

AGROECOLOGICAL AND CLIMATE-SMART STRATEGIES FOR MANAGING CUCURBIT FRUIT FLIES: USE OF BIO-INTENSIVE TOOLS, LANDSCAPE DESIGN AND FARMER KNOWLEDGE

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ABSTRACT

Cucurbit fruit flies (Diptera: Tephritidae), predominantly *Zeugodacus cucurbitae* (Coquillett), impose severe yield reductions (30–100%) on crops including bitter melon, chayote, and bottle melon through larval pulp consumption, compounded by polyphagy across >125 hosts, climate-mediated population surges, and regional pest complexes involving *Bactrocera* spp. This review integrates agroecological and climate-adaptive frameworks, prioritizing bio-intensive interventions (e.g., 25% cue-lure mass trapping, *Bacillus thuringiensis* applications, yellow sticky traps), landscape diversification (intercropping, cover cropping for natural enemy habitats), and farmer-centric knowledge systems to diminish synthetic insecticide dependence. Climate-smart components encompass meteorological-pest forecasting models, resilient cultivars, minimized tillage, and participatory IPM to mitigate weather-driven shifts in infestation dynamics and enhance agroecosystem resilience. Targeted research addressing neotropical contexts, long-term phenological modelling, and validation trials is advocated to optimize sustainable management, ensuring crop productivity, ecological integrity, and socioeconomic viability in vulnerable production landscapes. This synthesis aims to bridge current knowledge gaps by systematically evaluating the efficacy and interplay of these diverse management strategies within varying agroecosystem contexts, thereby informing the development of integrated pest management protocols tailored for cucurbit production. This comprehensive approach seeks to delineate synergistic relationships between different intervention types, aiming for a robust, multi-pronged defence against fruit fly incursions that is both environmentally sound and economically feasible for farmers. The overarching goal is to foster sustainable intensification in cucurbit farming systems, transitioning from reactive, chemical-dependent control to proactive, ecologically informed pest management paradigms.

KEYWORDS: Cucurbit fruit flies, agroecology, climate-smart agriculture, integrated pest management, landscape ecology, farmer knowledge.

INTRODUCTION

The Cucurbitaceae family (118 genera, 825 species) yields essential global vegetables, many domesticated. Cucumbers, gherkins, and long melons refresh salads; muskmelons and watermelons delight as fruits; ash gourd and pointed gourd sweeten traditions. Gherkins pickle perfectly, gourds and squashes shine in curries, stir-fries, soups. In India, they represent 5.6% of vegetable output, cultivated on 4,290,000 ha at 10.52 t/ha productivity. Its production has various challenges, among which the pests and diseases hold the major share in its challenge in production. Indeed, insect pests alone contribute to a significant 10-30% loss in vegetable crop yields and often serve as vectors for various viral diseases (Navendu, 2021). In Insect Pests the major and the notorious pest is the Fruit fly. Specifically, fruit fly infestations represent a major impediment to cucurbit production, consumption, and marketing across India, with infestation rates ranging from 16.6% to 63% depending on the specific cucurbit and region (Sunda *et al.*, 2024). Among these, the melon fruit fly is a particularly destructive species, capable of causing substantial damage and economic losses, especially in bitter melon cultivation, where it is identified as a key pest (Pillania *et al.*, 2021). Cucurbit fruit flies (Tephritidae) are among the most damaging insects across the globe. These fruit flies severely compromise cucurbit production by ovipositing eggs beneath the fruit epidermis, enabling larval feeding on internal tissues and facilitating secondary pathogen infections, which result in yield losses ranging from 30% to 100% (Sarkar *et al.*, 2018). This pervasive damage highlights the urgency for robust management strategies, especially considering that many cucurbit species, such as bottle melon and bitter melon, are widely cultivated across India and are highly susceptible to these pests (Halder *et al.*, 2020; Nath *et al.*, 2017). For instance, bitter melon, a crop highly valued for its nutritional and medicinal properties, frequently experiences significant yield losses due to melon fruit fly infestations, which can reach up to 31.3% (Nath *et al.*, 2017; Pillania *et al.*, 2021). This high susceptibility underscores the necessity of effective pest management strategies to mitigate economic losses and ensure sustainable agricultural practices (Alam & Khan 2021; Mallikarjunarao *et al.*, 2020). Hence

such a devastating pest of cucurbits necessitates a comprehensive understanding of its biology and effective management techniques to safeguard crop production and ensure food security (Pilania *et al.*, 2021). Conventional chemical pesticides, while offering immediate relief, pose significant environmental and health risks, including bioaccumulation, pest resurgence, and harm to non-target organisms, thereby necessitating a shift towards more sustainable and eco-friendly solutions (Kumari *et al.*, 2021; Saud *et al.*, 2024). This critical situation underscores the urgent need for integrated pest management strategies that incorporate agroecological principles, bio-intensive tools, landscape design, and traditional farmer knowledge to sustainably manage cucurbit fruit flies (Kumari *et al.*, 2021; Nath *et al.*, 2017). This includes exploring the biology of fruit flies and their natural enemies, applying bio-intensive tools, designing pest-suppressive landscapes, and integrating traditional farmer knowledge with modern climate-smart strategies (Saud *et al.*, 2024). Effective management of these pests is essential for successful cucurbit production, requiring an understanding of both the host plants and the pests themselves (Tripathi *et al.*, 2020).

Combining diverse tactics, landscape design, and local farmer knowledge yields effective field pest control. However, the larvae and pupae of melon fruit flies are often inaccessible to surface-applied insecticides, as they develop within fruits or in the soil, rendering chemical applications largely ineffective against these life stages (Nath *et al.*, 2017). This inaccessibility necessitates the exploration of alternative, more targeted approaches to disrupt the fruit fly life cycle and mitigate crop damage (Saud *et al.*, 2024). Such strategies include the judicious use of biopesticides, biological control agents, and resistant cultivars, alongside cultural practices like field rotation and trap cropping, to minimize risks associated with conventional chemical pesticides ("Cucumber Economic Values and Its Cultivation and Breeding," 2021; Hintenou *et al.*, 2023). Hence so we need to develop integrated pest management strategies that incorporate agroecological principles, bio-intensive tools, landscape design, and traditional farmer knowledge to sustainably manage cucurbit fruit flies (Tripathi *et al.*, 2020). This review will delve into the biology of fruit flies and their natural enemies, assess the application of bio-intensive tools, evaluate the efficacy of pest-suppressive landscape designs, and integrate traditional farmer knowledge with modern climate-smart strategies to provide a holistic framework for sustainable pest management (Deguine *et al.*, 2015; Materu *et al.*, 2018). By synthesizing these diverse approaches, this paper seeks to offer a comprehensive guide for enhancing cucurbit production sustainability and resilience against fruit fly infestations, thereby contributing to food security and environmental protection (Deguine *et al.*, 2015; Jaya *et al.*, 2023).

