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MORALITY BEFORE KNOWLEDGE

Innovative control of fruit fly (*Bactrocera dorsalis*) on tomato plants (*Solanum lycopersicum*) using the push-pull technique for sustainable food security

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ABSTRACT
Background: Pesticide residues in tomato (Solanum lycopersicum) cultivation pose serious health and environmental risks, exacerbated by the excessive use of synthetic pesticides to control fruit fly pests (Bactrocera dorsalis). This review aims to evaluate the push-pull technique an integrated pest management strategy using repellent plants like lemongrass (Cymbopogon nardus) and attractant plants such as basil (Ocimum basilicum), supported by yellow sticky traps as a sustainable solution for fruit fly control. **Methods:** This systematic literature review was conducted by screening 1,300 articles from scientific databases within the last 10 years using PRISMA guidelines, from which 4 studies were ultimately selected for qualitative synthesis. **Findings:** Based on the analysis of secondary literature, the synthesis of results shows that lemongrass releases volatile compounds capable of suppressing fruit fly populations by up to 40-60%, while basil and yellow sticky traps effectively lure fruit flies away from the main crop and can reduce infestation rates by 35-55%. This combination effectively suppresses pests, reduces dependency on chemical pesticides, and supports food security by stabilizing production. **Conclusion:** It should be noted that these findings are derived from a narrative data synthesis of secondary literature, not primary field trials, and this review does not include a quantitative meta-analysis to statistically measure the combined effect. This study concludes that the wider adoption of the push-pull system, coupled with farmer training and technological integration, offers an eco-friendly and efficient alternative for horticultural pest management. **Novelty/Originality of this article:** The novelty/originality of this article lies in systematically reviewing the push-pull technique combining lemongrass, basil, and yellow sticky traps as an eco-friendly integrated strategy for controlling tomato fruit fly pests.

KEYWORDS: *Bactrocera dorsalis*; integrated pest management (IPM); push-pull; *Solanum lycopersicum*; sustainable agriculture; food security.

1. Introduction

Tomato (*Solanum lycopersicum*) is a strategic horticultural commodity in Indonesia, with a national production rate of 1.14 million tons and an average per capita consumption of 4.3 kg per year in 2023 (BPS, 2024). However, tomato cultivation itself is not without challenges. This plant is known to be sensitive to temperature and rainfall fluctuations, susceptible to various diseases such as fusarium wilt and fruit rot, and is perishable due to its high-water content, thus requiring careful post-harvest handling (Gatahi, 2020). Amidst these cultivation challenges, farmers still have to face the threat of significant economic losses due to fruit fly (*Bactrocera* spp.) attacks, which can result in yield losses of up to 40% (Setlight et al., 2019). To address this issue, farmers often rely on the excessive use of

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synthetic pesticides without considering the long-term impacts. This massive use of pesticides raises serious public health concerns due to residues left on horticultural products. These residues can persist within plant tissues even after washing, thereby elevating the potential for long-term exposure among consumers (Dharmawan, 2023). This high risk is exacerbated by the fact that Indonesia is recorded as one of the largest users of pesticides globally, with consumption reaching 283 kilotons in 2021 (Dharmawan, 2023). Residue accumulation has been detected in various agricultural regions such as Indramayu and Brebes, and a study in Boyolali reported cases of food poisoning attributed to pesticide residues, where 86.11% of 252 residents experienced symptoms such as nausea, vomiting, and dizziness (Handoyo, 2014).

Based on research conducted in the Upper Citarum River Basin, pesticide use on tomato plants shows high and varied intensity. A survey involving 174 farmers, with 21 of them being tomato farmers, identified 13 different types of pesticides being applied to the tomato plants. Among these, Profenofos and Mancozeb were the most widely used by tomato farmers. The application frequency for vegetables like tomatoes is quite high, averaging 5-7 spray times per month. The study also found that farmers have developed their own mixture recipes and dosage rules based on their experience. Specifically, the pesticide-crop combination with the highest average annual use was Chlorothalonil on tomatoes, reaching 32.2 kg/ha/year (Utami et al., 2020).

