. This family is highly diverse and consists of over 5000 species in more than 500 genera (Scolaris *et al.* 2021), spread globally in tropical and sub tropical regions of the world (Allwood *et al.* 2001). These are ranked among world's most consequential pests of horticultural crops (Agarwal and Sueyoshi 2005) as maggots are known to feed internally on fruit pulp which predispose the host to secondary microbial infections and cause rotting and pre-mature dropping of fruits. Damage is usually identified at earlier stage when golden liquid ooze out of the ovipositional punctures. They impose damage on a variety of economically important vegetable crops, among which most affected are cucumber, sweet melon, sweet pepper, pumpkin, sponge cucumber, wax apple and tomato etc. (Wang *et al.* 2006; Clarke 2019). In India several species of tephritid fruit flies are present in the lower and mid hills of the Himalayan region, each with its unique ecological preference and impact on the local agricultural landscape. The Himalayan region is home to a diverse array of tephritid fruit fly species, with the genus *Bactrocera* being particularly dominant (Nugnes *et al.* 2018).

Himachal Pradesh situated between 32.1024° N longitude, 77.5619° E latitude with altitude range of 350 to 6975 m above sea level is an important producer of fruits and vegetables and fruit flies are reported to cause extensive economic damage to these crops (Gupta *et al.* 1992; Sood *et al.* 2010). The state is an important fruit producer and famous for quality fruits especially apples. However, the reports of incidence of *B. dorsalis* in apple and other fruits like pomegranate, kiwi fruit etc. in Himachal Pradesh (Gupta *et al.* 2013) was a matter of serious concern as this pest can potentially lead to substantial economic losses and

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affect livelihood security. Assessing the pest status of fruit flies is hence crucial owing to their significant economic impact on fruit production and trade.

Diversity and Distribution

In India, particularly nine tephritid species *viz.* melon fly, *Bactrocera cucurbitae;* oriental fruit fly, *B. dorsalis;* peach fruit fly, *B. zonata;* pumpkin fruit fly, *B. tau;* guava fruit fly, *B. correcta;* lesser pumpkin fly, *Dacus ciliatus*; ber fly, *Carpomyia vesuviana* and seed fly, *Acanthiophilus helianthi* are the major and economically important species. Fruit flies are also well spread across the districts of Himachal Pradesh and have been reported from 10 districts including Chamba, Hamirpur, Shimla, Una, Kangra, Mandi, Kullu, Sirmaur, Solan and Bilaspur (Prabhakar *et al.* 2012; Singh *et al.* 2023). Of 244 recognized tephritid species in 79 genera, reported from India, 47 species from 27 genera have been reported from Himachal Pradesh (Laskar *et al.* 2016). In a survey conducted in Himachal Pradesh, *B. latifrons, B. nigrofemoralis, B. dorsalis, B. zonata, B. diversa, B. cucurbitae, B. scutellaris, B. tau, Dacus longicornis, D. sphaeroidalis, Cyrtostola limbata, Pliomelaena uhampurensis* and *Dioxyna sorocula* were reported from 8 districts (Prabhakar *et al.* 2012). These species are native to tropical Asia, Australia and South Pacific regions while some species are also reported from some areas of African and European continents. *Acidoxantha* species was reported in 2019 from Himachal Pradesh (Sharma *et al.* 2019). Recently five new species *viz. Bactrocera divendri, B. watersi, B. zahadi, B. prabhakari* and *Z. sinuvittatus* were added to the fruit fly fauna of Himachal Pradesh (Prabhakar 2022; Singh *et al.* 2023; David *et al.* 2024). Hence continuous sustained efforts are required to identify the fruit fly fauna of the state in near future to understand their diversity.

