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METHYL EUGENOL: AN INDISPENSABLE TOOL FOR MODERN *BACTROCERA* FRUIT FLY MANAGEMENT

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ABSTRACT:
Methyl eugenol (ME) is one of the highly attractive male-specific semiochemicals commonly employed in managing economically important *Bactrocera* fruit flies. The high attractancy of ME has made it an essential ingredient in surveillance, monitoring, Male Annihilation Technique (MAT), Sterile Insect Technique (SIT), and area-wide integrated pest management programs. This article presents a review of the chemistry, mechanism of action, species specificity, formulations, and application of ME in fruit fly management. Advances in the design and fabrication of controlled-release dispensers, polymer matrix, and nanotechnology-enabled formulations to enhance ME lure life and field performance are also compiled and presented. Furthermore, this review highlights some of the biological, ecological and operational parameters that affect ME efficacy, such as species-specific response, lure breakdown and behavioural change. The current limitations with ME technology and novel ways for enhancing its efficacy are also addressed. Future research needs will focus on the development of durable formulations, delivery systems, female attractants, and integration of precision pest management technology.
KEYWORDS: Methyl eugenol; Semiochemical; Para-pheromone; Male annihilation technique; Sterile insect technique; Integrated pest management.

INTRODUCTION

Fruit flies (Diptera: Tephritidae) constitute a diverse and cosmopolitan group of insects comprising more than 500 genera and nearly 5,000 species worldwide (Scolari *et al*., 2021). These flies are the most economically important agricultural pests due to their ability to infest a diverse range of horticultural crops. As a result, considerable resources are devoted to risk assessment, monitoring, and management strategies. They are significant quarantine pests of international significance due to their strong invasive potential, quick spread, and destructive nature (He *et al*., 2023). A range of management strategies, including cultural, biological, chemical, and behavioural control, have been utilised to manage the losses brought on by fruit flies. In recent years, major focus has been given to plant volatiles, which are essential in influencing insect behaviour and have been extensively utilised in pest management strategies. Plants synthesise a diverse array of secondary metabolites that play essential roles in protection against pests and diseases, as well as in mediating interactions with other organisms. Among these compounds, phenylpropanoids are a major class of phenolics involved in plant growth, reproduction, and insect–plant interactions. Methyl eugenol (ME) is one of the phenylpropanoids that serves as a potent attractant for males of several economically important *Bactrocera* species (Tan and Nishida, 2012). ME was first observed as a fruit fly attractant by Howlett in 1912, who reported that male *Bactrocera* species were attracted to citronella grass (*Cymbopogon nardus*). Further research also revealed that ME was the substance causing this attraction (Howlett, 1915). Since then, ME has been identified as one of the strongest attractants for males of a number of economically significant *Bactrocera* species, and it has grown to be a key component of fruit fly management and monitoring initiatives across the globe (Shelly *et al*., 2010; Tan and Nishida, 2012).ME that is consumed by the male fruit flies is converted into metabolites, which act as sex pheromones, thereby enhancing mating efficiency (Wee and Rosli, 2025).

ME is extensively used in monitoring programmes and to investigate population dynamics. Furthermore, ME combined with insecticides has been successfully utilised in Male Annihilation Technique (MAT) programs to eradicate oriental fruit fly populations in several western Pacific islands. Recent studies have also highlighted the potential integration of ME into Sterile Insect Technique (SIT) programs to enhance the mating competitiveness of released sterile males (Karunaratne and Karunaratne, 2015).In Ethiopia, severe population declines of *Bactrocera dorsalis* (Hendel) were achieved in commercial guava farms within eight months by deploying ME-bait stations alongside other management interventions (Biasazin *et al*., 2021). Demonstrations have been done on ME feeding or aromatherapy treatments before release, improving sterile males' mating performance and increasing the effectiveness and financial sustainability of SIT programs aimed at *B. dorsalis* and *Bactrocera zonata* (Saunders) (Wee and Rosli, 2025).

Although ME - based technologies have been widely used and shown to be effective in suppressing fruit flies, but have short-term efficacy and do not directly target female populations because it is a male-specific attractants (Gupta and Regmi, 2022). Reinvasion from nearby untreated areas may potentially lessen the effectiveness of ME-based suppression programs, especially in fragmented agricultural landscapes. In addition, fruit fly population dynamics may change if dominant ME-responsive species are suppressed, which may result in the development or revival of non-target pest species (Biasazin *et al*., 2021).

Male responsiveness towards ME varies among groups, and host-associated variations in attraction may impact the effectiveness of monitoring and control (Fan *et al*., 2022). The toxicological characteristics of ME and its metabolites have also drawn criticism, underscoring the need for safer formulations and administration techniques (Zhang *et al*., 2022). These drawbacks highlight how crucial it is to create sustainable, coordinated strategies that improve the efficacy of ME-based fruit fly control initiatives. ME-based technologies have been widely used for more than a century, but their ability to completely suppress fruit flies is still limited by biological, ecological, operational, and regulatory issues. Relatively few evaluations have critically examined the constraints limiting ME's long-term viability under field conditions, despite the fact that many have documented its appeal and applicability. As a result, this review summarises chemistry, behavioural ecology, formulations, and uses of methyl eugenol in fruit fly control while emphasising the main drawbacks, new difficulties, and prospects for enhancing ME-based pest management techniques.