Such practices contribute to the development of pest resistance, which forces farmers to increase pesticide dosages, thereby increasing the accumulation of chemicals in the food supply. Long-term exposure to organophosphate pesticides is linked to neurological disorders, cognitive decline, and an increased risk of cancer. Furthermore, these toxic effects can be passed down to the next generation, causing genetic mutations and developmental abnormalities whose impacts are not yet fully understood (Chittrakul et al., 2022).

Beyond health impacts, pesticides also damage ecosystems. Chemical pesticides disrupt the growth, reproduction, and behavior of non-target organisms, including animals, plants, and microorganisms in both terrestrial and aquatic environments. Repeated exposure can reduce soil fertility by harming beneficial microbial populations and contaminate groundwater sources, threatening aquatic ecosystems. The decline of beneficial insect populations, such as pollinators and natural pest predators, further destabilizes the agricultural ecosystem's balance (Wan et al., 2025).

Given these risks, environmentally friendly pest control methods are urgently needed. The Food and Agriculture Organization (FAO) recommends Integrated Pest Management (IPM), which combines multiple techniques to manage pest populations with minimal ecological impact. One notable innovation is the push-pull strategy, which uses chemical and visual signals to divert pests away from the main crop toward trap plants (Mala et al., 2020). This method involves planting companion plants that repel pests (push) and trap crops that attract them (pull), effectively suppressing pest populations without relying on synthetic pesticides and offering ecological and economic benefits to small-scale farmers (Meats et al., 2012).

Although the push-pull strategy offers a promising solution, its adoption among tomato farmers in Indonesia remains very limited, even though the system has been proven effective in Africa for crops like maize, while also improving soil fertility and the presence of natural enemies. The low adoption of the push-pull system in Indonesia is due to a lack of outreach and technical knowledge regarding the selection of effective push and pull plant combinations for Indonesia's specific agroecosystems and pests. Additionally, there is still skepticism among farmers about its effectiveness and economic feasibility compared to the use of synthetic pesticides, which are considered more practical (Suprehatin, 2019).

Based on this background, this research aims to assess the effectiveness of the push-pull strategy as a pest control alternative for tomato plants, while also analyzing its economic feasibility and farmers' perceptions of its adoption. Furthermore, this study seeks to answer key questions about how effective push-pull is in suppressing pest populations and reducing synthetic pesticide use compared to conventional methods, and whether this strategy is economically viable for small-scale farmers.

2. Methods

This study was designed as a Systematic Literature Review (SLR). This approach was chosen to comprehensively identify, evaluate, and synthesize all relevant research on the effectiveness of the push-pull technique in controlling fruit flies (*Bactrocera dorsalis*) on tomato plants (*Solanum lycopersicum*). The literature search was conducted systematically in scientific databases (Google Scholar). To ensure broad coverage, a combination of keywords was used with Boolean operators (AND, OR). The main keywords included: ("push-pull technique" OR "companion planting" OR "intercropping") AND ("fruit fly" OR "*Bactrocera dorsalis*") AND ("tomato" OR "*Solanum lycopersicum*"). The literature search was limited to articles published within the last 10 years (2015-2025) to ensure the relevance and novelty of the findings.

The article selection process follows the rigorous PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow, as shown in Figure 1. The initial database search identified 1,610 records. After removing 310 duplicates, a total of 1,300 articles were screened based on their titles and abstracts. From this screening, 1,275 articles were excluded, leaving 25 reports for full-text eligibility assessment. Following the full-text review, 21 reports were further excluded for the following reasons: focus on the wrong pest (n=10), the method was not push-pull (n=7), or no empirical data was available (n=4). Ultimately, 4 studies met the inclusion criteria and were included in the final qualitative synthesis. The methodological quality of each of the 4 included studies was then critically appraised using the CASP (Critical Appraisal Skills Programme) instrument to evaluate its validity and potential for bias. Lastly, the data extracted from these quality-appraised studies were synthesized using a narrative thematic analysis approach, where key findings were grouped into main themes such as working mechanisms, effectiveness, and implementation challenges to construct a coherent and in-depth review.

