New approaches for sustainable management of the melon fruit fly, *Zeugodacus cucurbitae* Coquillett

Varun Arya, Srinivasa N, Parmanand Kumar Maurya, Nikhil Khemrajji Hatwar, Divyansh Jain

The melon fruit fly, *Zeugodacus cucurbitae* (Coquillett), is one of the most destructive pests of cucurbits, causing significant yield losses in India and across tropical and subtropical regions. Belonging to the tribe Dacini of the family Tephritidae, *Z. cucurbitae* is polyphagous, highly fecund, and widely distributed, with infestations reported in all cucurbitaceous crops. Larvae feed internally, forming galleries in fruit pulp, which results in pre and post-harvest damage, fruit distortion, rotting, and increased susceptibility to secondary infections. Effective management requires an integrated approach. Cultural practices, including field sanitation, destruction of fallen and infested fruits, and use of resistant cultivars, disrupt the pest's life cycle. Mechanical control, such as fruit bagging and pheromone-based male annihilation techniques, reduces adult population and oviposition. Biological control agents, including entomopathogenic nematodes, fungi, and parasitoids, provide eco-friendly suppression of larval and pupal stages. Recent biotechnological interventions, such as RNA interference (RNAi) and CRISPR/Cas-9-mediated gene editing, offer species-specific, heritable, and environmentally safe alternatives, targeting genes involved in reproduction, development, and pigmentation. Chemical control remains a last resort due to limited effectiveness against internal feeders and concerns over pesticide residues. A combination of these strategies, tailored to local agro-ecological conditions, forms the basis of a sustainable Integrated Pest Management (IPM) program for melon fruit fly, ensuring reduced crop losses and safer cucurbit production.

Keywords: *Zeugodacus cucurbitae, Integrated pest management, Male attractant lures, Biotechnological tools, Pest biology, Pesticides*

Varun Arya, Srinivasa N*, Parmanand Kumar Maurya, Nikhil Khemrajji Hatwar, Divyansh Jain
Department of Entomology and Agricultural Zoology, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh, India.

*Email: srinivasa@bhu.ac.in

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Introduction

Tephritids are one of the most diverse groups of organisms in the class Insecta. The family Tephritidae includes several subfamilies, namely, Blepharoneurinae, Dacinae, Phytalmiinae, Tachiniscinae, Tephritinae, and Trypetinae (NBAIR, 2021; Sahoo & Tripathy, 2021). Among these subfamilies, Dacinae includes the most notorious fruit flies of economic importance housed in the tribe Dacini. It is known to have 1/5th of the population of species in the Tephritidae family, containing quarantine-important pests of fruits and vegetables (Pape et al., 2011; Schutze et al., 2017). Dacini tribe members are generally frugivorous and florivorous, including four genera namely, *Bactrocera Macquart*, *Dacus Fabricius*, *Monacrostichus Bezzi* and *Zeugodacus Hendel* (David & Ramani, 2019). Out of 932 recognized species, only about 10 per cent are pests of commercially cultivated horticultural crops (White & Elson-Harris, 1992; Vargas et al., 2015) the majority of which are under genus *Bactrocera* and *Zeugodacus* (Verghese et al., 2002). *Bactrocera* is a large genus of fruit flies with close to 750 species identified and recognized worldwide, among which at least 50 species are economically important (Vargas et al., 2015; Drew & Hancock, 2022). Another important pest genus, *Zeugodacus*, which is now considered a subgenus under *Bactrocera* by Hancock & Drew (2018), is reported to have 196 species globally, with 30 described from India (David et al., 2024). The major economically important pests under *Zeugodacus* in India are *Z. cucurbitae* (Coquillett) (Sunda et al., 2024), *Z. tau* (Walker) (Boopathi et al., 2017), *Z. caudatus* (Fabricius) (Prabhakar et al., 2019), *Z. diversus* (Coquillett) (Nair et al., 2021), and *Z. scutellaris* (Bezzi) (Prabhakar et al., 2012), with *Z. cucurbitae* being the most damaging one (Chaudhary et al., 2025).

