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Management of Dacine fruit flies (Tephritidae: Dacinae: Dacini) in horticultural ecosystems: A review

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Abstract
Several species of fruit flies, particularly belonging to tribe Dacini are invasive pests of horticultural crops worldwide, due to their wide climatic tolerance, polyphagous nature, high reproduction potential, multivoltine nature and high capacity for dispersal. They pose enormous threats to fruit and vegetable production throughout the world, causing both quantitative and qualitative losses. Among dacini fruit flies, species belonging to three genera, *viz. Bactrocera* Macquart, *Dacus* Fabricius and *Zeugodacus* Hendel are economically important. Fourteen species belonging to these genera are most serious pests, causing enormous losses to all kinds of fruits and vegetables in India. Notes on pest status, male lures and distribution of these economically important species have been added. Besides, their nature of damage, methods of detection and inspection, monitoring, pest risk analysis and management practices have been incorporated in this review.

Keywords: Fruit flies, tephritidae, Dacini, management, horticultural ecosystems

1. Introduction

Global agricultural production includes a significant proportion of horticultural crops; and these crops are substantiated by high export value, high yield and returns per unit area (Ravichandra, 2014) [54]. Several species of fruit flies, particularly belonging to tribe Dacini are invasive pests of horticultural crops worldwide, due to their wide climatic tolerance, polyphagous nature, high reproduction potential, multivoltine nature and high capacity for dispersal (Prokopy, 1977) [53]. They pose enormous threats to fruit and vegetable production throughout the world, causing both quantitative and qualitative losses. The tribe Dacini comprises 932 described species (Doorenweerd *et al.* 2018) [19] and includes three economically important genera, *Bactrocera*, *Dacus* and *Zeugodacus*. These three are most economically significant fruit fly genera with at least 50 species considered to be important pests, many of which are highly polyphagous (White and Elson-Harris, 1992) [74]. Adult dacine mostly feed on plant secretions, nectar, sap, honey dew, bird dropping and microorganisms (Christenson and Foote, 1960) [12]. After maturation, they mate and females start depositing eggs in growing hosts. The larvae feeding and developing in pulp of fleshy fruits form a "non-interactive grazing system". The feeding activity of larvae destroy and convert the host tissue in to a bad smelling, semi-liquid mass. Other major class of food substrates constitute plant parts, e.g. shoots, flowers, roots and species utilizing such food operate in an "interactive grazing system" (Zwolfer, 1983) [75]. The mature larvae of fruit infesting tephritids drop to the soil to pupate while several non-frugivorous species pupate within the host. Fruit flies cause direct damage to fruits and vegetables by the puncture for oviposition by the female and the larval development inside the fruit (Aluja, 1994) [5]. These pests cause direct damage to important export crops leading to losses up to 40% to 80%, depending on locality, variety and season (Kibira *et al*., 2010) [39]. The presence of these pest species limits access to international markets; due to quarantine restrictions imposed by importing countries. The management of fruit flies is challenging because their life-stages occur at different sites and remains protected, e.g. eggs and larvae in the host, pupae in soil and adults are active flier. Consequently, both larvae and pupae in fruits and soils are protected from surface-applied insecticides. Besides, management of fruit flies is becoming increasingly difficult in many countries, as use of formerly effective broad-spectrum and systemic insecticides is not recommended against fruit flies because of consumers' reactions.

Due to progressively more stringent restrictions on the use of insecticides and increasing demand for healthy food around the world, new environmentally friendly techniques for fruit fly management are arising (Navarro-Llopis *et al*., 2011) [50].

2. Tribe Dacini

Dacini is a tropical and subtropical evolutionary radiation of flies with centers of diversity in Southeast Asia and Sub-Saharan Africa (Doorenweerd *et al*., 2018) [19]. All Dacini belong to 4 genera, *viz. Bactrocera* Macquart, *Dacus* Fabricius, *Zeugodacus* Hendel and *Monacrostichus* Bezzi. Of these, first 3 are economically important as the species in these genera are serious pests of most horticultural crops. The members of this tribe are characterized by scutum black/ brown/ reddish-brown with or without yellow medial and lateral postsutural vittae; significantly reduced chaetotaxy of head and thorax. Face fulvous to black with a pair of dark spots or a band; wing with cell bm deeper/broader than bcu; extension of cell bcu longer than bcu; costal band vary in width and may expand at apex in small or large spot; males usually with pecten; ceromata present, female with 2 spermathecae.

