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The melon fruit fly, *Bactrocera cucurbitae*: A review of its biology and management

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Abstract

The melon fruit fly, *Bactrocera cucurbitae* (Coquillett) (Diptera: Tephritidae) is distributed widely in temperate, tropical, and sub-tropical regions of the world. It has been reported to damage 81 host plants and is a major pest of cucurbitaceous vegetables, particularly the bitter gourd (*Momordica charantia*), muskmelon (*Cucumis melo*), snap melon (*C. melo* var. *momordica*), and snake gourd (*Trichosanthes anguina*). The extent of losses vary between 30 to 100%, depending on the cucurbit species and the season. Its abundance increases when the temperatures fall below 32° C, and the relative humidity ranges between 60 to 70%. It prefers to infest young, green, soft-skinned fruits. It inserts the eggs 2 to 4 mm deep in the fruit tissues, and the maggots feed inside the fruit. Pupation occurs in the soil at 0.5 to 15 cm below the soil surface. Keeping in view the importance of the pest and crop, melon fruit fly management could be done using local area management and wide area management. The melon fruit fly can successfully be managed over a local area by bagging fruits, field sanitation, protein baits, cue-lure traps, growing fruit fly-resistant genotypes, augmentation of biocontrol agents, and soft insecticides. The wide area management program involves the coordination of different characteristics of an insect eradication program (including local area options) over an entire area within a defensible perimeter, and subsequently protected against reinvasion by quarantine controls. Although, the sterile insect technique has been successfully used in wide area approaches, this approach needs to use more sophisticated and powerful technologies in eradication programs such as insect transgenesis and geographical information systems, which could be deployed over a wide area. Various other options for the management of fruit fly are also discussed in relation to their bio-efficacy and economics for effective management of this pest.

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Introduction

The dipteran family Tephritidae consists of over 4000 species, of which nearly 700 species belong to Dacine fruit flies (Fletcher, 1987). Nearly 250 species are of economic importance, and are distributed widely in temperate, sub-tropical, and tropical regions of the world (Christenson and Foote, 1960). The first report on melon fruit flies was published by Bezzi (1913), who listed 39 species from India. Forty-three species have been described under the genus *Bactrocera* including *cucurbitae, dorsalis, zonatus, diversus, tau, oleae, opiliae, kraussi, ferrugineus, caudatus, ciliatus, umbrosus, frauenfeldi, occipitalis, tryoni, neohumeralis, opiliae, jarvisi, expandens, tenuifascia, tsuneonsis, latifrons, cucumis, halfordiae, cucuminatus, vertebrates, frontalis, vivittatus, amphoratus, binotatus, umbeluzinus, brevis, serratus, butianus, hageni, scutellaris, aglaia, visendus, musae, newmani, savastanoi, diversus,* and *minax*, from Asia, Africa, and Australia (Syed, 1969; Cavalloro, 1983; Drew and Hooper, 1983; Munro, 1984; Fletcher, 1987). Amongst these, *Bactrocera cucurbitae* (Coquillett) is a major threat to cucurbits (Shah et al., 1948). Senior-White (1924) listed 87 species of Tephritidae in India. Amongst these, the genus, *Bactrocera* (*Dacus*) causes heavy damage to fruits and vegetables in Asia (Nagappan et al., 1971).

For cucurbits, especially bitter gourd, *Momordica charantia* Linn., the melon fruit fly damage is the major limiting factor in obtaining good quality fruits and high yield (Srinivasan, 1959; Lall and Singh, 1969; Mote, 1975; Rabindranath and Pillai, 1986). It prefers young, green, and tender fruits for egg laying. The females lay the eggs 2 to 4 mm deep in the fruit pulp, and the maggots feed inside the developing fruits. At times, the eggs are also laid in the corolla of the flower, and the maggots feed on the flowers. A few maggots have also been observed to feed on the stems (Narayanan, 1953). The fruits attacked in early stages fail to develop properly, and drop or rot on the plant. Since, the maggots damage the fruits internally, it is difficult to control this pest with insecticides. Therefore, there is a need to explore alternative methods of control, and develop an integrated control strategy for effective management of this pest. The available information on the melon fruit fly has been reviewed in this manuscript to explore the possibilities for successful management of this pest in cucurbits.

Distribution

The melon fruit fly is distributed all over the world, but India is considered as its native home (Table 1). It was discovered in Solomon Islands in 1984, and is now widespread in all the provinces, except Makira, Rennell-Bellona and Temotu (Eta, 1985). In the Commonwealth of the Northern Mariana Islands, it was detected in 1943 and eradicated by sterile-insect release in 1963 (Steiner et al., 1965; Mitchell, 1980), but re-established from the neighboring Guam in 1981 (Wong et al., 1989). It was detected in Nauru in 1982 and eradicated in 1999 by male annihilation and protein bait spraying, but was re-introduced in 2001 (Hollingsworth and Allwood, 2002). Although it is found in Hawaii, it is absent from the continental United States (Weems and Heppner, 2001).