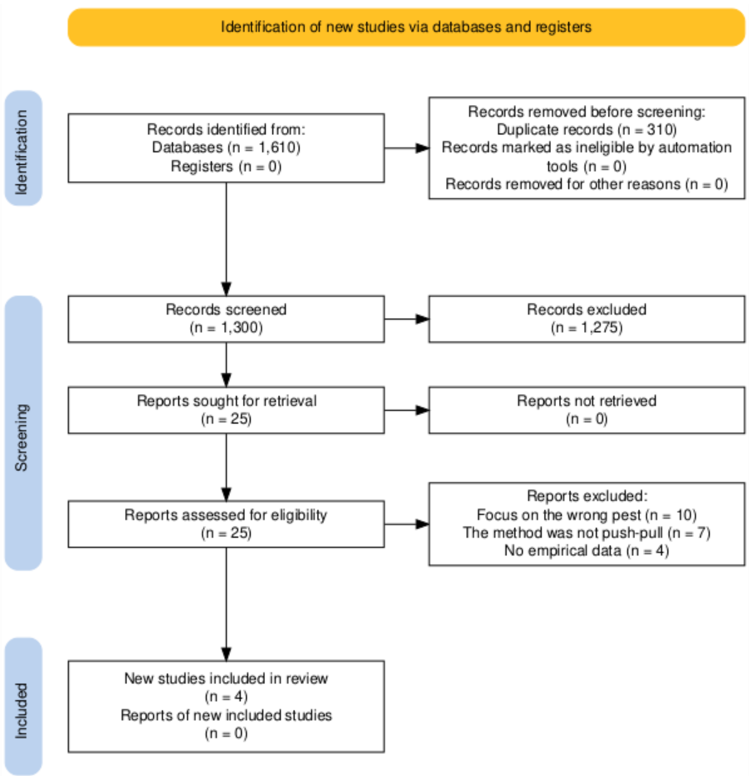

Fig. 1. PRISMA 2020 flow diagram for study selection

3. Results and Discussion

3.1 Infestation of Bactrocera dorsalis on tomato plants: Causal factors and infestation mechanisms

3.1.1 Contributing factors to Bactrocera dorsalis infestation on tomatoes

Tomato (*Solanum lycopersicum*) is one of the main horticultural commodities in Indonesia, known for its high nutritional value and richness in vitamins and antioxidants such as lycopene. However, its perishable nature and high-water content, approximately 94% of the total weight, make it sensitive and prone to physical damage as well as vulnerable to organisms and microorganisms (Jahanbakhshi et al., 2019). One of the common pests attacking tomato plants is *Bactrocera dorsalis*, a species of fruit fly originating from the tropical Asian region (Oriental Region). Fruit flies frequently attack tomatoes because the fruit provides an ideal environment for egg-laying and larval development. Ripe tomatoes are especially attractive to female fruit flies for oviposition due to their high nutrient content and softer texture, which facilitates the female fly's ability to insert its ovipositor and lay eggs inside the fruit (Bhoye, 2024; Roohigohar et al., 2022). The larvae that hatch from these eggs then consume the fruit flesh, causing damage such as rot, discoloration, and decreased fruit quality, ultimately reducing harvest yield. Fruit fly infestations on tomatoes can cause significant losses, ranging from 30% to 100%, depending on the season and attack intensity (Bhoye, 2024). Factors influencing fruit fly attack include fruit ripeness, harvest status, and nitrogen content in the tomato plants. Riper tomatoes are more vulnerable to attack because their softer, nutrient-rich flesh is easier to penetrate and more attractive for egg-laying (Bhoye, 2024; Roohigohar et al., 2022).