3. Indian scenario

India is the world's largest producer of tropical and subtropical fruits and vegetables. In the year 2015-16 total area under production of fruit and vegetables was 6.301 and 10.106 million ha, respectively while their production was 90.183 and 169.064 million tonnes, respectively (Horticultural Statistics at a Glance, 2017) [31]. Besides, India's potential for export of fruits and vegetables hitherto remain largely unexploited because of less export of fruits and vegetable. To achieve the desired goal, production of fruits and vegetables both qualitatively and quantitatively should be increased by mitigating biotic and abiotic constraints. Among the biotic constraints, larval stages of fruit flies are of serious concern. Many countries do not allow import of fruits and vegetables from India merely because of threat of entering of exotic fruit flies and other insect pests in their areas. These species have a direct effect on Indian economy and detail studies towards their management are experienced necessary.

In India, fruit flies have been identified as one of the ten most serious problems of horticulture because of their polyphagous nature and huge economic loss to fruits and vegetables, which varies from 2.5 - 100 per cent depending upon the crop and season (Verghese *et al*., 2004; Dhillon *et al*., 2005) [70, 16]. Indirect losses resulting from quarantine restrictions imposed by importing countries to prevent entry and establishment of unwanted fruit fly species. In India, nearly 14 dacine species belonging to the genera *Bactrocera* Macquart, *Dacus* Fabricius and *Zeugodacus* Hendel are most serious pests causing enormous losses to all kinds of fruits and vegetables (table 1).

Table 1: Important dacine flies, their attractant, pest status and distribution.

Common name	Fruit fly Species	Attractant	Host status	Distribution
Caryea fruit fly	*Bactrocera* (*Bactrocera*) *caryeae* (Kapoor, 1971)	ME	OP (minor, sporadically serious)	India (Goa, Karnataka, Kerala, Maharashtra, Tamil Nadu)
Guava Fruit Fly	*B.* (*B.*) *correcta* (Bezzi, 1916)	ME	PP	Cambodia, India, Bhutan, Myanmar, China (Yunnan, Guizhou), Nepal, Pakistan, Thailand, Vietnam, Malaysia (Peninsular), Sri Lanka, Bangladesh USA- Florida (not established), California (eradicated)
Mango fruit fly/ oriental fruit fly	*B.* (*B.*) *dorsalis* (Hendel, 1912)	ME	PP (mainly fruits)	Widespread Tropical Asia Introduced Africa and Oceania Eradicated- Japan (Ryukyu Archipelago including Okinawa), Mauritius USA - restricted distribution (California, Florida – eradicated), Hawaii, n. Marianas Islands (Rota, Saipan and Tinian) Europe- intercepted Belgium
Malaysian fruit fly/ solanum fruit fly	*B.* (*B.*) *latifrons* (Hendel, 1915)	Latilure	OP (mainly Solanaceae)	Asia- Pakistan to Taiwan, Indonesia (Kalimantan, Java, Sulawesi) Introduced- Kenya, Tanzania, Iran; USA (Hawaii; California- eradicated); Japan (Yonaguni Is.- Okinawa Prefecture- invaded)
-	*B.* (*B.*) *tuberculata* (Bezzi, 1916)	ME	PP	Bhutan, China (Yunnan), Myanmar, Thailand, Vietnam, India (Meghalaya, Tripura)
Peach fruit fly	*B.* (*B.*) *zonata* (Saunders, 1842)	ME	PP	Asia- Pakistan to Vietnam; Indonesia (Moluccas) Introduced - Mauritius, United Arab Emirates Réunion Island, Iran Sudan, Oman, Saudi Arabia (restricted distribution); Iraq, Israel (few occurrence); Oman, Yemen, Egypt, Libya (localized) USA- Trapped (in California but not established), Florida (eradicated)
Carambola fly	*B.* (*B.*) *carambolae* Drew & Hancock, 1994	ME	PP	Thailand, Malaysia, China (Yunnan), Singapore, Brunei Darussalam, Indonesia, Myanmar, Cambodia, s. Vietnam, India (Meghalaya, Andaman & Nicobar Is.). Introduced - Surinam, French Guyana, northern Brazil (Amapá), eradicated from Guyana
Chinese citrus fly	*B.* (*Tetradacus*) *minax* (Enderlein, 1920)	weak ME	Fruit pest (mainly citrus)	Bhutan, India (Sikkim, W. Bengal), Nepal, China
Lesser pumpkin fly/Ethiopian fruit fly/cucurbit fly	*Dacus* (*Didacus*) *ciliates* Loew, 1862	-	Cucurbits	Afrotropical region, Pakistan, Bangladesh, Comoros, St. Helena, Senegal, India, Nepal, Sri Lanka, Mali
-	*Zeugodacus* (*Zeugodacus*) *caudatus* (Fabricius, 1805)	CL	Mainly cucurbits	India, Myanmar, Cambodia, Nepal, China (Hainan), Bangladesh, Malaysia (East), Malaysia (Peninsular), Brunei Darussalam, Sri Lanka, Taiwan, Thailand, Vietnam, Indonesia
Melon fruit fly	*Z.* (*Z.*) *cucurbitae* (Coquillett, 1899)	CL	PP (mainly cucurbits- fruits and flowers)	Tropical Asia (widespread) Introduced - Afrotropical region and Oceania Eradicated Japan (Ryukyu Islands), Kiribati, Nauru, USA (California eradicated), Hawaii, N. Mariana Islands (restricted distribution)
-	*Z.* (*Z.*) *scutellaris* (Bezzi, 1913)	CL	Cucurbits	India, Bhutan, Nepal, Myanmar, Thailand, Pakistan, s. China, Peninsular Malaysia, Vietnam, Japan (Wakayam Prefecture)
Pumpkin fruit fly	*Z.* (*Z.*) *tau* (Walker, 1849)	CL	PP (mainly cucurbits)	Asia - Pakistan to Philippines; south to Sumatra and Sulawesi Trapped Japan (Ishigaki Island)
Three-striped fruit fly	*Z.* (*Hemigymnodacus*) *diversus* (Coquillett, 1904)	Weak ME	Mainly cucurbits	India, Bhutan, S. Vietnam, Bangladesh, Sri Lanka, Nepal, Pakistan, Thailand, China (Sichuan, Guizhou, Yunnan)