Host range

Melon fruit fly damages over 81 plant species (Table 2). Based on the extensive surveys carried out in Asia and Hawaii, plants belonging to the family Cucurbitaceae are preferred most (Allwood et al. 1999). Doharey (1983) reported that it infests over 70 host plants, amongst which, fruits of bitter gourd (*Momordica charantia*), muskmelon (*Cucumis melo*), snap melon (*Cucumis melo* var. *momordica*) and snake gourd (*Trichosanthes anguina* and *T. cucumeria*) are the most preferred hosts. However, White and Elson-Harris (1994) stated that many of the host records might be based on casual observations of adults resting on plants or caught in traps set in non-host plant species. In the Hawaiian Islands, melon fruit fly has been observed feeding on the flowers of the sunflower, Chinease bananas and the juice exuding from sweet corn. Under induced oviposition, McBride and Tanda (1949) reported that broccoli (*Brassica oleracea* var. *capitata*), dry onion (*Allium cepa*), blue field banana (*Musa paradisiaca* sp. *sapientum*), tangerine (*Citrus reticulata*) and longan (*Euphoria longan*) are doubtful hosts of *B. cucurbitae*. The melon fly has a mutually beneficial association with the Orchid, *Bulbophyllum patens*, which produces zingerone. The males pollinate the flowers and acquire the floral essence and store it in the pheromone glands to attract con-specific females (Hong and Nishida, 2000).

Nature and extent of damage

Maggots feed inside the fruits, but at times, also feed on flowers, and stems. Generally, the females prefer to lay the eggs in soft tender fruit tissues by

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Table 1. Geographic distribution of melon fruit fly, *Bactrocera cucurbitae*.

Country	Reference
Asia	Fletcher, 1987; Waterhouse, 1993
India	Shah et al., 1948; Narayanan, 1953; Narayanan and Batra, 1960; Fletcher, 1987; Vargas et al., 1920%; Gupta and Verma, 1992; Pareek and Kavadia, 1995; Weems and Heppner, 2001
Pakistan	Shah et al., 1948; Narayanan, 1953; Narayanan and Batra, 1960; Qureshi et al., 1974; Weems and Heppner, 2001
Nepal	Narayanan, 1953; Narayanan and Batra, 1960; Weems and Heppner, 2001
Sri Lanka	Narayanan, 1953; Narayanan and Batra, 1960; Tsuruta, 1998; Weems and Heppner, 2001
Myanmar	Narayanan, 1953; Narayanan and Batra, 1960; Weems and Heppner, 2001
Siam	Narayanan, 1953; Narayanan and Batra, 1960; Weems and Heppner, 2001
Malaysia	Hardy, 1949; Narayanan, 1953; Narayanan and Batra, 1960; Tan and Lee, 1982; Weems and Heppner, 2001
Indonesia	Hardy, 1949; Narayanan, 1953; Christenson and Foote, 1960; Narayanan and Batra, 1960; Weems and Heppner, 2001
China	Narayanan, 1953; Narayanan and Batra, 1960; Liang et al., 1993; Weems and Heppner, 2001
Singapore	Narayanan, 1953; Narayanan and Batra, 1960; Weems and Heppner, 2001
Philippines	Hardy, 1949; Narayanan, 1953; Christenson and Foote, 1960; Narayanan and Batra, 1960; Weems and Heppner, 2001
Taiwan (Formosa)	Narayanan, 1953; Narayanan and Batra, 1960; Fang and Chang, 1984; Wen, 1985; Chu et al., 1994; Weems and Heppner, 2001
Sarawak	Christenson and Foote, 1960
Timore	Christenson and Foote, 1960
Australic-Oceania	
Australia	Narayanan, 1953; Narayanan and Batra, 1960; Fletcher, 1987; Osmelak, 1920%
Hawaiian Islands	Back and Pemberton, 1917; Narayanan, 1953; Christenson and Foote, 1960; Narayanan and Batra, 1960; Uchida et al., 1920%; Weems and Heppner, 2001
Solomon Islands	Eta, 1985; Hollingsworth et al., 1997
Mariana Islands	Steiner et al., 1965; Mitchell, 1980; Wong et al., 1989; Weems and Heppner, 2001
Papua (New Guinea)	Hollingsworth et al., 1997; Weems and Heppner, 2001
Guam	Christenson and Foote, 1960; Wong et al., 1989
Nauru	Hollingsworth and Allwood, 2002
Islands of Rota	Wong et al., 1989; Weems and Heppner, 2001
Africa	
Cameroon	Fontem et al., 1999
Egypt	Weems and Heppner, 2001
Kenya	Christenson and Foote, 1960; Weems and Heppner, 2001
Tanzania	Christenson and Foote, 1960; Weems and Heppner, 2001
Mauritius	Christenson and Foote, 1960; Weems and Heppner, 2001
East Africa	Narayanan and Batra, 1960; Weems and Heppner, 2001
South America	
South Pacific Islands	Fletcher, 1987

piercing them with the ovipositor. A watery fluid oozes from the puncture, which becomes slightly concave with seepage of fluid, and transforms into a brown resinous deposit. Sometimes pseudo-punctures (punctures without eggs) have also been observed on the fruit skin. This reduces the market value of the produce. In Hawaii, pumpkin and squash are heavily damaged even before fruit set. The eggs are laid into unopened flowers, and the larvae successfully develop in the taproots, stems, and leaf stalks (Weems and Heppner, 2001). Miyatake et al.(1993) reported < 1% damage by pseudo-punctures by the sterile females in cucumber, sponge gourd and bitter gourd. After egg hatching, the maggots bore into the pulp tissue and make the feeding galleries. The fruit subsequently rots or becomes distorted. Young larvae leave the necrotic region and move to healthy tissue, where they often introduce various pathogens and hasten fruit decomposition. The vinegar fly, *Drosophilla melanogaster* has also been observed to lay eggs on the fruits infested by melon fly, and acts as a scavenger (Dhillon et al., 2005b). The extent of losses vary between 30 to 100%, depending on the cucurbit species and the season. Fruit infestation by melon fruit fly in bitter gourd has been reported to vary from 41 to 89% (Lall and Sinha, 1959; Narayanan and Batra, 1960; Kushwaha et al., 1973; Gupta and Verma, 1978; Rabindranath and Pillai, 1986). The melon fruit fly has been reported to infest 95% of bitter gourd fruits in Papua (New Guinea), and 90% snake gourd and 60 to 87% pumpkin fruits in Solomon Islands (Hollingsworth et al., 1997). Singh et al. (2000) reported 31.27% damage on bitter gourd and 28.55% on watermelon in India.