CUCURBIT FRUIT FLY BIOLOGY:

The melon fruit fly, *Bactrocera cucurbitae*, is a significant pest in tropical and subtropical regions, known to infest a wide range of host plants, particularly cucurbitaceous vegetables like bitter melon and muskmelon ("The Melon Fruit Fly, *Bactrocera cucurbitae*: A Review of Its Biology and Management," 2005). This species is notorious for causing substantial yield losses, ranging from 30% to 100%, through direct damage to fruits where females deposit eggs, and larvae subsequently feed on internal tissues (Gaddanakeri *et al.*, 2024; Sarkar *et al.*, 2018). The female adult utilizes its sharp ovipositor to puncture the soft epidermis of the fruit, laying eggs just beneath the surface, which hatch into maggots that immediately begin to feed (Srivastava & Joshih 2021). This destructive feeding behavior within the fruit leads to significant deterioration, rendering the produce unsuitable for consumption or market, and further compounded by the potential for secondary microbial infections (Saud *et al.*, 2024). The life cycle of *B. cucurbitae* encompasses egg, larval, pupal, and adult stages, with environmental factors such as temperature and humidity significantly influencing its duration and population dynamics (Dhillon *et al.*, 2005). Such insights into its developmental biology are critical for formulating integrated pest management strategies that effectively target vulnerable life stages, thereby minimizing economic losses in cucurbit cultivation ("Cucumber Economic Values and Its Cultivation and Breeding," 2021). Thrives in tropical/subtropical areas, it's a quarantine pest worldwide due to fast spread and high reproduction. The melon fruit fly is a polyphagous species, capable of infesting over 81 host plants, which contributes to its pervasive presence and the complexity of its management in agricultural systems (Dhillon *et al.*, 2005). *B. cucurbitae* life cycle includes egg, larva (3 instars), pupa, and adult stages. Warm, humid conditions enable multiple yearly generations and rapid buildup. Cycle usually lasts 3-5 weeks optimally.

Egg Stage:

The female melon fruit fly typically deposits her eggs within the epidermal layer of young, tender fruits, creating a puncture with her ovipositor, which can also occur without subsequent egg deposition, reducing market value (Pilania *et al.*, 2021). A single female is remarkably prolific, capable of laying up to 1,000 eggs during her oviposition period, which can span 39 to 95 days (Weems *et al.*, 1969). The eggs are inserted 2 to 4 mm deep into the fruit tissues, with development from egg to adult ranging from 12 to 28 days under summer conditions, though this can extend considerably in cooler temperatures (Dhillon *et al.*, 2005; Weems *et al.*, 2012). Egg incubation periods vary based on host and temperature, for instance, ranging from 4.0 to 4.2 days on pumpkin, bitter melon, and squash at $27 \pm 1^\circ \text{C}$, and 1.1 to 1.8 days on bitter melon, cucumber, and sponge melon ("The Melon Fruit Fly, *Bactrocera cucurbitae*: A Review of Its Biology and Management," 2005). In laboratory settings, the egg stage has been observed to extend up to 11 days, with an average duration of 1.73 days at an average temperature of 30°C (Weems *et al.*, 1969). Eggs are laid in small clusters, where larval survival is high. The eggs are slender, whitish, and slightly curved, resembling tiny grains of rice. The susceptibility of various cucurbits to *B. cucurbitae* infestation is influenced by factors such as fruit skin thickness, firmness, and the presence of chemical deterrents, which can affect oviposition success and larval survival (Aarthi *et al.*, 2024; Mir *et al.*, 2014). However, the optimal temperature range for egg development is between 25°C and 30°C , with temperatures outside this range significantly prolonging the incubation period or reducing viability ("The Melon Fruit Fly, *Bactrocera cucurbitae*: A Review of Its Biology and Management," 2005). Once hatched, the larvae, or maggots, emerge from these eggs and commence feeding within the fruit pulp, initiating the most destructive phase of the pest's life cycle (Deguine *et al.*

al.,2015). Egg hatching takes around 1 day in summer, 2-3 days in spring/autumn and 7-20 days in winter, whereas large development is 9-23 days. The pupa phase lasts 5-33 days and reaches sexual maturation as adults for mating for approximately 8-15 days in daylight but differs among cryptic species complexes (Hendrichs *et al.*,2015). Adult females lay eggs mainly under the epidermis using the ovipositor on fruits and vegetables which in this case is *Sechium edule* (Liu & Ji,2024). Specifically, *B. cucurbitae* females tend to lay eggs between 10:00 and 15:00, while *D. ciliatus* oviposits from 10:00 to 13:00, and *D. demmerezi* between 16:00 and 19:00, indicating species-specific diurnal patterns in egg-laying behavior (Deguine *et al.*,2015). Short-term high-temperature treatments ranging from 34 °C to 48 °C have been shown to impact egg development, alongside other life stages, suggesting temperature as a critical environmental factor influencing egg viability and developmental rates (Huang *et al.*,2020).