CL- cue-lure; ME- methyl eugenol; OP- oligophagous, PP- polyphagous

The adults of polyphagous species have high mobility, relatively long life span (often more than three months), high fecundity (> 1000 eggs/female) (Vargas *et al*., 1984) [68], scramble type competition in the larval stage, several generations per year and the ability to pass unfavourable periods of the year in a facultative reproductive diapause when necessary (Fletcher, 1987) [28].

During the last 100 years, insecticides for fruit fly control have included inorganic, synthetic and reduced-risk compounds. Insecticides, particularly bait sprays will continue to be a major component of fruit fly control systems. However, due to political, social, and environmental issues, reduced-risk compounds and biopesticides are being considered as replacements for synthetic insecticides (Mangan, 2014) [44]. The Fruit Fly Workers meeting held at the Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Distt. Nadia on 7th August, 2016 provided a unique platform to scientists working in the eastern and north-eastern parts of India on fruit flies; to interact, share their experience and finally to prioritize areas for future Research. In this meeting it was proposed that the researchers and managers of action programmes should choose the best trapping system available for a particular growing area or region and for a species or group of species and four critical parameters involved are: trap type, fly attractant, trap density and service interval (Jha *et al*., 2016) [34].

4. Damage

Damage caused by fruit flies may be in the form of

4.1 Plant injury: Female fruit flies most often lay their eggs in the fresh flesh of fruits, vegetables and other plant parts. The eggs hatch into larvae (maggots), which most often feed on the inside of the host and convert host tissues in a soft, spongy mess.

4.2 Economic injury: High population of fruit fly causes more severe damage and management practices need to be implemented.

4.2.1 The damage to crops caused by fruit flies result from

- Oviposition in fruit and soft tissues of vegetative/reproductive parts of certain plants
- Feeding by the larvae
- Decomposition of plant tissue by invading secondary microorganisms.

Most pest species are polyphagous, breeding in a large number of plant species in many plant families; however a few pest species are host specialists primarily breeding in hosts of a single family (Drew, 2004) [22]. Larval feeding in host tissues is the most damaging; and the damage usually consists of breakdown of tissues and internal rotting associated with maggot infestation (figure. 1). The feeding damage of fruit fly maggots (larvae) destroys the pulp, allowing the entry of secondary bacteria and fungi; and cause premature fruit drop and degrade the quality of production (Sarwar, 2015) [57]. Infested host becomes distorted, callused and usually drop. Mature attacked fruits develop a water-soaked appearance. The larval tunnels provide entry points for bacteria and fungi that cause the fruit to rot. Extent of damage done by these flies depends upon their population density, availability of different hosts, type, size and condition of host fruit, and weather factors.