Host range and preferences

Host plants have been reported as the most important environmental component affecting populations of various tephritid species (Ye and Liu 2007; Vayssieres *et al.* 2009). These are active throughout the year and their peak activity in Himachal Pradesh is observed from April to September. The most significant fruit fly species in Himachal Pradesh include *B. cucurbitae, B. tau, B. scutellaris, B. dorsalis* and *B. divendri* (Nitika *et al.* 2023). *B. tau* in particular is the most important pest of fruits and vegetables and it can attack more than 50 cultivated as well as wild plant species of families *viz*. Anacardiaceae, Cucurbitaceae, Elaeocarpaceae Moraceae Myrtaceae, Oxaalidaceae, Rutaceae, Sapotaceae and Solanaceae (Prabhakar *et al.* 2013; Huque 2005). More than 90 per cent area in state is predominantly characterized by hills and high mountains, however, activity of *B. tau* is most significant in low to mid hills of state, while being absent in high altitude regions (Prabhakar *et al.* 2013). *B. dorsalis* infestation is found on Papaya, peach, guava, mango, tomato, brinjal and cucurbits with mango being the most preferred host (Ye and Liu 2005; Verghese *et al.* 2011). *B. dorsalis* is known to cause extensive damage in late maturing varieties of mango (Singh *et al.* 2013a) and its peak incidence is observed during month of August-September, when the tomato and cucurbits season is towards the end with ripened and ripening fruits being highly favourable for fruit flies. Another serious tephritid species infesting cucurbits and causing heavy damage is melon fruit fly, *B. cucurbitae.* It is of Indian origin and has been established in over 40 countries (Hadapad *et al*. 2015). It has a wide range of 125 host plants and can cause damage from 40 to 89 per cent (Gupta *et al.* 1990). *B. tau and B. cucurbitae* have been reported as pests of regular occurrence in cucurbits and tomato fields in mid hills of Himachal Pradesh. Earlier *B. cucurbitae* was recognized as predominant species infesting cucurbit vegetables in Himachal Pradesh but now *B. tau* has become predominant in cucurbit growing areas of Kangra, Palampur, Solan and Una respectively (Prabhakar *et al.* 2009).

The third most important tephritid species of Himachal Pradesh is *B. scutellaris.* It has been reported from Solan, Una, Bilaspur, Kangra and Mandi district of Himachal Pradesh (Prabhakar *et al.* 2012) and found feeding on flowers of bottlegourd and pumpkin (Sunandita and Gupta 2007; Singh *et al.* 2013b). Additionally, *B. zonata* has also been reported on various fruit crops, causing serious losses to stone fruits, guava and mango in the state (Gupta *et al.* 1990; Singh *et al.* 2013a). In North Western Himalayas, it is found during April to October with peak occurrence in

July. It infests cucurbits, especially summer squash, citrus and ber fruits in April. Its peak occurrence correlates with the presence of papaya, peach, guava and mango in July. It is reported to be more dominant than *B. dorsalis* on brinjal, and their populations reduce drastically as the brinjal crop is over. (Stanley *et al.* 2015). These two tephritid species (*B. dorsalis* and *B. zonata*) are also serious pests of mango in Himachal Pradesh (Singh *et al.* 2013a). The guava fruit fly, *B. correcta*, is another destructive species that primarily targets guava, a popular fruit crop in the Himalayan foothills. A brief account of predominant fruit fly species, locations, and their host range has been presented in Table 1.

Economic losses

Fruit flies cause substantial economic damage to fruits and vegetable production globally attacking a wide range of crops and resulting in qualitative and quantitative losses. Adult fruit flies lay eggs inside the fruit so that their progeny can feed on the pulp. Damage is caused both by adults and maggots of fruit flies as the adult females puncture the rind of the fruits for oviposition, which also exposes the fruits to secondary infections as the wound on fruit acts as the point of entry for microbes, which causes the fruit to decay, ultimately leading to premature fruit drop and significant quantitative losses. Oviposition also results in deformation of fruits, which decline their qualitative value considerably and make them unmarketable. However, main damage to the infested fruit is caused by fruit fly maggots, which remain protected under the rind of fruit feeding on the pulp inside. This also helps maggots to escape the chemicals applied for their management and renders them out of the reach of predators and other natural enemies. In response to this, farmers usually apply excessive chemicals in hope of managing this pest, which in return result in increased cost of production and decreased monetary returns apart from high pesticide residues in fruits/ vegetables. These facts make fruit fly management a burdensome job for the growers.