2. Chemical Nature of Methyl Eugenol

Methyl eugenol (ME) is a phenylpropanoid chemical. It is a secondary metabolite derived from eugenol through the shikimate pathway, involving intermediates such as caffeic acid and ferulic acid. The chemical formula of methyl eugenol is $C_{11}H_{14}O_2$. It possesses a benzene ring substituted with two methoxy groups ($–OCH_3$) and an allyl side chain ($–CH_2–CH=CH_2$) as in Figure 1. These structural characteristics impart high volatility, strong aromatic properties, and a lipophilic nature to the compound, thereby enhancing its effectiveness as an attractant for several tephritid fruit flies, particularly males of *B.dorsalis* (Tan and Nishida, 2012). The pharmocophagy behind this is that males compulsively ingest ME and metabolise it into the precursors of sex pheromones, 2-allyl-4, 5-dimethoxyphenol and (E)-coniferyl alcohol, which are stored and sequestered in the rectal gland before being released as sex pheromonal components during dusk courtship. In comparison to ME-deprived conspecifics, ME-fed males produce a more attractive pheromone blend and have noticeably higher mating success (Zhang *et al*., 2025).

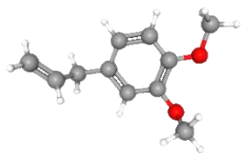

Figure .1.3 D Structure of 4-allyl-1, 2-dimethoxybenze

3. Mechanism of attraction

Fruit flies detect ME through a specialised olfactory system present in the antenna. In the antennal sensillum lymph, ME initially binds to odorant-binding proteins and chemosensory proteins (BdorOBP2, OBP56f-2, OBP69a, OBP13, and CSP3). These proteins exhibit high binding to ME, and their deletion or silencing dramatically decreases antennal and behavioural responses to ME (Zheng *et al*., 2012; Chen *et al*., 2021). Odorant receptors (ORs) in olfactory sensory neurons receive ME from these carrier proteins. RNA-Seq, qRT-PCR, and functional expression indicate that BdorOR88a and BdorOR94b1 are key ME receptors (Chen *et al*., 2022). They produce dose-dependent currents to ME when co-expressed with the co-receptor Orco, and silencing or knocking out these ORs or Orco significantly decreases or eliminates male attraction (Liu *et al*., 2017).

4. Species- Specificity

ME attracts mainly males of certain *Bactrocera* species, while many other fruit flies do not respond. The specific combination of olfactory proteins (receptors, binding, and carrier proteins) that each species (and sex) expresses in its antennae and other chemosensory tissues determines the species specificity. The molecular basis of specificity is that ME is detected in *B. dorsalis* by a single odorant receptor called BdorOR94b1; behavioural and physiological responses to ME are eliminated when this gene is disrupted, demonstrating a very strong chemical–receptor match (Liu *et al*., 2017). Another receptor, BdorOR88a, regulates ME responsiveness in adult males. Many odorant receptors and OBPs are male-enriched in *B. dorsalis*, according to antennal transcriptomics; some ORs, such as BdorOR13 and OR14, are highly and specifically expressed in male antennae and cluster with pheromone-related receptors, supporting sex- and species-specific tuning (Liu *et al*., 2016).In Table 1, the species which are responsive towards ME are described.

Table 1. Species response to Methyl Eugenol (ME).

Species	Response to Methyl eugenol	References
B.dorsalis	Strongly attracted	Hee *et al*., 2015
Bactrocera invadens (Drew, Tsuruta & White)	Attracted	
Bactrocera papayae (Drew & Hancock)	Attracted	
Bactrocera philippinensis (Drew &	Attracted	

Hancock)		
Bactrocera carambolae (Drew & Hancock)	Attracted, but at least 10× less sensitive than *B. dorsalis* and *B. papayae*	
Bactrocera musae (Tryon)	Attracted	Royer and Mayer, 2018
Bactrocera xanthodes (Broun)	Weakly responsive to ME	Royer *et al*., 2019
Zeugodacus diversus (Coquillet)	Weakly attracted	Royer *et al*., 2018b
B. zonata	Attracted	Gazit *et al*., 2024
Bactrocera correcta (Bezzi)	Attracted	Mekam *et al*., 2026
Bactrocera fulvicauda (Perkins)	ME – responsive	Royer *et al*., 2018a
Bactrocera seguyi (Hering)	ME – responsive	Royer *et al*., 2018a
Bactrocera speculifer (Walker)	ME – responsive	Royer *et al*., 2018a
Bactrocera unistriata (Drew)	ME – responsive	Royer *et al*., 2018a
Bactrocera visenda (Hardy)	ME – responsive	Royer, 2015
Bactrocera cacuminata (Hering)	ME – responsive	Royer, 2015
Bactrocera pallida (Perkins and May)	ME – responsive	Royer, 2015

5. Formulations of Methyl Eugenol and types of dispensers

Methyl eugenol is mostly used in the field as solid slow-release matrices or liquid lure on cotton dispensers, but more recent research has focused on nanocarriers and controlled-release systems to lower volatility, enhance handling, and extend field life (Vargas *et al*., 2014). The formulation science, longevity, and efficiency of the formulation depend upon the climate, trap design, toxicant compatibility, and maintenance interval, not only on whether the lure is attractive. In this section, the formulations that are used for methyl eugenol are detailed (Kean *et al*., 2023). The types of formulations are depicted in Fig.2