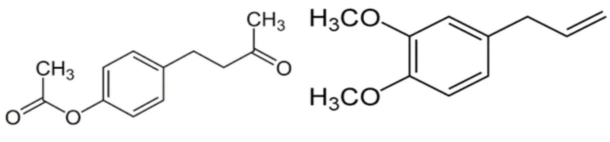
Fig 1: Infested cucurbits with *Zeugodacus* sp.

In India, hosts of fruit flies have been listed by Narayanan (1953) [46], Narayanan and Batra (1960) [47], Kapoor (1970) [36], Kapoor and Agarwal (1983) [38], Kapoor (1993) [37]. Host utilization by fruit fly is depending on adult's choice in terms of attraction to host, host texture for oviposition and the adaptation of larvae to survive and develop in the specific regime of nutrients supplied by the host. After hatching larvae bore their way into interior of the host, macerate the tissues and ingest the broken-down tissues and associated bacteria. The larval population also depends on hosts' abundance, number of eggs laid and hatching percentage (Agarwal and Kapoor, 1986) [3].

5. Male lures

Males of many dacine fruit flies are attracted to a small set of plant-derived secondary compounds termed male lures (Sivinski and Calkins, 1986) [60]. Earlier reports of attractant were essentially food lures based on natural plant products, essence and ammonia. Howlett (1912) [32] while working at Pusa (Bihar) India, observed that oil of citronella (*Cymbopogon nardus*, Fam. Poaceae) was attractive to males of *Z. diversus* and *B. zonata*. Further investigation (Howlett, 1915) [33] showed that the attractive component was phenyl proponoid methyl eugenol or 3-4 dimethoxy-1 allylbenzene, which was also attractive to males of *B. dorsalis*. Its effectiveness was rediscovered by Steiner (1952) [63]. Besides, in efforts made to screen other chemicals as lures for fruit flies, anisyl acetone or 4(p-methoxyphenyl)-2-butanone was observed to be an effective attractant for the melon fly (Barthel *et al*., 1957) [8]. A derivative cue-lure or 4(p-acetoxyphenyl)-2-butanone was found to be more attractive (Beroza*et al*., 1960) [10]. Drew (1974) [20] and Drew and Hooper (1981) [23] reported that each dacine species responded only to one of these attractants and some species did not respond to either. Methyl eugenol widely occurs in many plant parts of a number of plant species. Drew (1987) [21] showed that the component 2-butanone of cue-lure is produced by ripening fruits and some bacteria and cue-lure attract more dacine species as compare to methyl eugenol. Responses to dacine flies to male lures are also useful for identification, because of the consistency in responsiveness among species to a single fixed lure in principle (Tsuruta *et al*., 2005) [67]. Studies have now demonstrated that feeding on lures enhances male sexual behaviour and signalling, which results in increased mating success (Kumaran *et al*., 2013) [42]. These attractants (figure 2) are also used in the surveillance system targeting more than one species at a time and are a powerful monitoring tool for the early detection of a species and population monitoring. In fruit fly management using various lure combinations reduces the cost of operation

(Dominiak *et al*., 2011; Stringer *et al*., 2019) [18, 66]. However, some dacine species are weakly responsive to these lures. Recently in Oceania and Asia, more attractive male lures (isoeugenol, methylisoeugenol, dihydroeugenol, and zingerone) were identified for several weakly CL- and methyl eugenol (ME) responsive species (Royer *et al*., 2019) [56]. Manoukis *et al*. (2019) [45] suggested that benefits for control and eradication programmes would result from reducing the application density of MAT against *B. dorsalis* through reduced material use, labour costs, and higher effectiveness. Counter intuitively, they observed decreasing effectiveness (percent kill) with increasing application density.



Cue-lure **Methyl eugenol**

Fig 2: Fruit fly attractant

6. Detection and inspection

1. *Visual examination*: Host fruit with oviposition puncture(s) may have eggs/larvae of dacine species.
2. *Rearing*: Hosts infested with dacine species are kept in rearing jars on sand and covered with muslin cloth. Pupation takes place in sand and adult flies can be reared from the pupae.
3. *Trapping*: A number of attractants are available for trapping of adult male flies. Of these, methyl eugenol and cue-lure are most important and attract a number of dacine species. These attractant should be mixed with insecticide like malathion and then soaked in small ply wood blocks/ cotton wicks. Such impregnated blocks/ wicks are suspended in the self-made bottle trap.