Life Cycle

The melon fruit fly remains active throughout the year on one or the other host. During the severe winter months, they hide and huddle together under dried leaves of bushes and trees. During the hot and dry season, the flies take shelter under humid and shady places and feed on honeydew of aphids infesting the fruit trees. The lower developmental threshold for melon fruit fly was recorded as 8.1° C (Keck, 1951). The lower and upper developmental thresholds for eggs were 11.4 and 36.4° C (Messenger and Flitters, 1958). The accumulative day degrees required for egg, larvae, and pre-egg laying adults were recorded as 21.2, 101.7, and 274.9 day degrees, respectively (Keck, 1951). This species actively breeds when the temperature falls below 32.2° C and the relative humidity ranges between 60 to 70%. Fukai (1938) reported the survival of adults for a year at room temperature if fed on fruit juices. In general, its life cycle lasts from 21 to 179 days (Fukai, 1938; Narayanan and Batra, 1960). Development from

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Table 2. Host range of melon fruit fly, *Bactrocera cucurbitae*.

Common Name	Scientific Name	Reference
Cucurbitaceous vegetables		
Bitter gourd	*Momordica charantia*	Narayanan, 1953; Narayanan and Batra, 1960; Wen, 1985; Wong et al., 1989; Uchida et al., 1990; Pareek and Kavadia, 1994; Hollingsworth et al., 1997; Allwood et al., 1999; Weems and Heppner, 2001
Muskmelon	*Cucumis melo C. melo var. conomon*	Narayanan, 1953; Narayanan and Batra, 1960; Wen, 1985; Pareek and Kavadia, 1994; Allwood et al., 1999; Weems and Heppner, 2001
Snap melon	*C. melo var. momordica*	Narayanan, 1953; Narayanan and Batra, 1960; Allwood et al., 1999; Weems and Heppner, 2001
Snake gourd	*Trichosanthes anguina T. cucumeria*	Narayanan, 1953; Narayanan and Batra, 1960; Hollingsworth et al., 1997; Allwood et al., 1999; Weems and Heppner, 2001
Pumpkin	*Cucurbita maxima C. pepo C. moschata*	Back and Pemberton, 1917; Narayanan, 1953; Narayanan and Batra, 1960; Wen, 1985; Pareek and Kavadia, 1994; Hollingsworth et al., 1997; Allwood et al., 1999; Weems and Heppner, 2001
Cucumber	*Cucumis sativus*	Narayanan, 1953; Narayanan and Batra, 1960; Pareek and Kavadia, 1994; Allwood et al., 1999; Weems and Heppner, 2001
Long melon	*Cucumis utilissimus*	Narayanan, 1953; Narayanan and Batra, 1960; Pareek and Kavadia, 1994; Weems and Heppner, 2001
Water melon	*Citrulus vulgaris C. lanatus*	Narayanan, 1953; Narayanan and Batra, 1960; Pareek and Kavadia, 1994; Allwood et al., 1999; Weems and Heppner, 2001
Chinese melon	*Benincasa hispida*	Narayanan and Batra, 1960
Squash melon	*Benincasa hispida Cucumis vulgaris var. fistulosus*	Narayanan and Batra, 1960; Back and Pemberton, 1917; Narayanan, 1953; Narayanan and Batra, 1960; Allwood et al., 1999; Weems and Heppner, 2001
Bottle gourd	*Lagenaria vulgaris*	Narayanan, 1953; Narayanan and Batra, 1960; Pareek and Kavadia, 1994; Allwood et al., 1999; Weems and Heppner, 2001
Calabash	*Lagenaria siceraria*	Narayanan and Batra, 1960; Allwood et al., 1999; Wen, 1985; Weems and Heppner, 2001
Ribbed gourd	*Luffa acutangula*	Narayanan, 1953; Narayanan and Batra, 1960; Pareek and Kavadia, 1994; Allwood et al., 1999; Weems and Heppner, 2001
Sponge gourd	*Luffa cylindrica*	Narayanan, 1953; Narayanan and Batra, 1960; Pareek and Kavadia, 1994; Allwood et al., 1999; Weems and Heppner, 2001
Pointed gourd	*Trichosanthes dioica*	Narayanan, 1953; Narayanan and Batra, 1960; Allwood et al., 1999; Weems and Heppner, 2001
Wild cucurbits	*Cucumis trigonus; C. pubescens; C. anguria; Citrulus colocynthis; Sycos sp.; S. pachycarpus; Lagenaria amebicana; Coccinia grandis; C. dipsaceus; Momordica charantia var. muricata*	Narayanan, 1953; Narayanan and Batra, 1960; Uchida et al., 1990; White and Elson-Harris, 1994; Weems and Heppner, 2001; Dhillon et al., 2005b
Wild snake gourd	*Trichosanthes cucumerina*	Narayanan, 1953; Narayanan and Batra, 1960
Other vegetables		
Scarlet or ivy gourd	*Cocconia indica*	Narayanan and Batra, 1960
Kundru	*Cephalendra indica*	Narayanan, 1953; Narayanan and Batra, 1960
Grenadille	*Passiflora edulis; P. seemanni; P. quandrangularis*	Narayanan and Batra, 1960; Weems and Heppner, 2001
Tomato	*Lycopersicum esculentum*	Narayanan, 1953; Narayanan and Batra, 1960; Ranganath and Veenakumari, 1997; Weems and Heppner, 2001; Fontem et al., 1999
Brinjal	*Solanum melongena*	Narayanan, 1953; Narayanan and Batra, 1960; Weems and Heppner, 2001
Chilly/green pepper	*Capsicum frutescens*	Narayanan, 1953; Narayanan and Batra, 1960
Okra	*Abelmoschus esculentus*	Narayanan and Batra, 1960; Kumagai et al., 1996
Kohl rabi	*Brassica culorapa*	Narayanan and Batra, 1960; Ranganath and Veenakumari, 1996
Cauliflower	*B. oleracea var. botrytis*	Narayanan and Batra, 1960
Broccoli	*B. oleracea var. capitata*	McBride and Tanda, 1949
Cantaloupe	unidentifed *Melothria liukiuensis*	Weems and Heppner, 2001 Iwaizumi, 1993
Vegetable marrow		Back and Pemberton, 1917
Zingerone	*Bulbophyllum patens*	Hong and Nishida, 2000
Dry onion	*Allium cepa*	McBride and Tanda, 1949
Longan	*Euphoria longan*	McBride and Tanda, 1949
Grain legumes		
Long bean or cowpea	*Vigna unguiculata; V. sinensis; V. sesquipedalis*	Narayanan and Batra, 1960; Wong et al., 1989; Weems and Heppner, 2001
String / French bean	*Phaseolus vulgaris*	Narayanan and Batra, 1960; Wong et al., 1989; Weems and Heppner, 2001
Lime bean	*Phaseolus limensis*	Narayanan and Batra, 1960
Green gram	*Phaseolus radiatus*	Narayanan and Batra, 1960
Hyacinth bean	*Dolichos lablab*	Narayanan and Batra, 1960
Pigeonpea	*Cajanus cajan*	Narayanan and Batra, 1960
Other field crops		
Sunflower	*Helianthus annus*	White and Elson-Harris, 1994
Sweet corn	*Zea mays*	White and Elson-Harris, 1994
Fruits		
Balsam apple	*Diplocyclos palmatus*	Weems and Heppner, 2001
Galls grape vine	*Vitis trifolia*	Narayanan, 1953; Narayanan and Batra, 1960
Shaddock/pummelo	*Citrus grandis*	Narayanan, 1953; Tan and Lee, 1982
Papaya	*Carica papaya*	Narayanan, 1953; Narayanan and Batra, 1960; Wong et al., 1989; Vargas et al., 1990; Weems and Heppner, 2001
Guava	*Psidium guajava*	Narayanan, 1953; Narayanan and Batra, 1960; Wen, 1985
Peach	*Prunus persica*	Narayanan, 1953; Narayanan and Batra, 1960; Weems and Heppner, 2001
Date palm	*Phoenix dactylifera*	Narayanan, 1953; Narayanan and Batra, 1960
Pear	*Pyrus communis*	Narayanan and Batra, 1960
Strawberry	*Fragaria chiloansis*	Narayanan and Batra, 1960
Mango	*Mangifera indica*	Narayanan and Batra, 1960; Weems and Heppner, 2001
Tangerine	*Citrus reticulata*	McBride and Tanda, 1949; Narayanan and Batra, 1960; Weems and Heppner, 2001