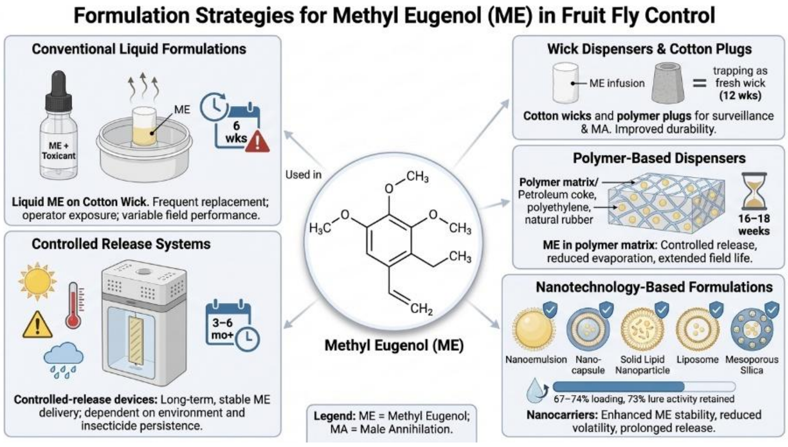

Figure 2.Types of Formulations used in Methyl eugenol

5.1. Conventional liquid Formulations

Liquid formulations of ME continue to be the most frequently used field tool for the monitoring and male annihilation of fruit flies. Liquid ME formulations are used together with a toxicant in the Jackson-type traps where liquid ME is loaded on an absorbent matrix, usually a cotton wick (Jang *et al*., 2013; Shelly *et al*., 2021). Traditional procedures used in Hawaii and other detection programs in the United States use 5–6 mL of ME on wicks with 1–5% Insecticide. The replacement of lures occurs about once every six weeks due to the rapid evaporation and decreased attractiveness of the lure.

Working with liquid ME lure can be associated with difficulties and increased operator exposure to the attractive chemical and insecticide (Jang *et al*., 2013; Shelly *et al*., 2022a). Additionally, experience shows that the loading rates and lure replacement intervals, as well as the type of toxicant, may be adjusted depending on the target fruit fly species, climate, and the goals of the surveillance program. Hence, despite the continued use of liquid formulations of ME as a standard for use in the field, their application is variable rather than standardised from one country to another in various pest management programs (Kean *et al*., 2023).

5.2. Wick Dispensers and Cotton plugs

Cotton wick dispensers of ME have been traditional dispensers due to simplicity, affordability, and the high attractivity of ME to male fruit flies. Field experiments showed that ME-infused cotton wicks efficiently attracted and trapped male *B. zonata* flies for up to nine weeks; hence, they became standard dispensers in surveillance and male annihilation programs (Qureshi *et al*., 1992). As a result of their efficiency, freshly formulated liquid ME on wicks remains the standard (Shelly *et al*., 2022a; Shelly *et al*., 2024a).In order to overcome the drawbacks of liquid wick dispensers, solid polymer-based plugs were developed as a more convenient way of releasing lures in the field. In Hawaii, ME plugs weighing 6 grams had a similar trapping effect as freshly prepared liquid-on-wick dispensers for 12 weeks of weathering; however, their efficiency decreased by 18 and 24 weeks of field use (Shelly *et al*., 2024b). Likewise, in a large-scale surveillance and male annihilation experiment, the efficiency of Scentry ME cones/plugs and FT Mallet ME wafers was found to be similar to that of the traditional ME-naled formulation. On the other hand, ME wafers exhibited better trapping efficiency for six months, suggesting that they were more durable than others (Vargas *et al*., 2010)

5.3. Polymer-Based Dispensers

Polymer-based dispensers were designed for the incorporation of ME into preformed solid matrices in order to limit handling, minimise rapid evaporation, and ensure the continuous release of ME without affecting the efficacy of the traps (Jang *et al*., 2013). When compared with conventional cotton wick dispensers, polymer wafers and plugs provide more ease of use in terms of application but exhibit similar field performance characteristics. Field studies have shown that attraction of male fruit flies using the polymer-based dispensers at concentrations equivalent to those of liquid ME sprayed on cotton wicks (Shelly *et al*., 2022a).

The efficiency of polymer-based dispensers greatly depends on the composition of the polymer matrix that determines the rate of release of ME. For instance, the composite matrix of petroleum coke, polyethene, oleic acid, and natural rubber prolonged the active field life of ME against *B. zonata* up to about 16-18 weeks, compared with 8 weeks when the conventional cotton wick dispensers are used. In addition, the controlled-release system of the mentioned composite decreased the impact of environmental variables such as time and temperature on the performance of lures (El-Adly *et al*., 2018). Similar findings were made in broader research on the eugenol delivery systems, where the encapsulation in polymers increased the stability of eugenol and extended the period of biological activity due to decreased degradation of the free volatile compound (Kowalewska and Majewska-Smolarek, 2023). All the above results point to the possibility of using polymer dispensers as an alternative to the traditional ME delivery systems.