7. Monitoring

Prevention is one of the most effective strategies for fruit fly management (Aluja, 1999) [6]. The monitoring of fruit flies is crucial to determine the population dynamics, in comparing infestation levels between different sites and evaluate the effectiveness of a control tactic (Eliopoulos, 2007) [26]. Monitoring helps to control fly hot spots; inside or outside the crop. The correct identification of a pest is prerequisite prior to undertake management practices and it is an integral component of monitoring. The polymerase chain reaction (PCR) has also been used for detecting the DNA of fruit flies for their correct identification (Dhami *et al*., 2016) [15]. Descriptions of important pest species are available in literature. Fruit fly monitoring with traps is currently performed with manual weekly counting. In this context, efforts to develop automatic insect traps have been intensified and accelerated. Molecular identification of European fruit flies based on COI barcode sequences has been executed and 73.3% of all included species could be identified based on their COI barcode gene, based on similarity and distances (Smit *et al*., 2013) [61].

8. Pest risk analysis

A number of dacine species, not existing in India are thus a major concern to quarantine security. The egg and larval stages in infested fruits or vegetables poses important threat as they may enter either during importation of infested hosts or infested fruits in passenger luggage. A few such species had already gained their entry in Indian territories. Some dacine species reported only from Andaman and Nicobar Islands are: *Bactrocera* (*Bactrocera*) *andamanensis* (Kapoor), *B.* (*B.*) *blairiae* Drew & Romig, *B.* (*B.*) *curtivitta* Drew & Romig, *B.* (*B.*) *patula* Drew & Romig, *B.* (*B.*) *ranganathi* Drew & Romig, *B.* (*Calodacus*) *harrietensis* Ramani & David, *Dacus* (*Mellesis*) *insulosus* Drew & Hancock, *Zeugodacus* (*Zeugodacus*) *fuscoalatus* (Drew & Romig) and *Z.* (*Z.*) *havelockiae* (Drew & Romig). The pest status of these species in not known; however, they may gain entry in Indian mainland in near future. Besides, pest species occurring in India's adjoining countries may also invade India.

9. Management

The management of fruit flies is challenging due to their biology, adaptation to various regions and wide range of hosts. Dias *et al.* (2018) [17] assessed the historical and current approaches of fruit fly management research worldwide, and established the current knowledge of fruit flies by systematically reviewing research on monitoring and control tactics, according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. The fruit fly management practices are basically dependent on the methods (applied singly or in combination) like cultural, physical, large scale application of bait sprays, use of traps (for population suppression) and post-harvest treatments. In some regions of the world other methods like biological, male annihilation and sterile insect technique (SIT) have also been used for successful population suppression/eradication of pest fruit flies. Narayanan and Batra (1960) [47], Kapoor (1993) [37] and Agarwal (2006, 2009) [1, 2] discussed different methods used for the control of fruit flies in India. The major steps in fruit fly management are:

- Report of infestation - detection system (trapping, rearing, inspection, sampling)
- Collection of adult flies
- Identification of pest species - diagnosis system (characters of pest species)
- Host plants and their phenology
- Ecology - nature of infestation, seasonal history, population studies
- Biological studies
- Behavioural studies (attraction to various lures, baits, etc.)
- Programme of quality management (preventive, eradicative, management)

9.1 Mechanical control

The mechanical control includes a number of tactics which assist in reduction of fruit fly population. Mass trapping is also one of the main tactics which has the potential to minimize or avoid the use of insecticides and has attracted interest due to their efficacy, specificity and low environmental impact. Mass trapping consists of the use of traps and baits that release specific volatile substances that attract insects to the trap, in which fruit flies are captured and killed (El-Sayed *et al*., 2009) [27]. Additionally, these techniques are applicable where the cost of labour is low.

9.1.1 Sound crop hygiene

a. The weeds and other undesirable plants should not be allowed to grow as these may harbour adults at rest.
b. Destruction of over-ripe, windfall and infested fruits is strongly encouraged to minimize the fly population. Such

fruits should be adequately destroyed, buried deep in the soil or fed to animals to have clean cultivation.

c. At harvest no fruit should be left unpicked as these may be source of further infestation.
d. Many types of fruits or vegetables are grown in homes for owners' consumption and such hosts are available to recruit the fly population. Such hosts need proper protection.