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Table 2, con't.

Common Name	Scientific Name	Reference
Orange	*C. sinensis*	Narayanan and Batra, 1960; Weems and Heppner, 2001
Fig	*Ficus carica*	Narayanan, 1953; Narayanan and Batra, 1960; Weems and Heppner, 2001
Avocado	*Persea americana*	Narayanan, 1953; Narayanan and Batra, 1960
Sour soap	*Anona muricata*	Narayanan and Batra, 1960
Custard apple	*Anona reticulata; A. squamosa*	Narayanan and Batra, 1960
Apple	*Pyrus malus*	Narayanan and Batra, 1960; Wen, 1985
Litchi	*Litchi chinensis*	Wen, 1985
Starfruit/carambolas	*Averrhoa carambola*	Wen, 1985; Armstrong et al., 1995
Chinese banana	*Musa sp.*	White and Elson-Harris, 1994
Blue field banana	*M. paradisiaca sp. sapientum*	McBride and Tanda, 1949

egg to adult stage takes 13 days at 29° C in Solomon Islands (Hollingsworth et al., 1997). High temperature, long period of sunshine, and plantation activity influence the *B. cucurbitae* abundance in the North-eastern Taiwan (Lee et al., 1992). Bhatia and Mahto (1969) reported that the life cycle is completed in 36.3, 23.6, 11.2, and 12.5 days at 15, 20, 27.5, and 30° C, respectively. There are 8 to 10 generations in a year (White and Elson-Harris, 1994; Weems and Heppner, 2001).

The egg incubation period on pumpkin, bitter gourd, and squash gourd has been reported to be 4.0 to 4.2 days at 27 ± 1° C (Doharey, 1983), 1.1 to 1.8 days on bitter gourd, cucumber and sponge gourd (Gupta and Verma, 1995), and 1.0 to 5.1 days on bitter gourd (Koul and Bhagat, 1994; Hollingsworth et al., 1997). The larval period lasts for 3 to 21 days (Renjhan, 1949; Narayanan and Batra, 1960; Hollingsworth et al., 1997), depending on temperature and the host. On different cucurbit species, the larval period varies from 3 to 6 days (Chawla, 1966; Chelliah, 1970; Doharey, 1983; Koul and Bhagat, 1994; Gupta and Verma, 1995). Egg viability and larval and pupal survival on cucumber have been reported to be 91.7, 86.3, and 81.4%, respectively; while on pumpkin these were 85.4, 80.9, and 73.0%, respectively, at 27 ± 1° C (Samalo et al., 1991).