Larval Stage (Maggots):

Following hatching, the larvae, which are apodous and dirty white in color, undergo three instars as they tunnel and feed extensively on the fruit's mesocarp, causing internal decay and providing entry points for secondary pathogens (Srivastava & Joshiah 2021; Weems *et al.*,1969). This feeding activity not only destroys the fruit pulp but also introduces bacteria and fungi, leading to rot and premature fruit drop (Alam & Khan,2021). The larval period includes three instars, Early instars are small and translucent, while later instars become creamy white and cylindrical with distinct mouth hooks used for feeding. The duration of the larval stage is variable, typically spanning 3 to 6 days depending on the host species and ambient temperature, with optimal development occurring around $27 \pm 1^{\circ}\text{C}$ ("The Melon Fruit Fly, *Bactrocera cucurbitae*: A Review of Its Biology and Management," 2005). The average larval period for the pumpkin fruit fly, for instance, is approximately 1.2 days for the first instar, 1.7 days for the second instar, and 4.0 days for the third instar (Gupta & Regmi,2022). The full larval developmental cycle, which culminates in the mature third-instar larva, can take between four and six days, at which point the larva measures approximately 8 mm in length and 1.4 mm in width (Weems 2012). Upon reaching maturity, these larvae cease feeding and exit the fruit, typically by burrowing into the soil where they transition into the pupal stage to complete their metamorphosis (Chen *et al.*,2023).

Pre-pupal and Pupal Stage :

The pre-pupal stage, a transitional period, is characterized by the larva's cessation of feeding and a reduction in mobility, preparing for pupation (Rashid *et al.*,2021). During this phase, the mature larva burrows into the soil to a depth of 0.5 to 15 cm, forming a hardened puparium from its last larval skin, which protects the developing pupa within (Said *et al.*,2017). The pupal stage typically lasts between 7 and 13 days, varying with temperature and host conditions, but can range from 3 to 43 days in other fruit fly species ("Cucumber Economic Values and Its Cultivation and Breeding" 2021; Halila 2024). Pupation occurs in soil or organic debris. In warm and moist conditions, adult emergence within six to nine days, whereas cooler or drier environments may prolong pupation. Soil characteristics strongly influence pupal survival and successful adult emergence. This stage is particularly vulnerable to environmental fluctuations and soil manipulation, which can significantly impact eclosion rates and adult emergence uniformity (Chen *et al.*,2024). Most larvae pupate in the upper layer of the soil, though in some instances, particularly in early generations or under specific conditions, pupation can occur within the fruit itself (Kavin *et al.*,2025; Keyhanian *et al.*,2024).

Adult Stage:

Newly emerged adults are typically elongated, pale, and exhibit folded wings, with visible meconium upon eclosion (Naseri-Karimi *et al.*,2024). The initial period following emergence is crucial for the development of full reproductive capacity and for adults to acquire the necessary resources for successful reproduction (Thomas *et al.*,1969). Adults typically emerge with energy reserves from the larval stage, enabling survival for approximately one to two days until they can locate external sources of carbohydrates and water (Hafsi ,2016). The process of eclosion, or adult emergence from the pupal case, is influenced by several factors, including the orientation of the pupa, burial depth, soil texture, and pH (Chen *et al.*,2024). Specifically, optimal pupal development and subsequent adult emergence are observed between 11 and 14 days post-pupa formation, with adult fruit flies typically emerging in the morning hours, between 6:00 AM and 12:00 PM (Sarwar 2019; Susanto *et al.*,2021). However, not all individuals successfully eclose, with studies indicating that emergence rates can be impacted by soil depth and moisture levels (Leksono *et al.*,2024). Sexual maturity is reached within one to two weeks after emergence, after which mating occurs. Adult longevity generally ranges from three to six weeks, though environmental factors and food availability may influence lifespan. Females tend to live longer than males. However, under favourable conditions of food, water, and cool temperatures, some adults may survive for up to six months or more (Thomas *et al.*,1969). Nutritional resources in the adult stage are critical; for instance, a diet rich in protein and sugar significantly enhances longevity and reproductive success, while diets high in carbohydrates can alter macronutrient allocation differently in males and females, affecting their fitness (Aceituno-Medina *et al.*,2023).

Reproductive Biology:

In fruit flies, sexual maturation exhibits clear sex-specific differences, with females requiring several days to weeks post-emergence to complete vitellogenesis, whereas males, despite their capacity for repeated mating, enter a prolonged refractory phase following each copulation. They then oviposit repeatedly, laying hundreds of eggs due to high fecundity. Females choose soft, ripe fruits using odour cues. Egg-laying punctures introduce microbes that speed fruit rot, benefiting larvae. Continuous deposition leads to overlapping generations when hosts are available. Natural populations maintain a 1:1 sex ratio, with slight environmental shifts. The lifespan of adult fruit flies is significantly influenced by diet, with studies showing that a mixture of sugar and yeast can extend female longevity to over 100 days and male longevity to nearly 90 days, compared to only 3 to 6 days when solely provided with water (Momen *et al.*,2025).

CUCURBIT FRUIT FLIES' COMPLEXES AND ITS ADAPTATIONS:

Within the family Tephritidae, several species are recognized as significant pests of cucurbit crops, collectively forming complexes that pose considerable economic challenges to agricultural production (Thakur *et al.*, 2017). These fruit flies, predominantly from the genera *Bactrocera* and *Zeugodacus*, infest a wide array of cultivated and wild fruits and vegetables, causing substantial damage that renders produce unmarketable (Eypert *et al.*, 2025). The melon fruit fly, *Zeugodacus cucurbitae*, stands out as a particularly destructive species within this complex, distributed across tropical and subtropical regions, and is considered a federal quarantine pest in Asia and Hawaii due to its capacity for 30% to 100% crop losses depending on environmental conditions and host susceptibility (Farooq *et al.*, 2019). This species is highly polyphagous, targeting a broad spectrum of cucurbitaceous vegetables and drastically reducing their yield through larval feeding on fruit pulp (Sowmiya *et al.*, 2020). This fruit fly primarily infests bitter melon (*Momordica charantia*), with infestation rates as high as 89% due to its preference for this host (Sunda *et al.*, 2024). The melon fruit fly (*Zeugodacus cucurbitae*) is a polyphagous species that utilizes at least 125 host plants, including a wide array of cucurbits like bitter melon, winter melon, cucumbers, luffa, melons, pumpkins, squashes, and watermelons, alongside other crops such as beans, eggplant, peppers, and tomatoes (Saud *et al.*, 2024). Additionally, it can attack flowers, stems, and root tissues, further extending its destructive potential beyond just the fruit (Weems *et al.*, 2012). *Z. cucurbitae* is classified as a quarantine pest globally, primarily due to its significant invasiveness, broad adaptability, and high reproductive capacity, which necessitates stringent detection, exclusion, and eradication protocols in many regions (Diksha *et al.*, 2023). This species is considered an invasive species due to its introduction into many regions of Africa, Indian Ocean islands, and Hawaii, where it has drastically curtailed the production of melons, cucumbers, and tomatoes (Asimakis *et al.*, 2019; Weems *et al.*, 1969). The economic impact of *Z. cucurbitae* is substantial, leading to crop losses ranging from 20% to 100% in cucurbit species, particularly bitter melon, bottle melon, cucumber, pumpkin, muskmelon, sponge melon, and snake melon (Deb *et al.*, 2024). Hence these tephritid fruit flies (family: Tephritidae) are diverse and cause huge losses all over the world. Tephritid fruit flies cause significant harm to industrial and economic income due to uncorrected morphology and identification (He *et al.*, 2023). Hence so such a pest causes a huge threat to production of various crops. Moreover these have many adaptive behaviour which is problematic for their control (Hendrichs *et al.*, 2015). This adaptability often includes physiological plasticity that enables them to overcome various control measures, such as developing resistance to insecticides or adapting to novel host plants (Tian *et al.*, 2023). The difficulty in distinguishing various fruit fly species, particularly those associated with cucurbits, further complicates management efforts, as misidentification can lead to ineffective control strategies (Sunda *et al.*, 2024). Another study has further stated that the reproduction rate of the cucurbit fruit flies is extremely high, with a shorter time of maturation; therefore, their different species are invasive and persistent (He *et al.*, 2023). Adults show a high olfactory behaviour to the host plant volatile and protein, hence this characteristic has been extensively used under monitoring and control schemes (Scolari *et al.*, 2021). Cucurbit fruit flies occur as a part of the pest complex that varies as per region, host preferences, cropping method and weather conditions. This intricate interplay of factors necessitates a comprehensive understanding of each species' biology and ecology to develop effective and sustainable management strategies (Liu *et al.*, 2025). Diversified agroecosystems having multiple-cucurbit hosts positioned closely in case of pest persistence, and complicate the management of pest infestation (Jasrotia *et al.*, 2023). The pest complex is also shaped by the presence of vegetation, wild cucurbit hosts and climatic situations in different regions. Supporting the varying factors, another research has mentioned that tephritid cucurbit-infesting insects select host crops and can alternate among the cucurbit crops of cucumber, melon, pumpkin, and chayote (Deguine *et al.*, 2015). This particular resilience pattern helps in season-to-season population of the insects for longstanding impact on Cucurbit crops like *Sechium edule* (chayote) (Mondal *et al.*, 2020). Although studies on pest complexes in *Sechium edule* have received comparatively less attention than those on other cucurbit crops, recent research has established that this species is a susceptible host to cucurbit fruit flies (Mondal *et al.*, 2020). Being characterised for its long fruiting period, Chayote is a favourable host for oviposition and larval development, which makes it more exposed to the pest impact than short-lived crops such as cucumber (Cadena-Íñiguez *et al.*, 2025). Gravid females use olfactory and visual cues to lay eggs on premature fruits in which *D. bivittatus* is the major species (Mokam *et al.*, 2018). This species causes 52.63–51.03% of total fruit loss, as chayote's immature-stage harvest heightens early infestation risk. Cucurbit fruit flies have specific traits like high fecundity, hidden larval feeding and a broad range of hosts, making it harder to control them with a single control method (Deguine *et al.*, 2015). These fruit flies also pose a notable pest threat to *Sechium edule* (Mokam *et al.*, 2018; Mondal *et al.*, 2020), bolstered by their climatic adaptability (Hendrichs *et al.*, 2015; Tian *et al.*, 2023) and agro-ecological conditions that sustain continuous reproduction (Cadena-Íñiguez *et al.*, 2025). Consequently, this adaptive pest complex in cucurbits elevates the need for climate-smart strategies in chayote cultivation (Martínez-Bauer *et al.*, 2021). Furthermore, the absence of natural enemies such as stingless bees, which are primary pollinators at higher altitudes, could exacerbate pest issues in certain chayote-growing regions (Martínez-Bauer *et al.*, 2021). This vulnerability highlights the critical need for comprehensive ecological research into chayote, particularly given its susceptibility to climate-induced geographical shifts, to safeguard its agricultural and economic importance (Martínez-Bauer *et al.*, 2021).

IMPORTANCE OF AGROECOLOGICAL STRATEGIES

The development and implementation of agroecological crop protection practices have been instrumental in managing fruit fly populations, significantly reducing pesticide reliance, and boosting chayote production in areas like Réunion (Deguine *et al.*, 2020). Such strategies integrate ecological principles to enhance biodiversity, promote natural pest control mechanisms, and foster sustainable agricultural systems, ultimately leading to improved crop quality and biosecurity while minimizing environmental impact (Cadena-Íñiguez *et al.*, 2024). This approach is particularly crucial for chayote, a non-traditional export vegetable with increasing commercial success, as it minimizes the application of high-impact synthetic