- **Direct production losses:** Due to its polyphagous nature and high fecundity, fruit flies can cause 30 to 100 per cent economic losses depending upon the crop and the season (Dhillon *et al.* 2005). The total damage caused by fruit flies exceeds US$ 2 billion every year (Shelly *et al.* 2014). Annual losses in the eastern Mediterranean due to tephritid infestation are estimated at US$ 192 million (Mumford 2001). It has

Table 1. Host range and locations of occurrence of predominant fruit fly species in Himachal Pradesh

Species	Location	Hosts and losses	References
B.tau	Bilaspur, Chamba, Hamirpur, Kangra, Solan, Mandi, Kullu, Una, Sirmaur and Shimla	Anacardiaceae, Cucurbitaceae, Elaeocarpaceae Moraceae Myrtaceae, Oxaalidaceae, Rutaceae, Sapotaceae and Solanaceae (Upto 80% losses)	Prabhakar *et al*. (2012); Singh *et al*. (2023)
B.cucurbitae	Bilaspur, Hamirpur, Kangra, Mandi, Solan, Una	Cucurbitaceous plants (upto 40-89%)	Prabhakar *et al*. (2012)
B. dorsalis	Kangra	Stone fruits, Guava, Mango, Papaya, peach, mango, tomato, brinjal and cucurbits (Upto 80%)	Prabhakar *et al*. (2012)
B. latifrons	Kangra	Solanaceous, cucurbitaceous. (60-80% Losses)	Mziray *et al*. (2010)
B. scutellaris	Solan, Una, Bilaspur, Kangra and Mandi	Cucurbitaceous plants (13-40% losses)	Prabhakar *et al*. (2012); Kumar (2021); Singh *et al*. (2023)
B. zonata	Kangra , Bilaspur	Cucurbits, ber, citrus, papaya, peach, guava and mango (25-100%)	Gupta *et al*. (1990); Prabakar *et al*. (2012); Stanley *et al*. (2015)

been correctly said by Dowell and Wagne (1986) that establishment of fruit flies in California can result in losses upto US$ 910 million yearly to the fruit industry and an eradication program would cost about US$ 290 million. Fruit flies can cause annual estimated damage to the tune of US$ 855.40 million (Prabhakar *et al.* 2009), hence these pest species have been identified as one of the ten most destructive pests of agriculture in India. *B. tau* is one of the most important pests of Tephritidae family which is reported to cause upto 80 per cent damage in vegetable crops (Prabhakar *et al.* 2009; Sood *et al.* 2010). The melon fly, *B. cucurbitae* causes infestation to the extent of 77.03, 75.65, 73.83 and 63.31 per cent in bitter gourd, ridge gourd, cucumber and pickling cucumber, respectively (Kumar *et al.* 2006). The fruit infestation of 31.3 and 28.6 per cent was recorded in bitter gourd and water melon, respectively in India due to this tephritid species (Singh *et al.* 2000). Cucurbits are one of the most seriously affected crops by fruit flies resulting in damage to the tune of more than 50 per cent. A study conducted at Assam revealed that yield losses in untreated cucumber plots can go upto 1087.91 kg/ha with 47 per cent avoidable yield losses (Ganesh *et al.* 2023). *B. zonata* is a pest native to South East Asia and damage caused by this pest can reach upto 100 per cent if not controlled (Jena *et al.* 2022). Himachal Pradesh is an important producer of fruits and vegetables and fruit flies are reported to cause damage ranging from 72 to 80 per cent in various fruits (Gupta *et al.* 1992; Sood *et al.* 2010). Temperate fruits such as apples, pears, peaches and plums are also reported to be severely affected by fruit flies. The losses caused by fruit flies in state are more significant as the infestation in apple can reach upto 30-40 per cent and in peaches and plums, it can be as high as 60-70 per cent (Boopathi *et al.* 2017).

- **Increased management costs:** The economic impact of tephritid flies extends beyond direct yield losses, as farmers incur additional expenses for their management, which often involves application of excessive insecticides due to their low efficacy on fruit flies, which also raise concerns about the safety of the produce. Although monitoring and trapping of fruit flies can be done by employing a low cost Palam fruit fly trap developed at CSK HPKV, Palampur, however, a comprehensive management programme needs to be followed for effective management of the pest.