The full-grown larvae come out of the fruit by making one or two exit holes for pupation in the soil. The larvae pupate in the soil at a depth of 0.5 to 15 cm. The depth up to which the larvae move in the soil for pupation, and survival depend on soil texture and moisture (Jackson et al., 1998; Pandey and Misra, 1999). Doharey (1983) observed that the pupal period lasts for 7 days on bitter gourd and 7.2 days on pumpkin and squash gourd at 27 ± 1° C. In general, the pupal period lasts for 6 to 9 days during the rainy season, and 15 days during the winter (Narayanan and Batra, 1960). Depending on temperature and the host, the pupal period may vary from 7 to 13 days (Hollingsworth et al., 1997). On different hosts, the pupal period varies from 7.7 to 9.4 days on bitter gourd, cucumber, and sponge gourd (Gupta and Verma, 1995), and 6.5 to 21.8 days on bottle gourd (Koul and Bhagat, 1994; Khan et al., 1993).

The males of the *B. cucurbitae* mate with females for 10 or more hours, and sperm transfer increases with the increase in copulation time. Egg hatchability is not influenced by mating duration (Tsubaki and Sokei, 1988). Yamagishi and Tsubaki (1990) observed that no sperms were transferred during the first 0.5 h of copulation. Sperm transfer increased to nearly 6400 until 4 h, and thereafter, the number of sperms remained almost unchanged up to 8 h of copulation. The pre-oviposition period of flies fed on cucumbers ranged between 11 to 12 days (Back and Pemberton, 1917; Hollingsworth et al., 1997). Pre-oviposition and oviposition periods range between 10 to 16.3, and 5 to 15 days, respectively, and the females live longer (21.7 to 32.7 days) than the males (15.0 to 28.5 days) (Koul and Bhagat, 1994). The adults survive for 27.5, 30.71 and 30.66 days at 27 ± 1° C on pumpkin, squash gourd and bitter gourd, respectively (Doharey, 1983). Khan et al. (1993) reported that the males and females survived for 65 to 249 days and 27.5 to 133.5 days respectively. The pre-mating and oviposition periods lasted for 4 to 7 days and 14 to 17 days, respectively. The females survived for 123 days on papaya in the laboratory (24° C, 50% RH and LD 12: 12) (Vargas et al., 1992), while at 29° C they survived for 23.1 to 116.8 days (Vargas et al., 1997). Mean single generation time is 71.7 days, net reproductive rate 80.8 births per female, and the intrinsic rate of increase is 0.06 times (Vergas *et al.* 1992). Yang et al. (1994) reported the net reproductive rate to be 72.9 births per female.

Bactrocera cucurbitae strains were selected for longer developmental period and larger body size on the basis of pre-oviposition period, female age at peak fecundity, numbers of eggs at peak fecundity, total fecundity, longevity of males and females, age

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at first mating, and number of life time matings (Miyatake, 1995). However, longer developmental period was not necessarily associated with greater fecundity and longevity (Miyatake, 1996). The peak larval, pre-oviposition, and oviposition periods were observed to be 6.48 versus 6.89, 14.0 versus 20.0, and 32 versus 62 days, respectively after nine and 24 generations of mass rearing and selection under laboratory conditions (Miyatake, 1997; 1998a). The egg hatchability and larval-pupal survival were 81.3 versus 89%, and 75.8 versus 77.2% after nine and 24 generations of mass rearing and selection. Miyatake (1998b) reported that males show heritable variation in pre-mating period, while no such effects were observed in the females. The population of *B. cucurbitae* mass reared for a long time has a shorter pre-mating period than the population reared for short-term. A genetic trade-off has been observed between early-fecundity and longevity. The mass reared population has a negative genetic correlation between early-fecundity and longevity indicating antagonistic pleiotropy. The selected strain had lower and early fecundity than the non-selected strain (Soemori and Nakamori, 1981; Kamikado et al., 1987; Kakinohana and Yamagishi, 1991 and Miyatake, 1997). Therefore, it may be interesting to examine the mating ability of the males of the selected strain, because the effectiveness of the sterile-male release technique depends on the mating ability of the sterile males released into the eco-system. The genetic trade-off between behavioral traits should be taken into account along with life history during mass rearing programs, which might result in significant pre-mating isolation in the melon fly populations (Miyatake, 1998a; Miyatake and Shimizu, 1999).

Strategies for integrated management of melon fruit fly

The fruits of cucurbits, of which the melon fly is a serious pest, are picked up at short intervals for marketing and self-consumption. Therefore, it is difficult to rely on insecticides as a means of controlling this pest. In situations where chemical control of melon fruit fly becomes necessary, one has to rely on soft insecticides with low residual toxicity and short waiting periods. Therefore, keeping in view the importance of the pest and crop, the melon fruit fly management could be done using local area management or wide area management.

Local area management

Local area management means the minimum scale of pest management over a restricted area such as at field level/crop level/village level, which has no natural protection against reinvasion. The aim of local area management is to suppress the pest, rather than eradicate it. Under this management option a number of methods such as bagging of fruits, field sanitation, protein baits and cue-lure traps, host plant resistance, biological control, and soft insecticides, can be employed to keep the pest population below economic threshold in a particular crop over a period of time to avoid the crop losses without health and environmental hazards, which is the immediate concern of the farmers.

Bagging of fruit. Bagging of fruits on the tree (3 to 4 cm long) with 2 layers of paper bags at 2 to 3 day intervals minimizes fruit fly infestation and increases the net returns by 40 to 58% (Fang, 1989a, b; Jaiswal et al., 1997). Akhtaruzzaman et al. (1993) suggested cucumber fruits should be bagged at 3 days after anthesis, and the bags should be retained for 5 days for effective control. It is an environmentally safe method for the management of this pest.