5.4. Nano-Based Formulations

The utilisation of nanotechnology-based delivery systems is currently one of the methods used to enhance the efficacy of methyl eugenol (ME) by overcoming its volatility, oxidizability, and poor field persistence. In comparison with conventional systems, nanocarriers preserve the active substance and deliver it gradually, thus providing additional stability and persistence (Eleleemy *et al*., 2020). There are numerous nanocarrier systems, such as nanoemulsions, nanocapsules, solid lipid nanoparticles, liposomes, and mesoporous silica, which have been studied in order to use them for ME and similar eugenol compounds delivery (Eleleemy *et al*., 2020). Specifically, mesoporous silica loaded with ME demonstrated 67.89–73.84 per cent loading efficiency and prolonged release, preserving 73 per cent of lure activity compared to pure

ME, which was the reason for an increased service life of the product. Similar achievements were made in research on eugenol-based substances delivery through nano-carriers; specifically, nano-delivery systems provided burst and sustained release of the active substance (Zuo *et al*., 2024). Additionally, chitosan–oleate nanoemulsions effectively stabilised volatile phenylpropanoids, preserving 70-80 per cent of the encapsulated substance throughout refrigerated storage during several weeks (Botti *et al*., 2025).

5.5. Controlled release systems

Controlled release technology has been considered a great milestone in ME delivery as it ensures a long-term release of the pheromone, thus reducing the lure replacement frequency and enhancing efficiency in monitoring and male annihilation of fruit flies (El-Adly *et al*., 2018; Shelly *et al*., 2021). The controlled release devices are supposed to ensure the continued release of ME at optimal levels of attraction. Research has established that ME solid dispensers weighing 3, 6, and 10 grams of ME with insecticidal strips trapped male fruit flies at levels similar to freshly made liquid ME formulation. Nevertheless, external conditions greatly affect the efficacy of dispensers. Dispensers have failed in warm environments due to the loss of activity of the insecticidal strip instead of depletion of the lure (Shelly *et al*., 2021). Other controlled-release techniques, including SPLAT-MAT-ME with spinosad, proved equally effective or more effective than Min-U-Gel-ME with naled Vargas *et al*., 2009). In turn, semi-synthetic ME formulations proved successful in the field, but the efficiency is highly dependent on the dose, composition of the formulation, and its release characteristics (Mekam *et al*., 2026). Thus, the optimisation of both the release characteristics of lures and the persistence of the insecticides is vital for the success of ME-controlled release. Comparison of conventional and controlled-release methyl eugenol dispenser systems for fruit fly management is depicted in Table 2.

Table 2. Comparison of conventional and controlled-release methyl eugenol dispenser systems for fruit fly management

Dispenser	Release type	Longivity	Advantages	Limitations	Reference
Cotton wick	Liquid absorbent, fast volatilisation	~6–8 weeks	Inexpensive, standard protocol, high initial attractancy	High evaporative loss, health risks, temperature-sensitive	(El-Aldy *et al*., 2018; Shelly *et al*., 2021)
Wooden block	Liquid absorbent, fast volatilisation	Up to 10 weeks	High fly capture, readily available, weather-resistant	Variable performance by wood type, bulky	(Mir and Ahmad, 2017; Naganna *et al*., 2023)

Fiberboard block	Liquid absorbent, fast volatilisation	~8 weeks	High capture rate, low residue loss (77% at 4 wk)	Performance declines after 8 weeks	(Mir *et al*., 2017;Naganna *et al*., 2023)
Polymer plug	Solid polymeric, slow release	12–18 weeks	Prepackaged, safer handling, fits existing traps	Reduced efficacy at 18+ wk; 3 g plugs lose attraction faster	(Amin, 2013)
Polyethylene matrix	Solid polymeric, slow release	≥12–24 weeks	Combined ME+RK lures, reduced handling risk	Large size cumbersome; killing agent may degrade	(Shelly *et al*., 2024a;Shelly *et al*., 2021)
Petroleum coke–polyethene composite	Solid composite, controlled release	16–18 weeks	Temperature-insensitive, 3× longer than cotton wick	Lower initial attractancy vs. cotton wick (first 6 wk)	(El-Aldy *et al*., 2018)
SPLAT-MAT-ME	Sprayable wax matrix, slow release	~2–4 weeks	Biodegradable, area-wide suppression, spinosad-compatible	Short field life; reapplication needed; less attractive over time	(Leblanc *et al*., 2011;Biasazin *et al*., 2021)
Mesoporous silica nanoparticles	Nanomaterial-assisted, controlled release	Up to 12 weeks	Sustained discharge, temperature-regulated release	Weak van der Waals interactions; requires precise dilution	(Dharanivasan *et al*., 2017)

6. Applications of ME in Fruit Fly Management

The use of ME has proved very useful in the management of economically important *Bactrocera* fruit flies due to its specificity and ability to attract mature males. ME has not only been used as an attractant but has also been effectively used in various approaches in the management of pests such as monitoring and surveillance, Male Annihilation Technique (MAT), enhancement of Sterile Insect Technique (SIT), and area-wide integrated pest management (AW-IPM)(Mekam *et al*., 2026). The largest amount of evidence for these uses has been found for *B.dorsalis*, though there has also been considerable success with *B.zonata* and various other methyl eugenol-responsive *Bactrocera* species (Wee and Rosli, 2025; Kean *et al*., 2023).