- **Trade restrictions and post harvest losses:** International movement of trade and passenger baggage has been the principal pathways for tephritid invasions. Plant protectionists and quarantine personnel consider tephritid flies as one of the most serious pests of horticultural produce and trade. The presence of fruit flies in agricultural produce can lead to trade restriction as the countries with strict bio-security measures often impose ban on import of produce from regions where fruit flies are prevalent. Quarantine restrictions imposed by importing countries result in economic losses overseas and within the country markets. These restrictions impose significant costs on the government and horticultural industries not only because of rejected produce but also due to the expenses associated with quarantine monitoring and regulatory inspections aimed at ensuring safety (Allwood and Leblanc 1997). International standards set by organizations such as the International Plant Protection Convention (IPPC) is essential for maintaining trade relationships as quarantine measures help ensuring the phytosanitary requirements of importing countries, thus facilitating the export of horticultural products. Fruit flies are responsible for the most restrictions on agricultural produce movement than any other pest as they can easily be transported along with different infested commodities. These tephritid flies are so devastating that quarantine restrictions/checks have been employed in various parts of the world. The European Union and United States have imposed restriction on import of fruits from countries with reported fruit fly incidence, and fruits from such countries are only accepted after strict inspection (Dhami *et al.* 2016). After fruit flies were detected in 207 consignments, during 2014, the European Union banned import of mangoes and some vegetables from India (Verghese *et al*. 2024). The outbreak of *B. dorsalis* in Florida during 2015-16 resulted in losses of millions of US dollars to fruit production sector (Stonehouse 1998). Likewise, interception of medfly *Ceratits capitata* infested commodities in US in 2001 resulted in a ban on imports from Spain with an estimated loss of €300 million (Pla *et al.* 2021). Economic implications due to fruit flies extend beyond the fields and orchards as their infestation also results in post harvest losses as farmers have to incur additional costs related to sorting, grading, and disposal of infested fruits, which further decreases the profit margins for producers.

Population dynamics of fruit flies

In Himachal Pradesh, fruit flies are active throughout the year and their peak activity is from April to September. All the prevalent tephritid species in HP showed a positive correlation with maximum temperature and sunshine, while a negative correlation with rainfall and relative humidity has been observed. Temperature actually plays a key role in fruit fly population growth, while other elements like relative humidity and rain have a minimal impact on their abundance (Nitika *et al.* 2023).

In the foot hills of Himalayas, incidence of *B. cucurbitae* was reported to be positively correlated with maximum and minimum temperature (Laskar and Chatterjee 2010). Shukla and Prasad (1985) also reported a significant positive correlation between maximum temperature, minimum temperature and rainfall with *B. cucurbitae* population at BCKV Burdwan. When the temperature comes down in December to February, their population declined and when temperature is high, during June to August, their incidence was quite high. *B. cucurbitae* incidence was high in gourds from June to October (Pujar *et al.* 2018); while *D. sphaeroidalis and D. longicornis* population in Himachal Predesh remained low and hence were categorized as minor species (Nitika *et al.* 2023). When the mean temperature was below 18^0C after November, fruit fly population declined drastically, while it reappeared when mean temperature rose above 18^0C during March. However, Stanley *et al.* (2015), observed that temperature alone cannot determine the status of fruit fly population in the region. Likewise, it has been reported that temperature along with rainfall has a synergistic effect on the population dynamics of fruit flies (Bota *et al.* 2018).

Seasonal abundance and multivoltinism

The tephritid fruit flies in the Himalayan region exhibit a high degree of multivoltinism, meaning they can complete multiple generations within a single year, which allow them to rapidly build-up their populations and become an increasingly severe threat to local crops. The abundance of these pests is highest during peak fruiting seasons of their host plants. Abundance and diversity of fruit flies are dependent on seasonal variations, particularly rainfall, RH and minimum temperature at the time of fruit maturity and the maximum population of fruit flies is observed during the ripening period (Patel and Das 2021; Megha *et al.* 2023). Presence of variety of hosts in the vicinity also affects the population of fruit flies. Throughout the year, suitable host crops are available for fruit flies and the species richness and abundance of individual species are highly dependent on the availability of the primary host and alternate hosts as the population of fruit flies are reported to be higher in mixed orchards compared to a homogeneous one (Megha *et al.* 2023). From May to August, the primary emergence of *B. dorsalis* is observed in mangoes and other fruits such as guava, papaya and lemon. While in September and October, their shift is noticed on the rainy season crops for continuing their life cycle. Fruit flies are additionally seen on different citrus fruits like mandarin, pummelo and orange in November-February (Megha *et al.* 2023). Hence, seasonality of fruit flies is associated with host plants that bridge the populations when their primary hosts are not available.