agrochemicals and promotes practices like pruning to reduce pest incidence, facilitating a transition towards organic farming (Cadena-Íñiguez *et al.*, 2024). Chemical insecticides have some limitations. The commonly utilized insecticides for the chemical control of fruit flies comprise organophosphates, neonicotinoids, and pyrethroids (Suma *et al.*, 2009). Authors note repeated, heavy use risks insect resistance, yielding only moderate efficacy. Moreover, the limitation of chemical control has a common need for repeated applications of pesticides which increases production costs and exposure of pests to sub-lethal concentrations (Suma *et al.*, 2009). In various areas, farmers face resistant pests that hardly vanish even after periodic application and lead to futile efforts towards agricultural protection (Bosch 2023). This scenario underscores the urgent need for integrated pest management strategies that incorporate agroecological principles to mitigate resistance development and ensure long-term sustainability in pest control (Cadena-Íñiguez *et al.*, 2024; Rayalu & Anuradha 2024). Agroecological Crop Protection offers a robust framework for addressing these challenges by emphasizing ecological sustainability, human health, and economic viability through methods such as diversified cropping systems, habitat management, and reduced chemical inputs (Deguine *et al.*, 2023). Chemical control also poses ecological and health hazard risks which are not conducive to managing pest infestation. The contribution of pesticides in soil degradation, contamination of water resources, and harm to microorganisms, essential for biodiversity, have been found (Kumari & Kumar 2025). Consequently, the resultant uneven distribution of fauna may undermine ecological equilibrium while potentially promoting fruit fly resurgence (Bosch 2023; Suma *et al.*, 2009). Further, it has been noted that exposure to the gases released by pesticides is extremely toxic to human health, such as acute poisoning and developmental issues, besides chronic health conditions (Kumari & Kumar 2025). Farmers and rural communities face long-term chemical exposure, demanding agroecological safeguards for safer settings. From an economic perspective, it has been identified that countries like Cambodia and Bangladesh have been facing high pest pressure that led to unsustainable usage of pesticides (Ediagbonya *et al.*, 2025). Farming trends pose human/environmental risks, highlighting agroecological alternatives to chemicals—essential for adapting to climate-exacerbated pest pressures despite limitations. Agro-Ecological Pest Management (APM) is a systematic approach that prioritises prophylactic control options for long-term effect through the application of bio-rational strategies (Owili *et al.*, 2024). Agroecological strategies harness ecological processes and biodiversity to regulate pest populations, avoiding toxic chemical suppression. However, agroecological strategies have been found to be exposed to uncertainty risk associated with the adoption of APM, probably due to a lack of expertise in adopting eco-friendly practices, training and effective information (Owili *et al.*, 2024). Crop diversification, intercropping, trap cropping, habitat management, and natural enemy protection reduce pest pressure while enhancing ecosystem services. For instance, agroecological systems in cucurbit systems have shown significant results in controlling fruit fly population and sustainable management of fruit damage compared to uncontrolled options (Bakengesa *et al.*, 2023). They reduce environmental risks and costs. Reviews confirm agroecology's vital role—merging bio-tools and crop practices—for resilient cucurbit fruit fly control. Also other practices of use of augmentorium, growing trap crop in between the main crop reduces the pest incidence through synergies between plant diversity and soil microbial ecology (Altieri *et al.*, 2024). Sexual trapping of fruit flies using pheromones also represents a targeted agroecological intervention, minimizing broad-spectrum impacts while effectively monitoring and controlling pest populations (Altieri *et al.*, 2024). Such approaches foster robust, resilient agroecosystems capable of maintaining productivity under stressful environmental conditions, thus contributing significantly to food security and biodiversity conservation (Vikas & Ranjan 2024; Zhu *et al.*, 2011). This holistic strategy moves away from unilateral interventions based on agrochemicals and transgenic crops towards integrating cultural practices and biological regulation processes for pest control (Altieri *et al.*, 2024). This paradigm shift not only mitigates the development of pesticide resistance but also enhances beneficial insect populations and soil health, contributing to overall ecosystem resilience (Deguine *et al.*, 2015; Raman *et al.*, 2024). Furthermore, these methods prioritize biological control, biopesticides, biostimulants, and pheromones, which, despite acceptance hurdles, represent a significant portion of worldwide crop protection efforts due to their emphasis on sustainability and reduced environmental impact (Raman *et al.*, 2024). This holistic framework, by restoring natural processes, is essential for transitioning from conventional agricultural models to sustainable production systems, effectively managing pest populations below harmful thresholds through integrated strategies (Eypert *et al.*, 2025).

Bio-intensive tools application in Agroecological strategy for management of fruit flies:

Bio-intensive tools in agroecological fruit fly management harness natural processes and biodiversity for sustainable pest control. This approach integrates various methods such as biological control agents, trap crops, biofumigation, sticky traps, and pheromones, which have been explored extensively for their effectiveness in pest management (Curk & Trdan 2024). For instance, the strategic planting of service plants around crop plots can deter pests or act as reservoirs for beneficial insects, thereby promoting faunistic balances and preserving biodiversity (Ryckewaert *et al.*, 2010). Agroecology integrates ecological principles into agriculture, promoting biodiversity, crop rotation, and soil health, alongside natural pest control methods like agroforestry, to enhance food security and mitigate climate change (Vikas & Ranjan 2024). The goal is to maintain harmonious coexistence between humanity and nature, reducing the reliance on chemical inputs that negatively impact the environment and human health (Vikas & Ranjan 2024; Win & Kang 2025). This holistic strategy systematically integrates a variety of non-chemical tools and practices to manage fruit fly populations, thereby minimizing reliance on synthetic pesticides and fostering long-term ecological stability within agricultural systems (Yarahmadi & Rajabpour 2024). For example, diversified cropping systems, including intercropping and agroforestry, have been demonstrated to reduce pest incidence by enhancing natural enemy populations and disrupting pest colonization processes (Deguine *et al.*, 2015). This multi-tactic approach aligns with the principles of Integrated Pest Management, which seeks to achieve pest suppression through eco-friendlier and systems-based methods, moving beyond the sole reliance on chemical controls to encompass a judicious use of pesticides when necessary (Kennedy & Lekshmi 2022). These tools include methods such as habitat manipulation, conservation biological control, and agroforestry, all designed to bolster natural pest control mechanisms within agricultural fields while minimizing reliance on synthetic