6.1. Monitoring and Surveillance

Methyl eugenol (ME) is one of the highly attractive male para-pheromone lures, which have been successfully used to detect and monitor economically important *Bactrocera* fruit flies, especially *B.dorsalis* (Shelly *et al*., 2010). Because of the high attractiveness and species specificity, ME serves as a basis for surveillance programs that allow early detection of invasive fruit fly populations, thus providing an opportunity to implement quarantine and control measures prior to widespread colonisation. Therefore, a number of countries, such as Australia, New Zealand and the US, include ME as one of the key para-pheromones in regular fruit fly surveillance programs (Kean *et al*., 2023). In addition to quarantine surveillance, ME-lured traps have been extensively used to monitor seasonal population changes, determine species distribution and abundance, and evaluate the success of management programs in orchards and area-wide pest management systems (Mekam *et al*., 2026). There are several factors, such as trap design, lure loading, climate and trap servicing periods, that affect the efficiency of ME-lure surveillance systems (Kean *et al*., 2023).

6.2. Male Annihilation Technique

The male annihilation technique (MAT) is arguably one of the most successful uses of ME in managing ME-responsive Bactrocera fruit flies. This is a technique which incorporates ME with an insecticide, whereby the use of ME attracts sexually mature male flies in order to kill them before they mate (Fan *et al*., 2022). Since its development in the 1950s, MAT has proved to be a useful technique in the management of fruit flies and has been used in suppressing and eradicating the flies. There are a variety of insecticides which have been incorporated with ME in the field of managing fruit flies, some of which include Malathion, spinosad, dichlorvos, fenthion, and fipronil. Their efficacy depends upon formulation types, insecticide susceptibility and environmental conditions. ME with spinosad continues to control *B. zonata* efficiently despite having been applied at lower concentrations, while there have also been successes in applying formulations like SPLAT-MAT-ME (Vargas *et al*., 2009).

6.3. Integration with the Sterile Insect Technique

ME integration with SIT has proven to be an efficient method for improving the performance of sterile males and implementing the two techniques simultaneously. Pre-release ME exposure increases the competitiveness of the males and decreases their attraction to ME-baited devices used in MAT. As a result, the two approaches become more compatible in practice (Fan *et al*., 2022; Wee and Rosli, 2025). In B.dorsalis, pre-release ME feeding led to an increase in egg sterility in the presence of 5:1 and 10:1 sterile-to-wild male ratios, meaning that similar results can be obtained with a smaller number of sterile males. In addition, ME feeding increases mating efficiency of the males and reduces their attraction to ME-baited traps afterwards (Shelly, 2020; Wee and Rosli, 2025). Experiments with the use of genetic sexing strains revealed that the pre-release feeding of six-day-old males followed by their release on the next day was an effective way of implementing MAT-SIT simultaneously (Shelly, 2020). In the case of *B. zonata*, five-hour ME aromatherapy of immature males aged five days old increased their mating efficiency and decreased attraction to ME lures. According to Haq (2018), air-blowing ME proved to be a more feasible alternative to feeding in terms of mass production but gave results similar to ME-fed males in terms of mating performance of *B. dorsalis*. Likewise, in the case of *B. zonata*, ME aromatherapy can provide a scalable method of ME delivery that makes possible the application of both MAT and SIT techniques at once (Rasool *et al*., 2023).

6.4. Area-Wide Integrated Pest Management (AW-IPM)

In AW-IPM programs, the effectiveness of ME is enhanced when it is combined with other compatible management tools such as protein bait sprays, orchard sanitation, biological control, and sterile insect releases, but not in isolation (Barclay *et al*., 2014; Niassy *et al*., 2023; Ballo *et al*., 2020). Massive guava management projects in Ethiopia revealed that a combination of ME-bait stations and GF-120 protein bait, together with orchard sanitation, brought about severe suppression of B.dorsalis populations within eight months. The use of orchard sanitation is always critical in such combinations because it ensures a reduction in re-infestations through removal of infested fruits, which form breeding grounds for the target pests. The use of protein bait sprays complements ME-based management since female fruit flies are less responsive to ME (Chailleux *et al*., 2021). Bio-control methods can work in harmony with AW-IPM approaches depending on the compatibility of the natural enemies with ME (Niassy *et al*., 2023). Furthermore, sterile insect releases can be effectively combined with the Male Annihilation Technique (MAT) approach, and modelling has shown that concurrent use of MAT and SIT is synergistic. In favourable conditions, ME treatment of sterile males prior to release could decrease their responsiveness to the MAT traps, thus reducing the rate of sterile male releases to about 5% of the number needed for SIT alone (Barclay *et al*., 2014).

7. Factors affecting the effectiveness of Methyl Eugenol

The efficiency of methyl eugenol (ME) in fruit fly control depends on various factors, which include biological, environmental, and operational factors. The determinants can be grouped into three major components, which are biological, field-related, and landscape-related constraints. According to the literature, ME works effectively in controlling responsive *Bactrocera* males only if there are favourable conditions in the environment and application is done using effective and coordinated area-wide management programs. However, the efficiency might be affected by differences between the ME responses of the species and variations in the physiological condition of male flies, as well as some operational problems like reinvasion from the surroundings where ME is not used. Moreover, reduced behavioural responsiveness to ME makes traps inefficient and negatively affects the efficiency of trap-based suppression programs (Mekam *et al*., 2026; DineshKumar *et al*., 2023). Factors are summarised in Fig. 3.