India is the second largest vegetable producer in the world next to China, contributing to 58.27% of the total horticultural production in the country during 2024 (DA&FW, 2025) and accounting for 10.6% of the global vegetable production (Research, 2024). The most important of them are cucurbits, accounting for 5.6% of the country’s total vegetable production (FAO, 2019). Among all the biotic factors, cucurbits are mostly infested by fruit flies, accounting for 79% of all fruit fly queries, followed by fruits (14%) and solanaceous vegetables (6%) (Sharma et al., 2015). *Z. cucurbitae*, also known as the “melon fruit fly,” is polyphagous pest species, majorly infesting cucurbits (Ghodekar et al., 2025). Depending on the cucurbit species and season, the extent of yield losses due to melon fruit fly ranges from 30 –100% (Dhillon et al., 2005); 41–89% in bitter gourd (Am et al., 2011), which is one of the most preferred hosts of the pest (Sen et al., 2019), 56.88% in cucumber (Shivangi & Swami, 2017), 9 –21% in bottle gourd, 14 –29% in ridge gourd, and 9–24% in pumpkin (Sohrab & Prasad, 2018). *Z. cucurbitae* (Coquillett) was first reported in India by Bezzi in 1913 and is native to Central Asia (Virgilio et al., 2010), the Oriental region (Mwatawala et al., 2009) and even more precisely India (Dhillon et al., 2005). It is the only fruit fly species spread uniformly in India (Mir et al., 2014).

Biology, nature and extent of damage

Z. cucurbitae is a holometabolous insect pest whose biology and damage potential are strongly influenced by environmental conditions and host availability. The eggs are white, elliptical, flattened ventrally and convex laterally, and are deposited either singly or in clusters of 4 –10 beneath the fruit epidermis using the female’s sharp ovipositor, with a fecundity of up to 300 eggs per female (Aarthi et al., 2024). After hatching, the larvae or maggots are apodous, elongated, translucent and possess a pointed anterior end with mandibular hooks. The larvae pass through three instars followed by a short pre-pupal stage before pupation. Mature maggots exit the infested fruit and pupate in the soil at depths ranging from 0.5–15 cm. Adult emergence varies with pupation depth, with emergence rates of 95 ± 2% and 86 ± 2.5% reported at soil depths of 4 cm and 10 cm, respectively (Susanto et al., 2022). The pupa is barrel-shaped, yellowish-brown and distinctly segmented into eleven segments. Adult longevity generally differs between sexes, with females surviving longer than males because of greater tolerance to starvation and environmental stresses (Miyatake, 1997). Developmental duration is highly influenced by seasonal conditions; for example, Barma and Jha (2011) observed that the total life cycle duration on pointed gourd ranged from 16–22 days during June-July but extended to 51–59 days during August-October. Similar seasonal variation in maggot duration was reported in bottle gourd (Bhowmik et al., 2014). Adult longevity is also influenced by diet, and Mir et al. (2014) reported the longest survival of males (40.4 ± 2.95 days) and females (48.6 ± 3.51 days) when adults were fed a mixture of water, molasses and Proteinex (9:0.5:0.5).

Z. cucurbitae, causes severe economic losses in cucurbit crops through oviposition and larval feeding. Females puncture the fruit surface during egg laying, resulting in the oozing of watery fluid that later forms a resinous brown deposit at the puncture site (Dhillon et al., 2005). The maggots feed inside the fruit pulp, creating galleries that lead to tissue breakdown, fruit distortion, premature fruit drop, and secondary microbial infection. Besides fruits, larvae may occasionally attack buds, flowers, and stems. Damage occurs at three stages; pre-set (ovary damage), post-set, and harvest stage (Sapkota et al., 2010). Pseudo-punctures, where oviposition occurs without egg deposition, also reduce market quality (Khursheed & Raj, 2012). Infestation levels vary among cucurbits: spine gourd (43.23% by number; 43.31% by weight) (Anant et al., 2019), long melon (39.08–44.08%) (Jakhar et al., 2020), ridge gourd (56.98%) (Shinde et al., 2021), and bitter gourd (55.20–56.53%) (Lad et al., 2020). In cucumber, 9.7% of female flowers remained unopened (Sapkota et al., 2010), while bottle gourd showed 43.85% ovary damage (Gautam et al., 2021). Under protected cultivation, ovary and post-set damage in cucumber were 8.44% and 7.86%, respectively (Subedi et al., 2021). However, pseudo-punctures by sterile females caused <1% damage (Miyatake et al., 1993). These factors make *Z. cucurbitae* a highly destructive cucurbit pest.