9.1.2 Wild host destruction
Polyphagous dacine species survive on non-cultivated wild hosts during dearth period when cultivated hosts are not available. Elimination/destruction of such hosts would certainly reduce the reproductive potential of pest species.

9.1.3 Raking/ploughing of the Soil
The pupae of dacine flies can be easily destroyed by raking/ ploughing. During such operations some pupae are killed due to mechanical injury while others are exposed and became prey to natural enemies.

9.1.4 Bagging of fruits
The technique of bagging of each fruit by a paper/ cloth/ plastic bag is being strongly encouraged in cases where less number of fruits is to be protected against oviposition by the fruit fly. The method may also protect host fruits from other pests. This practice is extensively followed in many countries. However, implementation of technology on a large scale may pose problem like (i) it is labour intensive, (ii) rain or storm may damage paper bags, (iii) difficult to wrap the fruits on large and old trees.

9.1.5 Early harvesting
Some fruits like banana, papaya and some mango varieties remain free from fruit fly infestation at green mature stage or colour-break stage. The chances of infestation can be reduced substantially if such fruits are harvested at colour-break stage.

9.1.6 Wire netting
The small orchard may be covered with fine wire netting. Although it is costly; however it may be effective in protecting fruits from fruit flies and birds.

9.1.7 Mass trapping
Mass trapping is a valuable tool for fruit fly population suppression. In India, Lall and Sinha (1960) [43], Grewal and Kapoor (1987) [29], Patel and Patel (1996) [52] and Verghese *et al*. (2006) [71] fabricated new traps for fruit fly collection. The efficacy of lure-and-kill and mass trapping has been demonstrated in crops attacked by fruit flies within IPM strategy. These techniques are effective when combined with bait spraying; however, the efficacy of both systems is highly dependent on pest density population. Unfortunately, cost is a limiting factor that should be taken into account, and mass trapping may be feasible only in high value crops. The application of this control method has increased notably in the last 10 years. However, in the same region, there is trend to replace mass trapping with lure-and-kill. The lure-and-kill approach does not require trapping the flies and has similar efficacy and strengths as mass trapping, with some additional advantages as its lower cost because a container to retain the flies is not required. Nowadays, both techniques are of common use in area-wide operational suppression programmes (Navarro-Llopis and Vacas, 2014) [49].

9.2 Biological control
The biological control of fruit flies is still in infancy state, though a number of efforts have been made to collect, rear and release of parasitoids. The major problem in use of natural enemies of fruit flies is because of their protected life stages (eggs and larvae in host and pupae in soil). Records of natural enemies of fruit flies are widely scattered. Narayanan and Chawla (1962) [48], Herting and Simmonds (1978) [30] listed tephritid parasitoids and predators. Entomologists in Hawaii have conducted a number of classical biological control programmes against *Bactrocera* species, resulting in establishment of some parasitoids and partial control (Clausen *et al*., 1965; Wharton, 1989) [13] [73]. Kapoor and Agarwal (1983) [38] and Kapoor (1993) [37] listed known parasitoids of Indian fruit flies. Some important parasitoids of *Bactrocera* species recorded in India are: *Fopius vandenboschi, F. persulcatus, Diachasmimorpha longicaudata* and *Fopius arisanus.*

F. arisanus is an egg–pupal parasitoid of tephritid fruit flies. Since its introduction to Hawaii in the late 1940s, it has caused substantial reduction of fruit fly populations. Rearing methodology developed by the US Department of Agriculture – Agricultural Research Service (USDA–ARS) in Hawaii in the 1990s allowed an increasing number of studies of the biology and behaviour of this parasitoid. Simultaneously, the parasitoid has been introduced to various parts of the world for classical biological control purposes (Rousse *et al*., 2005) [55]. Hymenopterous parasitoids of the Braconidae family were the main natural enemies of fruit flies studied and included *D. longicaudata* and *Psyttalia* spp. The egg parasitoid, *F. arisanus*, and the pupal parasitoids *Coptera haywardi* (Fam. Diapriidae) and *Aganaspis daci* (Fam. Figitidae) are considered as alternative species to fruit fly biological control with larval parasitoids.