3.1.2 Contributing factors to Bactrocera dorsalis infestation on tomatoes

The attack mechanism begins with female fruit flies inserting their ovipositor into ripe tomatoes to lay eggs. After hatching, larvae consume the fruit flesh, causing structural damage to the fruit (Bhoye, 2024; Roohigohar et al., 2022). Fruit ripeness and harvest status are key factors determining larval development success, where riper and harvested fruits are more susceptible to pest attacks (Li et al., 2023; Roohigohar et al., 2022). In Taraitak Village, North Langowan District, Minahasa Regency, *Bactrocera dorsalis* caused damage ranging from 9.08% to 15.50% during the fifth week of observation (Setlight et al., 2019). In the Kefamenanu Market, North Central Timor Regency, East Nusa Tenggara Province, the level of damage to traded horticultural commodities, including tomatoes, due to fruit fly infestation, ranges from 13.5% to 70% (Bay & Pakaenoni, 2021). Additionally, research in Boentuka Village, Batu Putih District, South Central Timor Regency, East Nusa Tenggara, found *B. dorsalis* as the primary cause of tomato fruit damage, with damage intensity reaching 80.9% in the fifth week of observation (Palang et al., 2023).

One of the most common methods to control fruit flies is the use of synthetic pesticides. These pesticides are highly effective in reducing pest populations; pesticides such as imidacloprid, sulfoxaflor, thiamethoxam, cyantraniliprole, and lambda-cyhalothrin have proven to decrease fruit fly and whitefly populations on tomatoes by over 80% shortly after application (Bughdady et al., 2020; Essam et al., 2022; Salam et al., 2023; Roh et al., 2023; Mao et al., 2022). However, the drawbacks and side effects of pesticide use include reduced tomato fruit quality despite increased yields, development of pest resistance due to repeated use, environmental pollution, and decline of natural pest enemies (Essam et al., 2022; Conboy et al., 2020; Dimase et al., 2024; Jaffar & Lu, 2022).

Besides synthetic pesticides, using natural predators to control fruit flies on tomato plants is an environmentally friendly approach aimed at reducing chemical pesticide usage. This method utilizes natural enemies of pests such as predatory insects and parasitoids to suppress fruit fly populations. However, its effectiveness depends on various factors and faces specific challenges in implementation. Over 50 species of predators and nearly 80 species of fruit fly parasitoids have been identified in America and Hawaii, with some used in biological control programs (Garcia et al., 2020). For example, the communal spider *Cyrtophora citricola* can capture fruit flies and other tomato pests by constructing large, dense webs that increase the likelihood of catching flying pests (Roberts-McEwen et al., 2022). Other predators, such as the mirid bug (*Macrolophus pygmaeus*) and predatory mite (*Amblyseius herbicolus*), also effectively suppress pests on tomatoes, although more studied on pests other than fruit flies (Eschweiler et al., 2019; Cardoso et al., 2025). Despite its promise, not all predators are effective against all fruit fly species or under all plant conditions. A study found predator adaptation to tomato glandular trichomes can reduce their effectiveness (Cardoso et al., 2025). Additionally, *C. citricola* spiders are vulnerable to egg parasitoids that reduce their populations (Roberts-McEwen et al., 2022). Some predators, like *Nesidiocoris tenuis*, may also damage tomato plants by feeding on plant tissues, causing necrotic wounds on stems and fruits (Ingels et al., 2022). Success in biological control also heavily depends on the availability of predators in sufficient numbers and their ability to survive in agricultural environments (Garcia et al., 2020; Roberts-McEwen et al., 2022).

Research by Meats et al. (2012) evaluated the effectiveness of push, pull, and combined push-pull methods in controlling *Bactrocera tryoni* on tomatoes. Their findings showed that oil sprays used as push methods were more effective than protein bait sprays used as pull methods, particularly in small-scale farms. The push-pull combination did not outperform push alone due to the rapid evaporation of protein bait sprays, especially under hot weather conditions. One main drawback of spray-based techniques is the need for regular and repeated applications, leading to increased operational costs, higher labor demands, and potential negative environmental impacts due to chemical accumulation. These factors highlight the necessity for more efficient and sustainable pest control strategies.