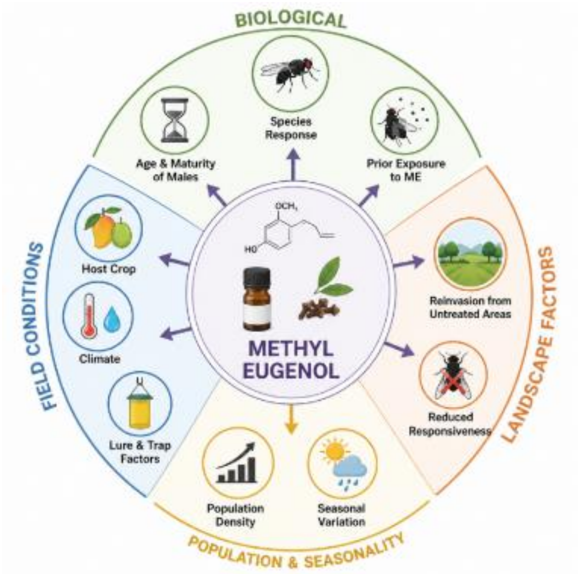

Figure 3. Factors affecting the efficacy of methyl eugenol

7.1. Biological Response

The biological response of fruit flies towards methyl eugenol (ME) is one of the principal factors determining the efficacy of the latter for fruit fly control due to differences in attraction to ME by various species, affecting the efficiency of the substance in the field depending on crops and geographic locations (Rasool *et al*., 2023; Ahmad *et al*., 2023; Dineshkumar *et al*., 2023). From the group of economically important tephritids, *B.dorsalis*, *B.zonata*, *B.correcta*, and *B.carambolae* show strong responsiveness to ME, while attraction of *Zeugodacus cucurbitae* (Coquillet) is relatively weak and therefore it is more efficiently controlled using cue-lure systems (Mekam *et al*., 2026; Ahmad *et al*., 2023). Nevertheless, even among ME-responsive species, the catches in the field can vary depending on the species composition in a certain region. So, in Pakistan, the major catch in ME-traps was *B. zonata*, while in orchards of Tamil Nadu, *B. dorsalis* dominated (Ahmad *et al*., 2023; Dinesh Kumar *et al*., 2023).

Age and sexual maturity of males significantly affect their ME responsiveness. For instance, attraction to ME in *B. zonata* increased with age until sexual maturity was reached, when mating started at about eight days of age and peaked at 16 days (Rasool *et al*., 2023; Gazit *et al*., 2024). A similar trend has been observed in *B. umbrosa*, where around 22 per cent of the males showed attraction to ME at 7 days post-emergence, with more than 50 per cent becoming responsive to ME at 10 days post-emergence, and the peak attraction occurred during the sexually mature age from 10-27 days (Wee *et al*., 2018). The only difference is that, unlike *B. dorsalis*, *B. umbrosa* has the ability to show attraction to ME even before reaching sexual maturity; however, there is a marked behavioural shift that occurs during the short maturation period (Shelly *et al*., 2008). Prior exposure to ME can also affect future behavioural response. In the case of *B. dorsalis*, previous feeding on ME or eugenol decreased the attraction of the males older than 10 days to the ME-baited trap (Pogue *et al*., 2024). Similarly, exposing *B. zonata* males to ME volatiles decreased their attraction to ME for at least four weeks (Gazit *et al*., 2024). These changes in behavioural response have operational significance because repeated exposure to ME may lead to a decreased trapping response (Rasool *et al*., 2023).

7.2. Crop and Environmental Conditions on ME efficacy

Field conditions have an important bearing on the efficacy of methyl eugenol (ME), as both host crops, environmental influences, and lure features affect trapping efficacy. The host crops impact the efficiency of ME through the modification of species composition and the dominance of fruit fly species in various cropping systems (Nahid *et al*., 2020; DineshKumar *et al*., 2023; Wee *et al*., 2018). In sweet gourd and cucumber systems, *Z. cucurbitae* often prevailed over *B. dorsalis*, leading to poor trapping efficiency of ME against the dominant species despite the reduction of infestation levels (Amin *et al*., 2019; Nahid *et al*., 2020). However, mango and guava orchards harboured numerous ME-attractive species, yet the species' dominance and diversity indices were different for various orchard types (DineshKumar *et al*., 2023). In addition, the developmental background may affect the behaviour, as the ME response was higher in *B. zonata* males that were raised on artificial larval food compared to those raised on fruit hosts (Gazit *et al*., 2024).

The climate factors are another very important variable determining ME effectiveness. One of the least variable environmental factors affecting ME trap captures is temperature, which positively correlates with capture in studies involving sweet gourd, cucumbers, and guava orchards (Amin *et al*., 2019; Nahid *et al*., 2020). In addition, field cage experiments with *B. dorsalis* showed that ME's reaction was enhanced by increasing temperatures and relative humidity levels (Pogue *et al*., 2024). However, the impact of relative humidity is quite inconsistent, as it shows positive but non-significant correlations, negative correlations, and orchard-specific correlations in Tamil Nadu (Amin *et al*., 2019; Nahid *et al*., 2020; Dineshkumar *et al*., 2023). On the other hand, rainfall usually occurred simultaneously with an increase in trap catches and population peaks and is known to have minimal independent contribution to trap catches. The effect of wind speed remains unclear, as it shows either positive or negative correlations depending on the orchard locality (DineshKumar *et al*., 2023). Operational parameters have also played a role in determining the efficacy of ME field performance. Greater lure loading, especially 1.5 mL of ME, performed better in pumpkin and field trapping experiments in comparison to low lure loading (Mekam *et al*., 2026; Kumar *et al*., 2024; Mulyadi *et al*., 2021). Trap inspection frequency can affect the number of trap catches, and trap inspection performed on a weekly and seasonal basis has been known to significantly affect male catches in Egyptian orchards (Morsi and Farag, 2025). Moreover, lure longevity is significant in monitoring male catches, and ME had a half-life of about five weeks in Senegal (Ndiaye *et al*., 2008).