inputs (Yarahmadi & Rajabpour 2024). These approaches promote biodiversity and ecological balance, fostering resilient agroecosystems that are inherently less susceptible to pest outbreaks (Vikas & Ranjan 2024). Bio-intensive pest control measures effectively replace conventional pest management approaches for controlling cucurbit fruit fly infestations (Bakengesa *et al.*, 2023). The scientific methods of using eco-friendly ways of pest trapping in the cultivation of cucurbit crops, where ethyl alcohol-based trapping and bait application have been prioritized (Ram *et al.*, 2025). Mass trapping and semiochemicals drive bio-intensive management, luring fruit flies of both sexes via pheromones. This strategy includes the utilization of attractants such as parapheromones to lure and capture male fruit flies, effectively disrupting their reproductive cycle and thereby diminishing pest populations (Fleury *et al.*, 2010). This method harnesses the specific olfactory cues that fruit flies use for mate location, effectively luring them into traps to prevent reproduction and reduce their population (Deguine *et al.*, 2015). Furthermore, kairomone compounds derived from plant parts can be utilized to screen for resistance to fruit fly species and to identify specific attractants that disrupt host-searching, mating, and oviposition behaviors (Mawtham *et al.*, 2022). This selective trapping not only reduces pest populations but also provides a monitoring tool to assess infestation levels and guide further management decisions (Kumari *et al.*, 2021). In ethyl-based trapping, ethyl alcohol can be mixed with cue lure and protein baits, and is effective in catching both males and females, resulting in a decrease in successful mating and population of fruit flies (Biasazin *et al.*, 2025). In ethyl alcohol bait trap tests conducted on the cucurbit crops have shown a significant reduction of the fruit infestation and larval populations. Although biopesticides have emerged in the market, their commercial adoption remains limited due to intense competition from synthetic chemical fumigants (Jaiswal *et al.*, 2022). Biopesticides provide key benefits: minimal toxicity to non-target organisms and lower pest resistance risk compared to synthetics. Recent research underscores microbial agents and botanicals for their safety and effectiveness. These position them as essential components for controlling fruit fly infestations in cucurbit systems via integrated pest management (Bakengesa *et al.*, 2023; Curk & Trdan 2024; Jaiswal *et al.*, 2022). Monitoring and decision tools optimize bio-intensive strategies by matching deployments to pest pressure and phenology. DNA barcoding is an important biological process that helps agricultural professionals in making informed decisions, adopting effective pest management practices and mitigating the economic impact of pests (Mitra *et al.*, 2025). This molecular tool, by providing rapid and accurate species identification, plays a crucial role in understanding pest distribution and diversity, thereby informing targeted control measures within IPM frameworks (Sahana *et al.*, 2024; Vargas *et al.*, 2015). For instance, distinguishing economically significant fruit fly species within the genus *Bactrocera* through molecular identification allows for the development of highly targeted management strategies, ranging from cultural practices to the judicious application of biopesticides (Vargas *et al.*, 2015). This genetic identification approach aids national plant protection organizations in enhancing monitoring strategies that are often hindered by cumbersome inspection equipment and the vast taxonomic diversity of intercepted species (Quandahor *et al.*, 2024). Precise identification of the species through various specification tests, such as DNA barcoding, enhances precision monitoring, which is a crucial procedure when it comes to intervention (Choudhary *et al.*, 2021). Their utilisation can increase the sustainability, minimise chemical reliance, and provide pest control in cucurbit cropping systems in the long term. This integrated approach, leveraging bio-intensive tools and precise identification methods, is crucial for developing robust and environmentally sound strategies to combat fruit fly infestations in agriculture (Dias *et al.*, 2018; Vargas *et al.*, 2015). Genetic approaches, such as RNA interference, also offer promising avenues for highly specific control by targeting essential genes in fruit flies, complementing traditional methods with advanced molecular techniques (Kotiyal & Mirza 2021). This precision in identification is critical for developing region-specific management strategies and for rapidly identifying invasive species, such as *Bactrocera* cilifera, which can devastate cucurbit crops (Pongen *et al.*, 2022). Moreover, bacterial diversity within fruit flies has been explored, revealing that certain bacteria can aid in the degradation of toxic substances and contribute to pesticide resistance, presenting both challenges and opportunities for novel control strategies (Chen *et al.*, 2023). Insights into fruit fly biology from genetics to microbes drive innovative sustainable pest management protocols. The implementation of such advanced strategies, including the use of genetically modified crops expressing dsRNA, demonstrates a paradigm shift towards highly targeted and environmentally benign pest control solutions (Mawcha *et al.*, 2024). The integration of these diverse methodologies, from advanced trapping systems and biopesticides to cutting-edge molecular diagnostics and genetic interventions like RNAi, forms a comprehensive framework for sustainable pest management (Mohanpuria *et al.*, 2021). Furthermore, advanced genetic pest management technologies, including CRISPR-based gene editing and gene drives, provide highly targeted and innovative solutions for pest population reduction by introducing specific genetic modifications, thereby enhancing the efficacy of integrated pest management programs (Bhandari & Paudel 2024). Such strategies often leverage detailed understanding of pest biology, including species-specific vulnerabilities and ecological interactions, to optimize their deployment and minimize off-target effects. Additionally, understanding the gut microbiota of fruit flies can provide novel avenues for pest control, as these microbial communities play a crucial role in insect physiology and could be targeted to develop biocontrol strategies (Charaabi *et al.*, 2025; Rupawate *et al.*, 2023). For instance, the application of RNA interference targeting essential genes in insects can lead to significant developmental and reproductive deformities, offering a highly specific and sustainable method for pest control (Mohanpuria *et al.*, 2021). Moreover, understanding the insect gut microbiome can pave the way for novel biocontrol strategies, as genetically modified *E. coli* fed to *Bactrocera dorsalis* has demonstrated high insect mortality, highlighting the potential of microbial interventions (Rupawate *et al.*, 2023). Comprehending the perspectives on these advanced technologies can facilitate a more compassionate involvement approach and enable the public to engage in knowledgeable decision-making regarding their application to preserve biodiversity (Raman *et al.*, 2024).

OTHER AGROECOLOGICAL STRATEGIES IN MANAGING FRUIT FLIES:

Agroecological strategies provide practical eco-friendly alternatives to molecular/genetic methods for controlling fruit flies in cucurbits. These methods often involve leveraging ecological principles to disrupt pest life cycles and enhance natural enemy populations, thereby reducing reliance on synthetic pesticides (Deguine *et al.*, 2015). Beyond bio-intensive tools, other agroecological approaches emphasize broader ecological principles, such as increasing plant diversity in agricultural landscapes and integrating practices like crop association, agroforestry, and composting to minimize pest damage while maximizing insect biodiversity (Deguine *et al.*, 2015). Such methods aim to create resilient ecosystems where pests are naturally regulated, reducing the need for external interventions. For instance, strategic intercropping, particularly with companion plants known to repel fruit flies or attract their natural enemies, can significantly reduce infestation rates by creating a less hospitable environment for pests (Deguine *et al.*, 2015). This approach not only deters pests but also fosters a more diverse and stable agroecosystem, promoting beneficial insect populations (Mullens *et al.*, 2024). Similar agroecological strategies extend to landscape design, farmer knowledge, and climate-smart practices detailed below, which enhance natural enemy populations and ecosystem resilience for sustainable fruit fly control in cucurbits (Deguine *et al.*, 2015; Hu *et al.*, 2025).