3.2 Principles of the push-pull technique in fruit fly management

Given these challenges and limitations of other methods, environmentally friendly and sustainable pest management strategies are critically needed. One promising approach gaining attention is the push-pull technique, which manages pests by leveraging natural interactions between plants and insects. The pull method utilizes traps or attractant sources to divert pests from the main crops and is usually implemented alongside the push strategy, which employs repellents to drive pests away from protected areas (Eigenbrode et al., 2015). Pull techniques often use pheromones or other attractants to reduce oviposition and effectively suppress pest populations (Wallingford et al., 2018; Alkema et al., 2019). This technique aligns with the behavioral ecology framework, where insect responses are guided by chemical cues such as volatile organic compounds (VOCs) emitted by plants (Benton, 2022). VOCs serve as infochemicals that either attract or repel insects, depending on their molecular composition. Lemongrass (*Cymbopogon nardus*), a commonly used push plant, emits citronellal and geraniol that interfere with the olfactory recognition of host crops, disrupting pest settlement (Saputra et al., 2020). Conversely, basil (*Ocimum basilicum*) emits attractants like methyl eugenol and linalool, guiding fruit flies toward trap areas (Niassy, 2023).

Considering the serious threat posed by *Bactrocera dorsalis* to national tomato production, there is a critical need for effective and environmentally friendly control methods. Female fruit flies lay eggs inside ripening or ripe fruits, including tomatoes, using their ovipositor to insert eggs beneath the skin. After hatching, larvae feed on the pulp, causing internal damage such as soft rot, discoloration, and deformation, which reduces fruit marketability and yield (University of Florida, Institute of Food and Agricultural Sciences Extension, 2023). This species has a rapid life cycle of about 16 days from egg to adult under tropical conditions and can produce over 1,000 eggs per female during its lifetime, making it highly invasive and difficult to control without integrated management (University of Florida, Institute of Food and Agricultural Sciences Extension, 2023). Moreover, integrated systems that use spatially optimized arrangements of push and pull elements have shown superior results. For instance, Khan et al. (2018) emphasized that spatial separation between repellents and attractants reduces sensory interference, thereby enhancing insect behavioral responses. Lemongrass is best planted along the perimeter to create a repellent barrier, while basil and yellow sticky traps are placed within or at corners to create attractant zones (Cook et al., 2007; Legaspi et al., 2024). This arrangement exploits both olfactory and visual cues to manipulate insect movement efficiently. Therefore, effective and sustainable control strategies are essential for maintaining yield stability and supporting national food security (Pawlak & Kołodziejczak, 2020).

3.3 Potential of push-pull plant components

In the push-pull system, the push strategy prevents pests from approaching the main crop by using repellents that release volatile compounds disliked by the pests (Cook et al., 2007). Selecting push plants requires consideration of the compatibility between volatile compounds and the targeted pest species to maximize repellent effects (Parker et al., 2013). One effective push plant is lemongrass (*Cymbopogon nardus*), which produces volatile compounds that act as natural repellents, including citronellal, geraniol, limonene, and citronellol (Saputra et al., 2020). Beyond chemical effects, lemongrass also creates a physical barrier by growing in dense clumps up to 1.5–2 meters tall, limiting fruit fly access to tomato plants and enhancing its role as a push plant in the push-pull strategy (Susilowati et al., 2024). Legaspi et al. (2024) reported that planting lemongrass as an intercrop can reduce fruit fly populations by 40–60% compared to conventional methods. In addition, their study highlighted lemongrass's ability to influence oviposition behavior and disrupt fruit fly movement patterns. Meanwhile, Saenong (2016) emphasized that lemongrass is easy to cultivate, does not compete with tomatoes for nutrients, and provides prolonged protection without requiring significant inputs.

Although the push strategy using lemongrass effectively deters fruit flies from approaching the main crop, it should be combined with the pull strategy to not only repel pests but also redirect them to controlled locations. The pull strategy employs plants or traps emitting natural volatile attractants to lure fruit flies away from the main crops and concentrate them in specific areas, thereby significantly reducing pest populations. One promising pull plant is basil (*Ocimum basilicum*), an aromatic herb widely used in ecological pest control systems, including managing *Bactrocera dorsalis* on tomatoes. Basil is known to produce volatile compounds such as methyl eugenol, linalool, estragole, and trans-anethole, which attract both male and female fruit flies, making it an effective trap crop in sustainable agriculture (Tangpao et al., 2021). This plant features green leaves with a strong characteristic aroma and small flowers that attract various insects, including pests and their natural enemies. With a relatively rapid life cycle and ease of cultivation, basil is an effective companion crop for tomatoes to lure fruit flies away from the main plants. Abdullah et al. (2020) reported that compounds such as methyl eugenol and estragole in basil can attract both male and female fruit flies. Supporting this, Niassy (2023) demonstrated that the use of basil oil extracts in traps increased fruit fly capture rates by up to 50% compared to control traps. Furthermore, Mefta & Fauzana (2021) found that planting basil as a pull crop reduced tomato fruit infestation levels by 35–55% in several tropical field conditions.