Field sanitation. The most effective method in melon fruit fly management uses primary component- field sanitation. To break the reproduction cycle and population increase, growers need to remove all unharvested fruits or vegetables from a field by completely burying them deep into the soil. Burying damaged fruits 0.46 m deep in the soil prevents adult fly eclosion and reduces population increase (Klungness et al., 2005).

Monitoring and control with parapheromone lures/cue-lure traps. The principal of this particular technique is the denial of resources needed for laying by female flies such as protein food (protein bait control) or parapheromone lures that eliminate males. There is a positive correlation between cue-lure trap catches and weather conditions such as minimum temperature, rainfall, and minimum humidity. The sex attractant cue-lure traps are more effective than the food attractant tephritlure traps for monitoring the *B. cucurbitae* in bitter gourd (Pawar). Methyl eugenol and cue-lure traps have been reported to attract *B. cucurbitae* males from mid-July to mid-November (Ramsamy et al., 1987; Zaman,

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1995; Liu and Lin, 1993). A leaf extract of *Ocimum sanctum*, which contain eugenol (53.4%), beta-caryophyllene (31.7%) and beta-elemene (6.2%) as the major volatiles, when placed on cotton pads (0.3 mg) attract flies from a distance of 0.8 km (Roomi et al., 1993). Thus, melon fruit fly can also be controlled through use of *O. sanctum* as the border crop sprayed with protein bait (protein derived from corn, wheat or other sources) containing spinosad as a toxicant. Cue-lure traps have been used for monitoring and mass trapping of the melon fruit flies in bitter gourd (Paw et al. 1991; Permalloo et al., 1998; Seewooruthun et al., 1998). A number of commercially produced attractants (Flycide® with 85% cue-lure content; Eugelure® 20%; Eugelure® 8%; Cue-lure® 85% + naled; Cue-lure® 85% + diazinon; Cue-lure® 95% + naled) are available on the market, and have been found to be effective in controlling this pest (Iwaizumi et al., 1991). Chowdhury et al. (1993) captured 2.36 to 4.57 flies/ trap/ day in poison bait traps containing trichlorfon in bitter gourd. The use of male lure cearlure B1® (Ethylcis-5-Iodo-trans-2-methylcyclohexane-1-carboxylate) have been found to be 4-9 times more potent than trimedlure® for attracting medfly, *Ceratitis capitata* males (Mau et al., 2003b), and thus could be tried for male annihilation strategies of melon fruit fly areawide control programs. A new protein bait GF-120 Fruit Fly Bait® containing spinosad as a toxicant have been found to be effective in the areawide management of melon fruit fly in Hawaii (Prokopy et al., 2003, 2004). The GF-120 Fruit Fly Bait® would be highly effective, when applied to sorghum plants surrounding cucumbers against protein-hungry melon flies, but would be less effective in preventing protein-satiated females from arriving on cucumbers. Maize can also be used as a border crop for melon fruit fly attraction through application of protein bait (Dhillon, personal observations). Although, the protein baits, parapheromone lures, cue-lures, and baited traps have been successful for the monitoring and control of melon fruit fly, the risk is the immigration of protein-satiated females. The risk of immigration of already-satiated females could principally be managed by increasing the distance these satiated immigrants must travel (Stonehouse et al., 2004).

Biological control. There are no reports on the successful use of bio-control agents against the melon fruit fly. Srinivasan (1994) reported *Opius fletcheri* Silv. to be a dominant parasitoid of *B. cucurbitae*, but the efficacy of this parasitoid has not been tested under field conditions in India. The parasitization of *B. cucurbitae* by *O. flatcheri* has been reported to vary from 0.2 to 1.9% in *M. charantia* fields in Honolulu at Hawaii (Wong et al., 1989). Similar level of parasitization (<3%) was also reported from northern India by Nishida (1963). However, Willard (1920), Newell et al. (1952), and Nishida (1955) have reported parasitization at levels of 80, 44, and 37%, respectively, from Hawaii. Thus, there is a need to reevaluate the parasitization potential of *O. flatcheri* before its exploitation as biocontrol agent for the management of *B. cucurbitae*. More recently, a new parasitoid, *Fopius arisanus* has also been included in the IPM program of *B. cucurbitae* at Hawaii (Wood, 2001). A Mexican strain of the nematode, *Steinernema carpocapsae* Weiser (*Neoaplectana carpocapsae*), has been reported to cause 0 to 86% mortality to melon fruit fly after an exposure of 6 days to 5000 to 5,000,000 nematodes/cup in the laboratory, and an average of 87.1% mortality under field conditions when applied at 500 infective juveniles/cm^2 soil (Lindegren, 1990). Sinha (1997) reported that culture filterate of the fungus, *Rhizoctonia solani* Kuhn, to be an effective bio-agent against *B. cucurbitae* larvae. While, the fungus, *Gliocladium virens* Origen, has been reported to be an effective against *B. cucurbitae* (Sinha and Singh 1998). Culture filtrates of the fungi *R. solani*, *Trichoderma viridae* Pers., and *G. virens* affected the oviposition and development of *B. cucurbitae* adversely (Sinha and Saxena, 1999).

The efficacy of most of these bio-agents is unclear under field conditions. Therefore, there is a need to evaluate the efficacy of these bio-control agents against *B. cucurbitae* for practical use in integrated pest management programs.