Key factors involved in the spread of tephritid flies are the trade of fruits and human movements (Nugnes *et al.* 2018). Regulation, quarantine services, and pest surveillance systems at border inspection points have been implemented to mitigate the risk of introduction, but the constant threat of new invasions remains a significant challenge. The change in the climatic conditions has further provided adaptive advantage to these fruit flies resulting in frequent outbreaks in various fruit crops (Sultana *et al.* 2017).

Management strategies

To address the growing threat of tephritid fruit flies in the Himalayan region, a multifaceted approach for pest management is necessary. IPM involves the strategic use of resistant varieties, incorporating a combination of cultural, physical, mechanical, biological and chemical control methods (Sharma *et al.* 2016) for the effective management of fruit flies.

Protein baits, fly resistance genotypes, parapheromone traps, bio-control agents and soft pesticides can all be used for effective management of fruit flies. Each of these management practices has its own set of benefits and drawbacks, and their use may or may not be effective in all situations (Nitika *et al.* 2023).

Cultural methods: Strategies such as the use of sanitation practices like fruit bagging, destruction of fallen infested fruits can help in reducing the overall population of these flies. The fallen fruits should be disposed in a pit 50 cm deep and should be covered with soil. Packaging of fruits with plastic bags and exposure to direct sunlight has been proved effective for management of *B. zonata* (Reddy *et al*. 2022). Fruit flies prefer semi ripened fruits for oviposition, hence early harvesting of fruits like orange, banana and mangoes can be done to avoid losses (Badii *et al.* 2015). Pruning of orchards is also an effective strategy for the management of fruit flies especially in case of guava. Trees pruned in August-September have lowest infestation as compared to unpruned trees (Choudhary *et al.* 2022).

For having an eco friendly approach for fruit fly management, various biological materials like *Beauveria bassiana,* neem-based insecticide and clay have also been used. These biological materials act as oviposition deterrents, thereby minimizing the fruit infestation and maximizing the yields and profits (Tomar *et al.* 2024).

Attractants

Fruit flies exhibit heavy emergence after rain showers and the chemicals applied for their management get washed off making it even harder a challenge to manage these pests. The most effective method for their management is hence the use of attractants for mass trapping and monitoring. The production and perception of chemical cues are vital in many behavioural interactions of fruit flies such as finding mating partners and hosts and based on these, species-specific chemical compounds (para pheromones) have been discovered which provide a solid base for developing novel tools for pest management. They play a pivotal role in surveillance, which has importance in mitigating the populations of fruit flies in an eco-friendly manner and without affecting non-target insects. Control strategies of fruit flies also rely on these semiochemical based approaches, most notably male specific attractants. Furthermore, incorporation of semiochemical based techniques in IPM enhances the effectiveness of techniques like Sterile Insect Technique (SIT) and Male Annihilation Technique (MAT) (Scolari *et al.* 2021).

In tephritids, volatile pheromones are a mixture of various chemical compounds with different isomers. These chemicals are either synthesized in body or are diet derived (Nishida *et al.* 1990). The pheromone mixture comprises of major, minor and trace components which are more effective together rather individually (Light *et al.* 1999). Fruit fly management employs three main lures *viz*. methyl eugenol (4-allyl-1,2-dimethoxybenzene-carboxylate), cuelure (4-(p-acetoxyphenyl)-2-butanone) and trimedlure (tert-butyl 4 (and 5)-chloro-2-methylcyclo-hexane-1-carboxylate). Methyl eugenol is known to attract males of genus *Bactrocera*, cuelure attracts males of certain *Bactrocera* and *Zeugodacus* spp. and trimedlure attracts males of *Ceratits* spp. Of these, only methyl eugenol is a natural compound occurring in over 450 plant species (Shelly *et al.* 2024). Various lures are investigated for different species of Tephritidae and some of them are specific to a single lure while some have shown attractancy towards more than one lure (Table 2). Lures like iso-eugenol, dihydroeugenol, lati-lure and zingerone are being studied for several species which have a very low response towards cuelure and methyl eugenol. Many species which are non-responsive towards any lure have been reported to be managed by employing zingerone while lati-lure has been suggested to manage *B. latifrons* (Vasudha and Agarwal 2019).