Management of *Z. cucurbitae*

Cultural control

It largely depends on orchard sanitation and crop hygiene to disrupt the pest life cycle, which requires a sound understanding of fruit fly biology (Reddy et al., 2020). A key practice is preventing maggots from completing development and pupating in the soil, as larvae from infested fruits usually drop to the ground and pupate at depths of 3–5 cm for about 6–8 days. Therefore, regular field sanitation through the collection and destruction of infested fruits from both vines and the ground is considered the most effective primary strategy for fruit fly management (Vadivelu, 2014). Unharvested or damaged fruits should be buried deeply in the soil to interrupt the reproductive cycle. Burying crop residues at about 15 cm depth significantly reduces adult emergence, with mortality ranging from 17.8% in clay loam to 11.1% in silty clay loam soils (Khan et al., 2020). Soil conditions also influence emergence; silty clay loam tends to inhibit fruit fly emergence, whereas sandy loam promotes pupation (Soltani et al., 2007). Environmental factors such as soil moisture also affect pupal survival, and prolonged waterlogging through irrigation or rainfall can significantly suppress melon fruit fly populations (Khan et al., 2020). Soil water content has been reported to account for about 48.47% of the variation in adult emergence, particularly affecting newly formed pupae aged 4–7 days (El-Gendy & AbdAllah, 2019). The use of resistant cultivars further strengthens cultural control. Bitter gourd cultivars such as Thusi, Katahi, Preethi, Phule Green Gold and Improved Hirkani show relatively low infestation (11–20%) (Mallikarjunarao et al., 2020). Similarly, ridge gourd cultivars AHRG-57, AHRG-29 and Pusa Nasdar show moderate resistance with 15–18% infestation (Haldhar et al., 2015), while sweet gourd cultivars BD 274 and BD 277 exhibit infestation levels around 19.3–19.7% (Afroz et al., 2021). In cucumber, the variety

Kamini has been reported to yield the highest (26.66 t/ha) with comparatively lower fruit fly infestation (Maharjan et al., 2015). Thus, sanitation, soil management and resistant cultivars together form an effective cultural strategy for fruit fly management.

Mechanical control

Mechanical management of melon fruit fly includes physical protection of fruits and trapping techniques to prevent oviposition and reduce adult populations. Fruit bagging with cloth or paper bags within 1–3 days after anthesis and retaining them for about 7–10 days effectively protects fruits from infestation. In bitter gourd, bagging increased fruit edibility from 73.42–100% and improved fruit size by 31.12–56.53% (Pokhrel, 2019). Similarly, Mukherjee et al. (2007) reported the lowest infestation (29.91 ± 2.02%) in sweet gourd when fruits were bagged two days after anthesis, while bagging combined with soil insecticide treatment reduced bitter gourd infestation to 8.91% (Sarkar et al., 2017). Although labour-intensive, bagging remains an effective non-chemical method (Badii et al., 2015). Semiochemical-based trapping is another important strategy. Cue-lure [4-(p-acetoxyphenyl)-2-butanone] is highly effective in attracting melon fruit fly males and is widely used in monitoring and mass trapping programmes (Vargas et al., 2010). Trap catches in cue-lure traps (169.08–174.55 males/trap/week) were significantly higher than those in methyl eugenol traps (78.20–85.18 males/trap/week) (Khan et al., 2010). Installation of 10–15 cue-lure traps per acre from flowering to harvest is recommended for effective management (Arya et al., 2022) Figure 1. Botanical attractants such as *Ocimum sanctum* extracts and protein hydrolysate baits also attract fruit flies and can be integrated into sustainable cucurbit pest management programmes (Singh et al., 2020; Baloch et al., 2017).