Host plant resistance. Host plant resistance is an important component in integrated pest management programs. It does not cause any adverse effects to the environment, and no extra cost is incurred to the farmers. Unfortunately success in developing high yielding and fruit fly-resistant varieties has been limited. The sources of resistance to fruit fly are listed in Table 3. There is a distinct possibility of transferring resistance genes in the cultivated genotypes from the wild relatives of cucurbits for developing varieties resistant to melon fruit fly through wide hybridization.

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Table 3. Sources of resistance to melon fruit fly, *Bactrocera cucurbitae*.

Crop	Genotypes	Remarks	Reference
Bitter gourd	IHR 89 and IHR 213	Resistant, thick and tough fruit rind	Pal et al., 1984
	Hisar II, Acc. 3, and Ghoti	Resistant	Srinivasan, 1991
	Acc. 23 and Acc. 33	Resistant	Thakur et al., 1992
	C 96	Stable yield, resistant	Thakur et al., 1992
	NBTI 1	Stable resistance	Thakur et al., 1994
	BG 14	Resistant, high yield	Thakur et al., 1996
	Kerala collection 1 and Faizabad collection 17	Resistant, high yield	Tewatia et al., 1997
Wild bitter gourd accessions	IC 256185 and IC 248256	High resistance	Dhillon et al., 2005a, b
	IC 213311, IC 248282, IC 256110, IC 248254, IC 248281, and IC 248292	Resistant	
Pumpkin	IHR 35, IHR 40, IHR 79-2, IHR 83, and IHR 86	High resistance	Nath, 1966
	Arka Suryamukhi	Resistant	Mahajan et al., 1997
Bottle gourd	NB 29	High resistance	Nath, 1966
	NB 22, NB 25, NB 28, and Pusa Smooth Purple Long	Moderate resistance	Nath, 1966
Sponge gourd	NS 14	Moderate resistance	Nath, 1966
Ridge gourd	NR 2, NR 5, and NR 7	Moderate resistance	Nath, 1966
Round melon	Arka Tinda	Resistant	Mahajan et al., 1997
Wild melon	Cucumis callosus	High resistance	Chelliah, 1970

Chemical Control. Chemical control of the melon fruit fly is relatively ineffective. However, insecticides such as malathion, dichlorvos, phosphamidon, and endosulfan are moderately effective against the melon fly (Agarwal et al., 1987). Bhatnagar and Yadava (1992) reported malathion (0.5%) to be more effective than carbaryl (0.2%) and quinalphos (0.2%) on bottle gourd, sponge gourd, and ridge gourd. The application of molasses + malathion (Limithion 50 EC) and water in the ratio of 1: 0.1: 100 provides good control of melon fly (Akhtaruzzaman et al., 2000). Application of either 0.05% fenthion or 0.1% carbaryl at 50% appearance of male flowers, and again at 3 days after fertilization is helpful in reducing the melon fly damage (Srinivasan, 1991). Gupta and Verma (1982) reported that fenitrothion (0.025%) in combination with protein hydrolysate (0.25%) reduced fruit fly damage to 8.7 % as compared to 43.3 % damage in untreated control. Application of carbofuran granules at 1.5 kg a.i./ ha at the time of sowing, vining, and flowering gave 83.35% protection to bitter gourd against *B. cucurbitae* (Thomas and Jacob, 1990). Dicrotophos (at 600g a.i.) and trichlorfon (at 1920g a.i./ ha) has been found to give good control of *B. cucurbitae* in muskmelon (Chughtai and Baloch, 1988). Formathion is more effective than trichlorfon (Talpur et al., 1994). Diflubenzuron has also been reported to be effective in controlling the melon fly (Mishra and Singh, 1999). Reddy (1997) reported triazophos to be the most effective insecticide against this pest on bitter gourd. Highest yield and lowest damage were observed in pumpkin when treated with carbofuran at 1.5 kg a.i./ ha at 15 days after germination (Borah, 1998). An extract of *Acorus calamus* (0.15%) reduced the adult longevity from 119.2 days to 26.6 days when fed continuously with sugar mixed with extract (at 1 ml/g sugar) (Nair and Thomas, 1999). Neem oil (1.2 %) and neem cake (4.0 %) have also been reported to be as effective as dichlorvos (0.2 %), (Ranganath et al., 1997).

Wide area management

Wide area management is not a unitary concept, but incorporates a number of related but distinct methods including local area management. The methods used for a wide area management approach include male-sterile insect release, insect transgenesis, and quarantine control techniques in combination with available local area management options. The aim of wide area management is to coordinate and combine different characteristics of an insect eradication program over an entire area within a defensible perimeter. The area must be subsequently protected against reinvasion by quarantine controls, for example, by pest eradication on isolated islands. The USDA-ARS areawide IPM programs of melon fruit fly started in 1999 in collaboration with the Hawaiian State Department of Agriculture and University of Hawaii, using the environmentally sound strategies such as field sanitation, male annihilation with male lures and attractants, protein bait sprays/traps, augmentative releases of biological control agents (*Fopius arisanus and Psyttalia fletcheri*), and sterile insect release. It has proved to be economically viable, environmentally sensitive, sustainable, and has suppressed fruit flies below economic thresholds with the minimum use of organophosphate and carbamate insecticides (Wood, 2001; Mau et al., 2003b; Vargas et al., 2003; Klungness et al., 2005). An IPM program that used field sanitation, protein bait applications, male annihilation, and release of sterile flies and parasites reduced fruit fly infestation from 30 to 40% to less than 5%, and cut organophosphate pesticide use by 75 to 90% (Vargas, 2004).