7.3. Effect of Population Density and Seasonality

The efficiency of methyl eugenol (ME) depends on factors such as population density and seasonality, because the number of flies collected at a trap is indicative not only of the lure's efficiency but also of the number of responsive male fruit flies present in the field (Amin *et al*., 2019; Dineshkumar *et al*., 2023; Nahid *et al*., 2020). The number of flies caught in the traps is generally high during seasons that are warm and humid, promoting the activity and growth of fruit flies. In Bangladesh, traps were more effective in catching fruit flies during summer months as compared to autumn and winter (Amin *et al*., 2019; Nahid *et al*., 2020). Similarly, in Senegal, fruit fly dynamics in relation to rainfall have been demonstrated (Ndiaye *et al*., 2008), and in guava orchards in Pakistan, *B.zonata* and *B. dorsalis* peaked in numbers in April. Nevertheless, higher trap catches do not always imply more successful pest control. In some agroecosystems, certain dominant species may outcompete other fruit fly species and modify the composition of the entire trap community, as was seen in *B. invadens* in Senegal (Ndiaye *et al*., 2008). Thus, seasonal variations, along with changes in population numbers, may affect the composition of target species and the efficiency of ME-based trapping programs (Lengkong *et al*., 2025; Dineshkumar *et al*., 2023).

7.4. Reinvasion and Resistance

The issue of reinvasion by the adjacent untreated area is one of the major landscape-level problems affecting the success of ME-based strategies in the long run. In the case of Ethiopia, the ME-based strategy was unsuccessful in smallholder farms because the fruit flies would travel farther than the extent of the farm, due to which they migrated to adjacent untreated areas (Biasazin *et al*., 2021). As such, MAT tends to be more effective in isolated cases or in area-wide management programs coordinated well as compared to fragmented landscapes. Another important limitation includes the development of decreased responsiveness to ME. Populations of the field *B. dorsalis* in China displayed decreased sensitivity to ME when compared to laboratory strains of *B. dorsalis*, with the most resistant population displaying a 5.88-fold decrease in responsiveness to the lowest dose of ME (Fan *et al*., 2022). It has also been found from both laboratory and field experiments that non-responsive males can be maintained in MAT despite the consistent selection pressure on them without suffering any reproductive cost (Fan *et al*., 2022; Yeh *et al*., 2026). In addition, the presence of high concentrations of ambient ME can accidentally favour the males through increased mating efficiency without trapping them in ME-baited traps (Yeh *et al*., 2026). These results clearly show that the efficacy of ME is dynamic and not constant.

8. Limitations and Challenges of ME–Based Technologies

Methyl eugenol is one of the most effective para-pheromones for fruit flies, but its use is limited by a number of biological, ecological, operational, and legal constraints. First, the most significant biological restriction is that the compound attracts only males, but species- and population differences in sensitivity can also affect the efficiency of traps. Ecological difficulties, such as reinvasion from untreated regions, hinder the efficacy of control measures in the long run. Moreover, quick depletion, constant replacements, and handling contribute to increased operational expenses, especially when used on a large scale. There are also toxicological and country-specific regulatory issues related to the use of methyl eugenol preparations in combination with insecticides. Thus, while being an efficient component in monitoring and male annihilation practices, it is vital to consider these limitations in the context of methyl eugenol usage in integrated pest management programs (Fan *et al*., 2022; Vargas *et al*., 2010; Kean *et al*., 2023).

Biologically, the main limitation of the methyl eugenol (ME) compound is its specificity in targeting male fruit flies, which does not contribute to the suppression of females, who are responsible for oviposition and subsequent damage to fruits (Vargas *et al*., 2010; Sahetapy *et al*., 2023; Chailleux *et al*., 2021). Therefore, the use of ME-based monitoring and management practices is commonly used in combination with attractants based on food, among other options, for the improvement of detection and control of ME-resistant species (Kean *et al*., 2023; Royer *et al*., 2019; Niassy *et al*., 2023). Moreover, different fruit fly species and even certain ME-susceptible species demonstrate different responsiveness to ME. For instance, the fruit fly *B. xanthodes* demonstrates rather weak responsiveness to ME in comparison with methyl isoeugenol, which allows capturing a larger number of males in the field (Royer *et al*., 2019). Finally, long-term utilisation of ME can result in the persistence of less responsive male insects that still have mating capabilities (Fan *et al*., 2022; Yeh *et al*., 2026).