Biological control

Among entomopathogenic nematode (EPN), *Heterorhabditis bacteriophora* decreases fruit fly adults emergence from pupae upto 19–52% in greenhouse and 25–31% in field conditions when applied as spray onto soil surface of 100 IJs (infective juvenile nematodes) in 100 ml distilled water (Usman et al., 2021). Kamali et al. (2013) reported moderate mortality of fruit fly larvae and pupae by *H. bacteriophora* and *Steinernema carpocapsae* at the rate of 150–300 IJs/cm^2 soil application under greenhouse. *H. taysearae* and *S. kandii* survive in soil for 30 to 32 weeks, respectively. However, EPNs can also be applied as infected insect cedavers of *Galleria mellonella* L. at the rate of 100 IJs per larvae with 10% substrate humidity to avoid severe environmental factors that impair EPNs life and efficacy, such as UV radiation, desiccation, and high temperatures (Godjo et al., 2021). For a more comprehensive understanding of the biological control agents, including parasitoids, entomopathogenic bacteria, fungi, etc., targeting *Z. cucurbitae*, readers are referred to Diksha et al. (2022).

Biotechnological control

It refers to modern biological and molecular tools to manipulate pest populations or their interactions with the environment in a target-specific, eco-friendly, and sustainable manner. One of the widely popular is the RNA interference (RNAi) technology, which works by introducing double-stranded RNA (dsRNA) molecules that specifically match a target gene in the insect. Once inside the insect’s cells, the dsRNA triggers a gene-silencing mechanism, degrading the corresponding messenger RNA (mRNA) and thereby blocking the production of essential proteins (Baum & Roberts, 2014; Yan et al., 2020). Another modern genome editing technology, CRISPR/Cas9, functions by using a guide RNA (gRNA) to direct the Cas9 enzyme to a specific DNA sequence in the insect’s genome, where the enzyme creates a targeted double-strand break.

The cell's natural repair mechanisms then introduce mutations or insertions that disrupt or modify the target gene (Singh et al., 2022; Moon et al., 2022). By editing genes responsible for reproduction, development, or insecticide resistance, CRISPR/Cas-9 enables precise, heritable, and species-specific control of pest populations in an environmentally sustainable way. In *Z. cucurbitae*, CRISPR/Cas-9 has been applied to knockdown the male accessory glands-specific gene in adult males, which significantly reduces female fecundity after mating, functioning similarly to a sterile insect technique (Wang et al., 2024). Additionally, Paulo et al. (2025) successfully silenced the ebony gene, which encodes N-β-alanyldopamine synthetase, a key enzyme regulating cuticular pigmentation, locomotion, and reproduction (Su et al., 2025). The resulting mutants exhibited dark pigmentation ("black pupa" phenotype) along with reduced fertility, highlighting the ebony gene's critical role in physiological and reproductive processes.