The main advantages of using basil in the pull system include its effectiveness as a natural trap crop, ease of cultivation, added value as a culinary and medicinal herb, and its ability to attract natural enemies such as parasitoids that play a role in biological pest control (Chang et al., 2009). Thus, planting basil as a trap crop provides a sustainable solution to reduce reliance on chemical insecticides while enhancing pest control effectiveness through more environmentally friendly ecological approaches.

In addition to plants, yellow sticky traps also serve as effective supplementary methods within the pull strategy. Female fruit flies, especially when searching for oviposition sites, are strongly attracted to the yellow color, which resembles unripe tomato fruit. These traps are coated with a special adhesive that captures fruit flies and prevents them from reproducing further. According to Mefta & Fauzana (2021), yellow sticky traps reduced fruit fly infestation by 35–55% in tropical field conditions. When combined with basil as a trap crop and lemongrass as a repellent, the push-pull system provides a synergistic effect that effectively minimizes fruit fly populations. Chang et al. (2009) emphasized the role of basil as an attractant in sustainable pest control, while Abdullah et al. (2020) discussed its additional benefits as a multipurpose crop with medicinal and culinary value.

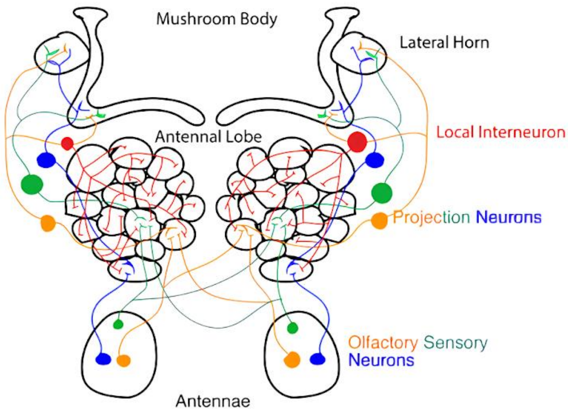

Fig. 2. Mechanism pathway of volatile compounds on the fruit fly olfactory system (Mallick et al., 2025)

The biological basis for the success of the push-pull strategy lies in the olfactory system of the fruit fly. When volatile compounds from lemongrass are released into the air, these molecules enter the fruit fly's antennae and bind to Odorant Binding Proteins (OBPs). These OBPs transport the odor molecules to olfactory receptor neurons, which then send signals to the antennal lobe, the main olfactory processing center in the fly's brain. Volatile compounds from lemongrass compete with the tomato odor, creating a masking effect that blocks the transmission of tomato scent signals to the fruit fly's brain, making it difficult for the pest to locate its host plant. The processed signals are then forwarded to the mushroom body and lateral horn, brain areas involved in odor learning and behavioral decision-making. In the push-pull system, lemongrass (*Cymbopogon nardus*) functions as a repellent due to its emission of volatile compounds such as citronellal and geraniol. These compounds interfere with the olfactory recognition of host plants by the fruit fly, causing them to avoid the treated area (Saputra et al., 2020; Legaspi et al., 2024). These compounds from lemongrass act as competitive antagonists at the fruit fly's olfactory receptors (Saputra et al., 2020; Mallick et al., 2025). This means that the citronellal and geraniol molecules compete with the tomato's volatile compounds to bind at the active sites on the insect's olfactory sensory neurons. When the lemongrass volatiles successfully bind to these sites, the olfactory signal from the tomato fails to reach the antennal lobe for processing, rendering the pest chemically 'blind' to its host plant (Benton, 2022).