Currently, methyl eugenol is acknowledged as the most effective male lure with attraction thresholds ranging from nanograms to micrograms (Wee *et al.* 2002; Hee *et al.* 2015). Methyl eugenol has been used extensively because of its effectiveness as it is attractive to 85 *Bactrocera* species representing about 15 per cent of total identified species of this genus. In males of *B. dorsalis* methyl eugenol is biotransformed into (E)-coniferyl alcohol (ECF), 2-allyl-4,5-dimethoxyphenol (DMP) and trace quantities of (Z)-

Table 2. Species specific parapheromones against tephritid fruit flies

Species	Parapheromones effective (Stanley *et al.* 2015; Prabhakar *et al.* 2012)
B. nigrofemoralis	Cue lure, Baculure
B. dorsalis	Methyl eugenol
B. zonata	Methyl eugenol
B. diversa	Methyl eugenol
B. cucrbitae	Cue lure, Baculure
B. scutellaris	Cue lure, Baculure
B. tau	Cue lure, Baculure
Dacus longicornis	Cue lure
D. sphaeroidalis	Cue lure

3,4-dimethoxycinnamyl alcohol (DMC) (Nishida *et al.* 1988a; Nishida *et al.* 1988b) which act as sex pheromones to attract females of same species. Similarly, in *B. correcta,* males have been shown to convert methyl eugenol into (Z)-3,4-dimethoxycinnamyl alcohol (DMC) and (Z)-coniferyl alcohol (ZCF) (Tokushima *et al.* 2010) and â-caryophyllene (CAR) which are more effective than methyl eugenol.

Endosymbiont exploitation

Manipulation of symbionts for the control of tephritids was first proposed in 1929-30 (Baker *et al.* 1944) and copper carbonate and antibiotics for killing endosymbiotic bacteria were employed, however, these approaches failed to be commercialized as copper carbonate had low efficacy and antibiotics like streptomycin have hazardous residual effects. However, the basic idea of manipulation of endosymbionts is still an area of interest. Endosymbiotic bacteria are known to perform variety of functions in biological system of fruit flies and even obligate relationships between some tephritids and their symbionts have been established such as in case of olive fruit fly, *B. oleae*; which is unique in its ability to feed on unripe olives which contains high contents of defensive substances like "Oleuropein". Olive fruit fly achieves this with the help of a major bacterial symbiont '*Candidatus Erwinia dacicola*' which contributes to larval development by aiding its host *B. oleae* to overcome the unripe fruit chemical defence (Pavlidi *et al.* 2017). The interdependence between tephritids and their symbionts has been well established and it has been reported that endosymbiotic bacteria have useful roles in host nutrition, reproduction, development, pathogen resistance, pesticide resistance, mate selection and copulation (Behar *et al.* 2005; Ben-Yosef *et al.* 2015; Cheng *et al.* 2017). Thus, endosymbionts are an important aspect of pest management, which could be manipulated for disrupting the ecological and biological balance of target pest species. They can be used as attractants to trap adult flies, and for enhancement of effectiveness of techniques like SIT as diets enriched with pro-biotics have proven effective in enhancing the survival and mating competitiveness of mass reared sterile males in comparison to wild males of tephritids (Gavriel *et al.* 2011). *Wolbachia* has already been used for pest management as it has ability to induce uni-directional or bi-directional cytoplasmic sterility in its host and reduce fertility. Similarly, *W. pipientis* is known to induce high levels of cytoplasmic male sterility in *Ceratitis capitata* (Zabalou *et al.* 2009). Understanding the phenomenon of symbiosis in fruit flies has further opened new vistas for their management. Manipulation of gut symbionts *via* CRISPR-Cas9 mechanism has been appreciated as one of the top 10 insect pest control methods by *Science Magazine* (Rupawate *et al.* 2023). Use of plasmids or transposon to manipulate symbionts of insect pest in paratransgenesis is yet another future management option. Targeting specific gene from host insect via symbiont mediated RNAi has paved the way for novel approach in controlling insect pests in general and fruit flies in particular. Methods such as the sterile insect technique coupled with the incompatible insect technique have proven crucial in fruit fly studies. The advent of metagenomics and transcriptomics paved the way to identify the precise role of symbionts so that one can target the microbiome to impede the development of the particular host. Hence, detailed studies of symbiotic microbes and their manipulation can open up a new era in the pest control strategy. Advancements in molecular biology and genetic techniques have revolutionized insect research. Genome sequencing and CRISPRCas9 gene editing have allowed scientists to manipulate insect genes, enabling use of these noble technologies for their management.