The efficiency of methyl eugenol-based management depends on ecological factors. Constant reinvasion of the area from neighbouring regions that are not treated leads to a reduction in the effectiveness of the male annihilation programs in the long run, especially in open agriculture ecosystems where the implementation of area-wide strategies is not possible (Fan *et al*., 2022; Chailleux *et al*., 2021). Furthermore, the efficiency of the trapping depends on species diversity and abundance. For example, when there is a high abundance of *B. dorsalis*, the traps containing ME might be dominated by this species, thus making the identification of other fruit fly species difficult (Kean *et al*., 2023). Despite being specific for target fruit flies, the lack of attraction to some other insects, such as bees and syrphid flies, has been documented, which means that the ecological impacts of methyl eugenol are relatively low but are not insignificant (Vargas *et al*., 2010).

Management with methyl eugenol is affected even more by toxicological and regulatory factors. Despite the efficacy of methyl eugenol as an attractant, its use necessitates adequate safety precautions, and new research shows that it should be used with enclosed dispensers, as well as protective gear for those who apply it in the field (Shelly *et al*., 2022a; Mekam *et al*., 2026). Moreover, when it comes to SIT programs, exposure to methyl eugenol should be regulated due to its toxicity, which means that feeding applications are not applicable (Haq *et al*., 2018). Furthermore, methyl eugenol products should be deployed based on regulations specific to each country, which involve the registration of insecticides and traps (Kean *et al*., 2023). Finally, high cost and import regulations can limit the use of methyl eugenol products even though they have been proven to be very effective (Niassy *et al*., 2023).

The practical application of methyl eugenol (ME)-based management is also limited by several operational constraints. Firstly, traditional liquid ME lures are highly volatile, require accurate measurements during application, and should be replaced regularly, increasing labour and maintenance costs (Shelly *et al*., 2022b). Furthermore, ME replacement schedules depend on the climate and surveillance program, which complicates its standardisation (Kean *et al*., 2023). Moreover, the use of ME in SIT programs is complicated by the fact that currently available technologies for the mass reproduction and release of insects are unsuitable for the mass distribution of ME among millions of sterile insects, whereas alternative methods of ME application are still difficult to implement industrially (Haq *et al*., 2018). To solve these issues, recent research has been dedicated to the development of pre-loaded solid dispensers, slow-release formulations in the form of nanogels, aromatherapy delivery systems, and cost-effective local manufacturing of trapping devices (Bhagat *et al*., 2013; Rasool *et al*., 2023; Khan *et al*., 2025).

9. Future Prospects

Despite methyl eugenol (ME) proving to be an effective tool for managing *Bactrocera* fruit flies, there are some issues that hamper the effectiveness of this tool and the scalability of the process. Future research should be conducted in three directions: development of female-specific lure components, creation of a controlled-release system using environmentally safe toxicants and implementing climate-resistant and precision-based management systems (Biasazin *et al*., 2021; Shelly *et al*., 2022b; Kean *et al*., 2023). The development of an effective female-specific lure is the top priority of future research, as females are the cause of crop infestation and losses. Although male-specific lures based on ME have proved to be efficient, current female lures are less specific and have shorter lifespans in the field, and their effectiveness varies between species (Biasazin *et al*., 2021; Gupta and Regmi, 2022). Furthermore, protein-based baits undergo quick degradation and catch other organisms too. There are some advances made in developing female-specific volatile blends and weather-resistant bait formulations; however, transferring the results from lab to field is still a difficult task.

Lure formulation and dispensing optimisation also represent priorities. MEs become less effective with a decline in release rates caused by weathering processes, making reapplication required frequently and costly (Shelly *et al*., 2022b). Future research should aim at developing durable controlled-release dispensers capable of ensuring constant emission rates regardless of environmental conditions. Polymer matrices, wax emulsions, and other technologies used for the gradual release of chemicals require further research. At the same time, it is reasonable to substitute conventional organophosphate insecticides with reduced-risk toxicants like spinosad and spinetoram (Vargas *et al*., 2010; Kean *et al*., 2023).

Precision agriculture and climate-smart technologies may be helpful in improving ME management. Climatic factors play a critical role in influencing lure longevity, activity of the pest species, and efficiency of the traps (Pogue *et al*., 2024). Future research is expected to consider automation of monitoring and decision-making processes as well as climate modelling to ensure efficient scheduling of lure replacement. Additionally, improvement of multi-target lures capable of attracting several economically important fruit fly species will help make area-wide management more efficient. Overall, future advances in female-biased attractants, durable controlled-release technologies, safer toxicants, and climate-informed precision deployment will strengthen the sustainability and effectiveness of methyl eugenol-based fruit fly management and support its continued role in integrated pest management programmes.

10. CONCLUSION

Methyl eugenol (ME) has emerged as an essential component of the management of *Bactrocera* fruit flies because of its ability to attract males effectively as well as its use for surveillance, male annihilation technique (MAT), and sterile insect technique (SIT) based programmes. This widespread utilisation of methyl eugenol has contributed greatly to the improvement of early detection, population reduction, and area-wide management by reducing dependence on chemical insecticides. It should be noted that methyl eugenol cannot serve as a sole measure of controlling *Bactrocera* fruit flies because of its gender specificity, differences in sensitivity to it by species and populations of fruit flies, susceptibility of lures to weather conditions, and reinvasion from uncontrolled areas. Therefore, the use of this attractant should be combined with other measures of IPM.

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Declaration of competing interests

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Data availability

No datasets were generated or analysed in the current study.

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