This mimics a competitive inhibition mechanism well-known in biochemical receptor theory. The resulting disorientation triggers an avoidance response and alters oviposition behavior, effectively reducing pest pressure in the treated area (Cook et al., 2007). As illustrated in Figure 2, its effectiveneolfss stems not merely from an unpleasant scent, but is rooted in a sophisticated neuro-sensory mechanism at the molecular level (Mallick et al., 2025). These compounds from lemongrass act as competitive antagonists at the fruit fly's olfactory receptors. This means that the citronellal and geraniol molecules compete with the tomato's aromatic compounds to bind to the active sites on the insect's olfactory sensory neurons. When the lemongrass compounds successfully bind to these receptors, the chemical signal from the tomato is effectively blocked and fails to be processed by the fly's brain. Consequently, the insect becomes chemically 'blind' to the presence of its host plant. This inability to detect its food source creates disorientation and triggers an instinctive avoidance behavior, compelling the fruit fly to move away from the protected area. This interference with the pest's olfactory recognition system is what fundamentally makes it more difficult for the flies to locate host plants, ultimately reducing oviposition activity on tomato fruits. Although long-term neurological disruption has not been confirmed in *B. dorsalis*, behavioral studies indicate that continuous exposure to repellents may reduce pest settlement and oviposition activity in the field. However, this effect is behavioral rather than neurotoxic and should be interpreted within the context of field-based ecological management (Cook et al., 2007).

This overwhelmingly powerful signal can 'hijack' the insect's decision-making system, overriding other environmental cues and triggering an instinctive and irresistible approaching response. This compulsive approaching behavior effectively draws the fruit flies away from the tomato plants. Through this mechanism, the basil functions as a 'behavioral sink', concentrating the pests in a designated location and away from the protected main crop. In order to critically assess existing approaches and identify practical gaps, Table 1. summarizes key studies involving push-pull and biological control strategies for *Bactrocera* spp. management in tomato crops.

Table 1. Comparative analysis of push strategies for fruit fly management in tomato cultivation

No	Study (Year)	Target pest & crop	Technique component	Key findings	Strengths	Limitations
1	Meats et al. (2012)	Bactrocera tryoni on tomato	Push: essential oil sprays Pull: protein baits Combined push-pull	Push was more effective than pull and the combined approach	Simple application, effective in small-scale farms	Protein bait evaporates rapidly; requires frequent reapplication; labor- and cost-intensive
2	Legaspi et al. (2024)	Bactrocera dorsalis on tomato	Push: lemongrass (Cymbopogon nardus)	Reduced fruit fly population by 40–60%	Dual action: chemical repellent and physical barrier; easy cultivation	Does not kill pests directly; requires integration with traps or attractants

Conversely, volatile compounds from pull plants such as basil (*Ocimum basilicum*) are processed through the same olfactory pathway but produce an opposite effect. Attractant compounds like methyl eugenol found in basil act as a superstimulus, a concept where an artificial signal mimics a natural stimulus (like a food source or pheromone) with a far greater intensity (Abdullah et al., 2020; Chang et al., 2009). Superstimuli like methyl eugenol do not merely trigger recognition but exploit the insect's instinctive sensory pathways by generating exaggerated stimulus intensity (Chang et al., 2009; Abdullah et al., 2020).

Tabel 2. Comparative analysis of pull strategies for fruit fly management in tomato cultivation

No	Study (Year)	Target pest & crop	Technique component	Key findings	Strengths	Limitations
1	Niassy (2023)	Bactrocera dorsalis on tomato	Pull: basil (Ocimum basilicum)	Increased fly trap capture rate by 50%, infestation reduced by 35–55%	Attracts both male and female flies; high-value herbal crop	Strong attractant but not lethal; untrapped flies may still infest crops
2	Mefta & Fauzana (2021)	Bactrocera dorsalis on tomato	Pull: yellow sticky traps	Reduced infestation by up to 55% in tropical field trials	Cost-effective visual lure; simple and widely available	Glue may deteriorate; traps require frequent replacement; less effective in rainy conditions

This concept, derived from Tinbergen's theory of supernormal stimuli, posits that insects display stronger behavioral responses to artificially amplified cues. Methyl eugenol, when detected by the antenna, induces an intense neural signal to the antennal lobe and lateral horn—areas critical for behavioral decisions (Mallick et al., 2025; Benton, 2022). This hijacks the insect's orientation system and induces an irresistible approach, making basil a powerful behavioral sink to draw fruit flies away from the crop (Niassy, 2023; Legaspi et al., 2024). When a methyl eugenol molecule binds to a receptor on the fruit fly's antenna, it generates an exceptionally strong neural signal that is sent to processing centers in the brain, such as the Lateral Horn.