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The recent wide area management program eradication program of *B. cucurbitae* in Seychelles demonstrated a three tier model including a) initial population reduction using bait sprays, b) elimination of reproduction using parapheromone lure blocks to eradicate males and thus prevent oviposition by females, and c) intensive surveying by traps and fruit inspection, until it can be certain that the pest is entirely eradicated (Mumford, 2004). Although, the sterile insect technique has been successfully used in area-wide approaches, the wide area management needs more sophisticated and powerful technologies in their eradication program, such as insect transgenesis, which could be deployed over wide-area and is less susceptible to immigrants. Above all, the use of the geographical information system has been used as a tool to mark site-specific locations of traps, host plants roads, land use areas and fruit fly populations within a specified operational grid (Mau et al., 2003a).

Male-sterile technique. In this technique, sterile males are released in the fields for mating with the wild females. Sterilization is accomplished through irradiation, chemo-sterilization, or by genetic manipulation. In sterile insect programs the terms 'sterility' or sterile insect' refer to the transmission of dominant lethal mutations that kill the progeny. The females either do not lay eggs or lay sterile eggs. Ultimately, the pest population can be eradicated by maintaining a barrier of sterile flies. A sterile insect program is species specific, and is considered an ecologically safe procedure and has been successfully used in area-wide approaches to suppress or eradicate pest insects in entire regions such as the pink bollworm, *Pectinophora gossypiella* in California (Walters et al., 2000), the tsetse fly, *Glossina austeni* in Zanzibar (Vreysen, 2001), the New World screwworm, *Cochliomyia hominivorax* in North and Central America (Wyss, 2000), and various tephritid fruit fly species in different parts of several continents (Klassen et al., 1994). Chemo-sterilization (by exposing the flies to 0.5 g tepa in drinking water for 24 h) and gamma irradiation are the only widely tested and accepted male-sterile techniques against melon fly (Gojrati and Keiser 1978; Odani et al., 1991). Nakamori et al. (1993) found in Okinawa that frequent and intensive release of sterile flies did not increase the ratio of sterile to wild flies in some areas, suggesting that it is important to identify such areas for eradication of this pest. Eradication of this pest has already been achieved through sterile-male release in Kikaijma Islands in 1985, Amami-oshima in 1987, Tokunoshima, and the Okierabu-jima and Yoron-jima Islands in 1989 (Sekiguchui, 1990; Anonymous, 1991a, Anonymous, 1991b; Yoshizawa, 1997). In the Mediterranean fruit fly (medfly), *Ceratitis capitata*, release of sterile males increased the effectiveness of the sterile insect program (Hendrichs et al., 2005). The use of male-sterile and male annihilation techniques has successfully eradicated the melon fly from Japan for over 24 years (Shiga, 1992; Liu, 1993). However, the suppression of *B. cucurbitae* reproduction through male annihilation with cue-lure may be problematic. Matsui et al. (1990) reported that no wild tephritids were caught with cue-lure traps after intensification of distribution of cue-lure strings, but the mating rates of mature females did not decrease as compared to those on control islands. Conventional sterilization based on ionizing radiation causes chromosome fragmentation without centromeres, where the chromosome fragments will not be transmitted correctly to the progeny, and can have adverse effects on viability and sperm quality, resulting in reduced competitiveness of sterilized individuals (Hilbrook and Fujimoto 1970; Hooper and Katiyar, 1971; Mayer et al., 1998; Cayol et al., 1999)

Transgene based, embryo-specific lethality system. Although, the sterile insect technique can be used successfully to suppress economically important pest species, conventional sterilization by ionizing radiation reduces insect fitness, which can result in reduced competition of the sterilized insects (Horn and Wimmer, 2003). A transgene-based, female-specific expression method of a conditional dominant lethal gene (Atkinson et al., 2001; Handler, 2001; Horn et al., 2002), has been well tested in *Drosophila melanogaster*, and might be transferable to other insect pest species (Heinrich and Scott, 2000; Thomas et al., 2000; Horn and Wimmer, 2003). Thus, the transgene based, dominant embryo lethality system can generate large numbers of competitive and vigorous sterile males, and can be used successfully in a sterile insect program.

Quarantine. The import and export of infested plant material from one area or country to other non-infested places is the major mode of the spread of insect-pests. The spread of the melon fly can be blocked through tight quarantine and treatment of fruits at the import/export ports. Cold treatment at 1.1 ± 0.6° C for 12 days disinfested Hawaiian

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starfruit, *Averrhoa carambola,* of tephritid eggs and larvae (Armstrong et al., 1995). Heat treatment of avocado fruits infested with eggs and larvae of *B. cucurbitae* for 40° C for 24 h reduced the estimated surviving population by 99.5 to 100% (Yang 1996). Import controls carried out in airports in France since 1993 on tropical fruits have revealed the presence of 12 non-European and one European species of Tephritidae, (Bayart et al., 1997).

Conclusion

Keeping in view the importance of the pest and crop, the melon fruit fly can be managed or suppressed locally at the growers fields using any of the option combinations available including, bagging of fruits, field sanitation, cue-lure traps, spray of protein baits with toxicants, growing fruit fly-resistant genotypes, augmentative releases of biological control agents, and soft insecticides. On the other hand, the incorporation of a number of different techniques including the sterile insect technique, transgene based embryo-specific lethality system, and quarantine, in addition to the available local area management options, could be exploited for better results in wide area management of melon fruit fly. The local area management aims mainly at suppression, rather than eradication. Use of wide area management to coordinate and combine different parts of an insect eradication program over an entire area, within a defensible perimeter, can subsequently protect against reinvasion by quarantine controls. The use of a geographical information system could also be used as an IPM tool to mark site-specific locations of traps, host plants roads, land use areas and fruit fly populations within a specified operational region. Although, sterile insect programs have been successfully used in area-wide approaches, more sophisticated and powerful technologies should be used in their eradication program such as insect transgenesis, which could be deployed over wide areas.

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