LANDSCAPE DESIGN AND FARMER KNOWLEDGE FOR PEST SUPPRESSION

Integrated landscape management, encompassing the arrangement and connectivity of different habitat types, plays a crucial role in enhancing biodiversity and supporting populations of natural enemies that can suppress fruit fly outbreaks (Mullens *et al.*, 2024). For instance, the strategic integration of non-cropping plants within and around orchards can bolster natural enemy populations, contributing to pest control in fruit tree crops and fostering healthy agroecosystems (Alhmedi *et al.*, 2023). Farmer knowledge and landscape design play key yet overlooked roles in agroecosystem pest suppression. Entomology and agroecology studies show landscape complexity and functional habitats boost natural pest control services. Environmental research discovered that the wildflower strips augmented parasitoid abundance by 2.3-fold and augmented edge-dwelling natural energy diversity by 41% (Hu *et al.*, 2025). Ecologically diverse landscapes (semi-natural areas, floral strips, hedges, cover crops, plant refuges) outperform plain fields in suppressing pests, boosting natural predator, parasitoid, and pollinator numbers. These organisms prey on or parasitize fruit flies, curbing populations without synthetic chemicals.

Non-crop areas in complex field mosaics ensure year-round resources for natural enemies, stabilizing populations, boosting biodiversity, and strengthening ecosystem services like pest suppression. Within the framework of landscape design, farmers' indigenous knowledge and practices for preventing cucurbit fruit fly damage represent critical determinants of pest management success (Angon *et al.*, 2023; Deguine *et al.*, 2015). The role of IPM has been discussed, focusing on the knowledge of farmers in adopting cutting-edge methods of maximising natural controls usage instead of synthetic pesticides (Angon *et al.*, 2023). However, there is limited research on cucurbit fruit flies in the literature; but similar surveys on agricultural practices indicate that most growers dependent on chemical pesticides although organic concepts are emergent (Benbrook *et al.*, 2021). Research indicates that farmers often lack sufficient knowledge of alternative IPM strategies, rendering them unaware of core principles such as biological, cultural, physical, and other control mechanisms (Angon *et al.*, 2023). Surveillance through weather monitoring and ecological landscape design represent critical factors for effective fruit fly and larval control, enabling timely interventions aligned with pest phenology and habitat manipulation (Bouri *et al.*, 2023; Hu *et al.*, 2025). This persistent information deficit among farmers—particularly regarding IPM principles, pest biology, and alternative strategies—is directly responsible for the limited success of integrated approaches in overcoming reluctance to adopt sustainable practices over chemical pesticides (Angon *et al.*, 2023; Benbrook *et al.*, 2021). This knowledge gap often leads to the overuse and misuse of chemical pesticides, further exacerbating ecological imbalances and hindering the efficacy of natural pest control mechanisms (Eypert *et al.*, 2025; Materu *et al.*, 2018). This reliance on chemical interventions, despite their drawbacks, highlights the urgent need for enhanced knowledge transfer and participatory approaches to empower farmers with the understanding and tools necessary for effective agroecological pest management (Mkenda *et al.*, 2020). To address this, comprehensive farmer education programs, emphasizing the ecological and economic benefits of integrated pest management techniques, are crucial for fostering a shift towards more sustainable agricultural practices (Raman *et al.*, 2024). Furthermore, farmer education in managing pest infestation is an essential aspect of controlling cucurbit fruit fly management. Engagement of farmers and participatory learning institutions, such as Farmer Field Schools (FFS) have supported and accelerated the IPM adoption capabilities across gender (Transforming Agriculture through Modern Extension Education Techniques 2025). Another study illustrates that the FFS approach delivers experiential learning in ecology via problem-solving and exploratory methods, thereby strengthening farmers' capacity to evaluate farm operations, identify pests, and test remedies (Transforming Agriculture through Modern Extension Education Techniques 2025). When farmers can identify pests and beneficial organisms, establish economic thresholds, and adopt ecosystem-oriented strategies to bolster natural pest control services, Farmer Field Schools play a pivotal role in shaping their management practices (Materu *et al.*, 2018; Transforming Agriculture through Modern Extension Education Techniques 2025). Widespread participation in FFS and comparable educational initiatives across diverse regions has significantly reduced pesticide reliance while enhancing farmers' ecological knowledge in various cropping systems (Mkenda *et al.*, 2020; Transforming Agriculture through Modern Extension Education Techniques 2025). These participatory training efforts, especially when collaborative, empower farmers to make informed decisions and actively engage in the development and validation of IPM strategies, moving beyond top-down technology transfer initiatives (Deguine *et al.*, 2021). Despite these advancements, persistent barriers to the widespread adoption of new farming practices, such as limited access to information, remain (Jeanneret *et al.*, 2016). The inadequacy of current extension services, coupled with a lack of awareness regarding the comprehensive

application of IPM technologies, further perpetuates this challenge, necessitating targeted interventions to enhance farmers' capacity for sustainable pest management (Materu *et al.*,2018).