The integration of artificial intelligence and machine learning in entomology will further assist in fruit fly monitoring and prediction, thereby contributing to more effective management strategies. Better understanding of fruit fly status, ecological significance, combined with innovative technologies and interdisciplinary collaborations, will lead to effective and sustainable management of this dreaded pest.

Chemical management

Chemical management of Tephritid fruit flies and other significant agricultural pests involves a multifaceted approach primarily centered on the application of insecticides. Chemical control is the most common method used and pesticides formulations have shown effectiveness for various fruit fly species. Despite the ill effects of chemical application well known, the method is still the most preferred management approach against the insect pests (Bilal *et al.* 2021). First synthetic insecticide used to control fruit flies was DDT, which was eventually replaced with organophosphates (Ganie *et al.* 2022). Against fruit flies, insecticides are mostly applied as covering sprays and as baiting poisons. From starting of 20th century, fruit flies have been managed by using the combination of baits with various pesticides. Fenthion (0.025%) with protein hydrolysate (0.25%) was also recommended for the management of fruit flies (Gupta and Verma 1978). Hydrolyzed protein and partially hydrolyzed yeast along with organophosphates like malathion in ratio 4:1 have been used globally for baiting fruit flies and now malathion is being replaced with specific, potent and environmentally friendly pesticides like spinosad (Reddy *et al.* 2020). When egg laying has taken place in fruits, chemical management becomes difficult therefore flies can only be controlled at adult stage, when they start hovering over the vegetation, or just before pupation; when final instar larvae come outside the infested fruit and is about to enter the soil (Agarwal *et al.* 1987). Different chemicals have been reported to target different developmental stages of fruit flies as malathion target the adults while diazinon targets the popping larvae and emerging adults (Bilal *et al.* 2021). Diazinon has been reported as one of the most toxic compounds to *B. zonata* followed by malathion, lufenuron and methoxy fenozide (Mosleh *et al.* 2011). Diazinon has been employed in soil drenching to control immature fruit fly stages, mature larvae, pre-pupa and pupae (El-Gendy *et al.* 2021). In case of emergency or major outbreaks, use of 80 per cent trichlorfon with 150g brown sugar has resulted in effective control of these pests (He *et al.* 2023). The use of systemic insecticides is not recommended for fruit fly management as many insecticides have mammalian toxicity, which necessitates strict precautions during application and waiting period before consumption (Vasudha and Agarwal 2019). The integration of chemical management with other tactics is crucial for sustainable fruit fly control. Chemical methods alone are not sufficient due to the potential development of resistance among pests and their adverse effect on non-target organisms and environment. New molecules with low mammalian toxicity and minimal residue are vital to minimize health risks and maintain effective pest control. As fruit flies peak their population during fruit ripening, timing of chemical application at right stage is of utmost importance and consideration of waiting period before consumption of commodity is most critical. Research into alternative pesticides that are both effective against fruit flies and safe to humans and beneficial insects is most demanding.

Conclusion

The comprehensive exploration of diversity of tephritid pests in state clearly indicate that understanding the intricate dynamics of host range and pest populations is crucial for effective management practices. The economic losses incurred by farmers due to direct or indirect impacts of tephritid flies necessitates the pressing need for strategic interventions in pest management and effective management of fruit flies can only be done by incorporating multiple pest management strategies. Potential of semiochemicals and manipulation of symbionts for use in pest management is inevitable as they are efficient, economical, and ecologically sound means to control these pests. By fostering a deeper understanding of these elements, it is possible to better navigate the complexities of fruit fly management and ensuring the integrity and economic viability in the face of ongoing challenges.

Conflict of interest: Authors declare no competing interest.

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