Soil treatment with fungal pathogens to kill the mature maggots and pupa is a recent method of fruit fly control, targeting the immature stages of the fruit flies (maggots and puparia). The control with entomopathogenic fungi has shown interesting results, e.g. *Beauveria bassiana, Isaria fumosorosea* and *Metarhizium anisopliae* had the strongest influence on fecundity in laboratory (Daniel and Wyss, 2009) [14]. Sookar *et al*. (2014) [62] obtained promising result against *Z. cucurbitae* using entomophatogenic fungi species. The fungus *M. anisoplie* is being used as a biological pesticide against fruit flies and is formulated as granules and can be dispersed by hand and then raked into the soil; where it can persist for over a year (Ouna, 2010) [51]. Entomopathogenic nematodes, such as *Heterorhabditis* spp. and *Steinernema* spp. were used for control of larvae and pupae of *Dacus ciliatus* (Kamali *et al*., 2013) [35]. A number of predatory insects, rodents, birds, myriapods, spiders, toads, geckos, etc. feed upon adults and immature stages of fruit flies (Agarwal, 2006) [1].

9.3 Chemical control
In case of fruit flies only adults are exposed to control measures while eggs, larvae and pupae remain protected from non-systematic insecticides. The use of systematic insecticides is not recommended due to consumers' reaction. Many insecticides have high mammalian toxicities, which necessitate strict precautions during application and time delay between final spray and consumption. For the control of fruit fly populations two techniques are commonly used, in one bait mixed with insecticide is sprayed and the technique

has been termed 'Bait Application Technique' (BAT). Bait sprays are particularly suitable for 'Area Application', aimed at suppression of entire breeding populations. Bateman (1982) [9] suggested bait/insecticide mixture should be applied only at some spots with an adequate uniformity over an entire area. The other technique is based on the use of attractant/insecticide system, in which males are annihilated from the environment and called 'Male Annihilation technique' (MAT). Simultaneous use of bait and attractant mixed with insecticide (double attack method) has been observed consistently more effective than either technique alone (Bateman, 1982; Boller, 1983) [9, 11]. Such formulations can be used in traps and are highly effective because of their specificity and environmental compatibility.

9.3.1 Bait Application Technique: Fruit fly suppression is mainly based on the use of food baits mixed with a killing agent that attract both male and female flies; however, such baits are not species-specific. Protein bait application is less time consuming and less demanding of labour. A number of locally derived baits, e.g. protein, sugar, jaggery, molasses, fruit juice, fermented materials, toddy, yeast, etc. have been used as baits against fruit flies. Spraying of a mixture consisting of 1 ml malathion 50 EC + 10 g crude sugar or jaggery in 1 liter water is recommended for spraying. Brewery waste yeast is also a good source of protein and can be used as bait. Treatment should be carried out at regular intervals throughout the activity period, typically at weekly intervals at the during peak activity. Bateman (1982) [9] proposed 'spot spray' of 100 ml solution (prepared by mixing 20 g protein + 10 g a.i. malathion per liter of water) at spots of 15 m distance, regularly throughout the active season.

Fig 3: Bottle trap

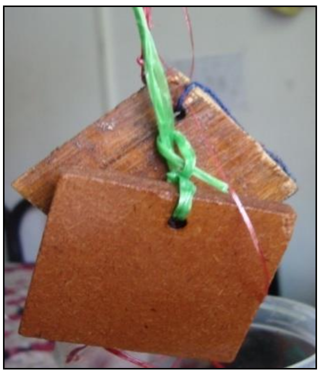


Fig 4: Plywood block

9.3.2 Male Annihilation Technique: Use of combination consisting of ethanol + attractants like methyl eugenol or cue-lure + malathion 50 EC (or any other insecticide) (6:4:1 V/V) can be successfully used in annihilation of male flies from the environment. Such mixture should be soaked in ply wood blocks (5 x 5 x 1.2 cm) (figure 4) and suspended in self-made plastic bottle traps (made of 1 litre mineral water bottle – figure 3).

9.3.2.1 The trap can be constructed as described below.

a. Make two holes/windows (3 cm diameter) opposite to each other on the wall of the bottle.
b. Cut the lower portion of bottle horizontally above 3-4 cm above the base.
c. Make a hole in the lid of bottle to insert the galvanized wire tied with ready to use plywood block and hang the block in the centre of bottle.
d. Lower cut portion of the bottle should be fixed in the bottle upside down and flies can be collected by removing it.