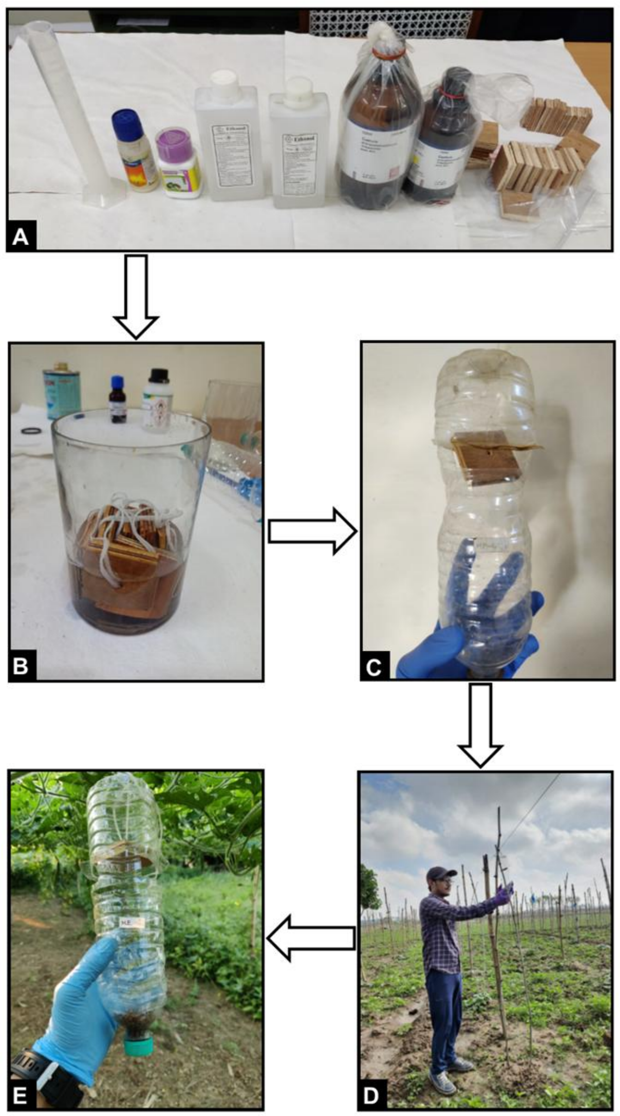

Figure 1. Preparation and installation of low-cost cue-lure bottle traps for managing *Z. cucurbitae* using MAT: (A) materials (cue-lure, ethanol, fipronil, wooden blocks, bottles), (B) lure solution (6:4:1) soaked for 24–48 h, (C-E) traps preparation and installation 1–1.5 m above ground in cucurbit pandals, with weekly fly collection

Chemical control

Insecticide application is generally considered a last resort, as it is effective against adult flies but largely ineffective against maggots, which feed internally. The issue of pesticide residues is more pronounced in fruits than in other plant parts (Donkor et al., 2016). Çelik et al. (1995) reported that volatilization is the dominant process influencing pesticide degradation in nature, although it varies with the chemical's properties, application methods, and plant physiology. However, in fruits, many lipophilic compounds are actively absorbed into the fruit skin, making degradation less effective and more time-consuming (Keikotlhaile & Spanoghe, 2011). Among cucurbit crops, El-Sheikh et al. (2022) reported the highest pesticide residues in cucumber, which was contaminated with 15 different pesticides, followed by zucchini with 12, with chlorpyrifos, lambda-cyhalothrin, and acetamiprid being the predominant contaminants. Based on a careful reassessment of registered pesticides, the Central Insecticides Board and Registration Committee (CIBRC, 2025) has now recommended only two chemical formulations for use against fruit flies infesting cucurbits in India, as detailed in Table 1.

Table 1. Recommended chemicals for the management of *Z. cucurbitae* by the Central Insecticide Board and Registration Committee (CIBRC, 2025)

Crop	Dosage per hectare			Waiting period (in days)
	Active ingredient (in g or ml)	Formulation (g or ml)	Dilution in water (in litres)	
Cyantraniliprole 10.26 % OD				
Gherkins (*Cucumis anguria*)	90	900	500	5
Flubendiamide 8.33 % + Deltamethrin 5.56 % w/w SC				
Cucumber (*Cucumis sativus*)	18 + 12 to 22.50 + 15	200–250	500	05

Conclusion

Z. cucurbitae is a highly polyphagous and economically significant pest of cucurbits in India and other tropical and subtropical regions. Its widespread distribution, high fecundity, and internal feeding habits make it a persistent threat to vegetable production, causing substantial pre and post-harvest losses. IPM approaches, including cultural, mechanical, biological, biotechnological, and chemical control, offer environmentally sustainable solutions. Among these, cultural practices and field sanitation, mechanical barriers and traps, biological agents such as entomopathogens and parasitoids, and emerging biotechnological tools like RNAi and CRISPR/Cas-9 provide species-specific, eco-friendly, and cost-effective control measures. Chemical insecticides are reserved as a last resort due to their limited efficacy against internal feeders and the potential for residue accumulation. Overall, a well-coordinated IPM strategy, combining multiple approaches and tailored to local agro-ecological conditions, is essential for effective management of melon fruit fly and sustainable cucurbit production.

Conflict of interest statements

The authors declare no conflicts of interest.

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