ROLE OF CLIMATE-SMART STRATEGIES UNDER INTEGRATED PEST MANAGEMENT FOR CUCURBITS

Climate-smart integrated pest management strategies for cucurbits focus on adapting pest management practices to the impacts of climate change while simultaneously contributing to climate change mitigation and adaptation (Mohapatra *et al.*,2022). These strategies integrate ecological principles with technological advancements to build resilient agricultural systems capable of maintaining productivity under varying climatic conditions (Materu *et al.*,2018). This approach emphasizes the utilization of climate-resilient crop varieties, optimized water management, and diversified cropping systems to reduce susceptibility to climate-induced pest outbreaks (Sharma 2023). It further incorporates advanced monitoring systems, utilizing real-time climate data to predict pest population dynamics and optimize the timing of interventions, thereby minimizing chemical inputs and enhancing environmental sustainability (Sharma 2023). The integration of digital technologies, precision agriculture, and biotechnological innovations further enhances the efficacy of these climate-smart IPM approaches, facilitating more precise and adaptive pest control measures (Khokhar & Kumar 2024). However, the effectiveness of these advanced strategies can be undermined by farmer resistance to change, often stemming from concerns about the perceived complexity or efficacy of new IPM methods, alongside limited access to crucial education and training (Yarahmadi & Rajabpour 2024). Climate-smart pest management (CSPM) is a concept proposed to incorporate adaptation, mitigation and sustainability into the conventional integrated pest management (IPM) models to deal with the increasing impacts of climate change on pest population and crop production systems (Bouri *et al.*,2023). Within climate variability, the pests (such as the cucurbit fruit flies) may shift in terms of abundance, distribution and seasonality, and this may lead to a higher risk of outbreaks, and lower the efficiency of fixed pest control strategies (Skendzić *et al.*,2021). CSPM aims to achieve system robustness through harmonisation of IPM plans with climate risk evaluation and adaptive culture, hence diminishing the exposure of crop production systems to weather extremes and prolonged climatic variations. This adaptive approach integrates various methods such as crop diversification, selection of resilient crop varieties, and conservation tillage, to enhance the system's resilience against climate change-induced pest pressures (Heeb *et al.*,2019). Risk gauging and prediction represent two important aspects of climate-sensitive IPM. This allows for proactive pest management by anticipating changes in pest dynamics due to climate shifts, thus enabling timely and appropriate interventions (Ashfaq *et al.*,2024). The involvement of a combination of climate information and pest monitoring for pest pressure forecasting, as well as the time of intervention (Bouri *et al.*,2023). Forecasting models using temperature, humidity, and pest history predict fruit fly proliferation timing. This enables optimal deployment of traps and biocontrol for peak effectiveness. This active monitoring is considered the key to a successful CSPM, as it allows the identification of issues in an early stage and prompt responses to ensure that the cucurbit fruit flies population stays within economic limits (Buja *et al.*,2021). Climate-smart strategies are linked to advanced biocontrol agents that have a lower impact in the process of pest management(Richard *et al.*,2021). Research indicates a strong linkage between stochastic weather variability and pest invasions, underscoring the critical need for early intervention in pest population growth to avert detrimental effects (Du *et al.*,2022). Therefore, Biological pesticides and entomopathogens work on different environmental variability compared to synthetic compounds. These are more capable of suppressing pests without augmenting climatic effects associated with the use of fossil fuel-derived measures. Notably, CSPM is attributed to reduce reliance on insecticides that cover different types of pest control, which have been demonstrated to distort functionality of natural enemy populations (Sekabira *et al.*,2023). However, it may lose effectiveness in different climatic conditions. This emphasizes the necessity of developing climate-adapted pest management approaches that remain efficacious across a broader spectrum of environmental fluctuations (Kayastha *et al.*,2024). Future research must therefore prioritize the development of novel integrated pest management alternatives and the dissemination of existing efficacious strategies to new regions, considering potential shifts in pest survival strategies due to climate change (Bhagarathi & Maharaj 2023). Moreover, strengthening institutional support and infrastructure for effective information and knowledge exchange between stakeholders is essential for catalyzing the adoption of climate-smart pest management approaches (Heeb *et al.*,2019). This involves fostering robust two-way linkages between extension services and research institutions to facilitate continuous engagement and the co-creation of knowledge for climate-smart pest management (Heeb *et al.*,2019). Lastly, addressing institutional and socio-economic concerns is essential to create a broader scope for CSPM adoption (Abbas *et al.*,2025; Heeb *et al.*,2019; Yarahmadi & Rajabpour 2024). It has also been observed that farmers' decisions regarding climate-smart Integrated Pest Management adoption are influenced by climatic variability because of the absence of supportive services, inadequate training, and lack of access to adequate climatic information (Abbas *et al.*,2025). Moreover, adaptive strategies are identified as vital for climate change, but their effectiveness requires ideal practices, technologies and innovation without which community-oriented application is not possible (Sekabira *et al.*,2022). Strategies such as extension outreach, farmer field schools, and Participatory Scenario Planning can effectively surmount these barriers by uniting stakeholders and diverse perspectives in the development of pest management strategies (Heeb *et al.*,2019; Sharma 2023).This is expected to result in stronger cropping systems in general. Additionally, robust monitoring and evaluation systems are crucial to assess the impact of these IPM strategies, track pest populations, and measure economic and ecological outcomes for ongoing optimization (Yarahmadi & Rajabpour 2024). These evaluations should feed back into adaptive management frameworks, allowing for continuous refinement and adaptation of CSPM strategies to evolving climatic conditions and pest pressures (Bhagarathi & Maharaj 2023).

CONCLUSION AND FUTURE DIRECTIONS

Managing cucurbit fruit flies demands agroecological and climate-smart pest strategies to strengthen systems against evolving dynamics. Forecasting models combining climate factors like temperature and humidity with real-time pest monitoring allow timely actions, such as traps and biocontrol during peak outbreaks, reducing dependence on synthetic pesticides that harm natural enemies and the environment. Climate change amplifies challenges—higher pest numbers, range expansions, and outbreak risks—requiring IPM-CSPM fusion: early alerts, climate-resilient varieties, crop diversification, ecological tactics, and adaptive practices to tackle pest complexes while curbing emissions and building resilience. Enhancing habitat variety via intercropping and cover crops fosters biodiversity, supporting predator populations for self-sustaining farms resilient to weather extremes. Forward-looking research on cucurbit pests under climate variability, still underexplored—must emphasize climate-pest models from long-term field data and niche forecasts to predict outbreaks and guide responses. Validate interventions through farmer-led trials, extension programs, and scenario planning to address gaps in training and info access, leveraging digital platforms for grower data exchange. Agriculture research should prioritize resilient IPM options, backed by strong monitoring, institutional ties, and policy support, to combat rising pest threats in a warming world. This paves the path for climate-proof food systems sustaining future generations. Success hinges on interdisciplinary teamwork across entomology, agroecology, climatology, and socioeconomics, turning science into farmer-ready strategies. With rigorous science, stakeholder involvement, and policy backing, this framework shields production from climatic surprises and pest shifts, nurturing resilient agroecosystems that mitigate climate impacts, preserve biodiversity, boost rural growth, and ensure global food security amid mounting pressures.

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