These traps should be hanged below the trees at about 2 m height in places having no direct sunlight (Agarwal, 2009) [2]. Species like *B. carambolae, B. caryeae, B. correcta, Z. diversus, B. dorsalis, B. tuberculata* and *B. zonata* respond to methyl eugenol while *Z. caudatus, Z. cucurbitae, Z. scutellaris, and Z. tau* are attracted by cue-lure. Addition of protein bait also increases the efficacy of the combination. Annihilation of male flies from the environment reduces reproductive compatibility of females and would be effective in reducing the pest fruit fly population to a very low level if carried on a large scale.

9.3.3 Control with natural product insecticides

Natural product insecticides containing mainly plant and fungi extracts have been used against fruit flies. Plant-derived insecticides, such as azadirachtins, were included in these studies (Singh, 2003; Silva *et al*., 2013) [59, 58]. Ali *et al*. (2011) [4] used different plant extracts and minimum percent damage (41.94%) was found in neem seed extract treated plots. The results of the experiment revealed that botanicals can be replaced for the management of melon fruit flies instead of using the synthetic pesticides in order to save the environment from their hazards. The soil can also be inoculated with neem cake and other botanical formulations to kill pupating larvae (Ekesi and Billah, 2006) [25].

9.4 Area-wide management

An area-wide management programme is a long-term planned campaign against a pest population in a relatively large predefined area. The mission of the area-wide pest management is to develop, integrate, and evaluate multiple strategies and technologies into system approaches for management of insect pests. Area-wide management (AWM) involves synchronised pest management implemented across a geographical area, often including non-commercial land and urban settings where the pest can reproduce (Vreysen *et al*., 2007) [72]. This involves trapping, protein baiting, cultural control, male annihilation technique, cover spraying and scouting, release of natural enemies, Sterile insect releases, within a large area (Vargas *et al*., 2015) [69]. Therefore growers and the rest of the community need to undertake management practices all year round – not just at harvest time.

9.5 Sterile insect technique (SIT)

Repeated release of sterile males for suppressing wild populations of the same species was first proposed by E.F. Knipling (1955) [40]. This technique is well suited for the suppression or eradication of some dacine species. Scientists from Hawaii and Australia carried out the original pilot SIT tests to eradicate *Z. cucurbitae* from Rota in the Northern Mariana Islands (Steiner *et al*., 1965) [64], *B. tryoni* in Australia (Andrewartha *et al*., 1967) [7], *B. dorsalis* in Micronesia (Steiner *et al*., 1970) [65] and *Z. cucurbitae* from Japanese islands (Koyama *et al*., 2004) [41].

9.6 Vapour heat treatment (VHT)

Vapour heat treatment is a post-harvest treatment and performed to kill immature stages of fruit flies, if any present in the host(s). It is performed under a state of high temperature and saturated water vapours with the goal to kill the insects without injuries to the hosts. The high moist saturated air protects evaporation of water from fruits. The treatment has advantages over chemical fumigation and there is no necessity for anxiety about chemical residues. The thermal efficiency of VHT is better than dry heat treatment. Mango varieties, e.g. Alphnaos, Banganpally, Chausa, Dashehari, Kesar, Langra, Malika, Neelam and Totapari when treated at 50^0C resulted into 100 per cent mortality of eggs and mature larvae (Dutt, 1999) [24]. The APEDA (Agricultural Processed Export Development Authority) had already established a VHT Laboratory at Indian Agricultural research Institute, New Delhi.

10. Integrated management

The multidimensional IPM practice against dacine flies involves under noted components:

- Collect and destroy fallen fruits at weekly intervals starting from initiation of fruit maturity
- Soil raking around and below trees to a depth of 6 cm in orchard crops
- Deep ploughing to expose hibernating stages
- Continuous picking of fruits with total harvest
- Spot application of 0.1% malathion and 10% jaggery or protein hydrolysate or molasses solution should be done at spots of 15 m distance. The application should be done weekly starting 45 days prior to fruit maturity and also throughout the active season. Apply bait spray in spots to surroundings hedges also. Avoid spraying on fruits
- Annihilate male flies in methyl eugenol traps (cue-lure in case of flies infesting cucurbit hosts) or blocks (10 traps/blocks ha^{-1}). Start trapping about a month prior to fruit maturity
- Avoid delay in harvesting.

11. References

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