Tabel 3. Comparative analysis of biological control strategies for fruit fly management in tomato cultivation

No	Study (Year)	Target pest & crop	Technique component	Key findings	Strengths	Limitations
1	Roberts-McEwen et al. (2022)	Tuta absoluta (not B. dorsalis) on tomato	Biological control: communal spider (Cyrtophora citricola)	Capable of capturing flying tomato pests	Minimal input; broad-spectrum predation	Susceptible to egg parasitoids; predator population unstable
2	Cardoso et al. (2025)	Bemisia tabaci on tomato	Biological control: predatory mite (A. herbicolus)	Effectively reduced whitefly populations	Enhances biodiversity, contributes to IPM	Ineffective on tomato surfaces with glandular trichomes; limited mobility
3	Alkema et al. (2019)	Drosophila suzukii (soft fruits)	Context-based push-pull concept	Emphasized the importance of ecological context	Provides flexible design for integrated pest systems	No quantitative field data; not directly tested on tomatoes or B. dorsalis

3.4 Effectiveness and field implementation of the push-pull system

A critical review of existing studies reveals that while individual push-pull components show promise in managing fruit fly populations, their efficacy is often constrained by spatial design, ecological context, and signal interaction. Meats et al. (2012), for example, compared push-only (repellent spray), pull-only (protein bait), and a combined push-pull strategy against *Bactrocera tryoni* in small tomato plots. Interestingly, the push-only treatment achieved the highest deterrent effect, reducing fly landings by approximately 70%. In contrast, the push-pull combination was less effective, which the authors attributed to signal interference where close proximity between attractant and repellent cues led to sensory confusion in flies. Additionally, overlapping volatile compounds may have diminished the attraction zone's efficacy, and the limited spatial separation likely prevented clear behavioral differentiation. This highlights the importance of strategic spatial arrangement in designing integrated pest management systems.

Other studies support the effectiveness of individual components under specific conditions. Niassy (2023) reported that aqueous *Ocimum tenuiflorum* solutions increased fly trap captures by 50% and reduced mango fruit infestation by up to 55%. Similarly, Mefta & Fauzana (2021) observed a 1.5 to 2.8 - fold increase in *Bactrocera* spp. attraction on chili plants with increasing doses of *Ocimum basilicum* extract, although the absence of randomized design and environmental controls limits the reliability of the findings. Their trial also demonstrated that yellow sticky traps could reduce infestation by 35–55%, particularly under dry-season conditions, supporting their use as a low-tech visual capture method.

Biological control approaches have also shown potential, albeit with context-specific limitations. Roberts-McEwen et al. (2022) documented that colonies of the communal spider *Cyrtophora citricola* could capture over 30 *Tuta absoluta* adults per week, yet their performance was reduced by egg parasitism and seasonal instability. Meanwhile, Cardoso et al. (2025) reported that predatory mites (*Amblyseius herbicolus*) could suppress *Bemisia tabaci* populations by 40–65% under greenhouse conditions, although their movement was significantly hindered on tomato cultivars with glandular trichomes, reducing efficacy by up to 50%. Alkema et al. (2019) further emphasized the importance of ecological context and behavioral tuning in push-pull systems, though their conceptual work lacked empirical field data.

These findings collectively underscore the fragmented nature of existing control strategies and the necessity for a more spatially coordinated, multimodal system. Rather than relying on single tactics, the present study proposes a synergistic model that integrates lemongrass-based repellents, basil as a behavioral attractant and potential ecological habitat, and yellow sticky traps as a visual capture mechanism. This approach aligns with the spatial separation principle advocated by Cook et al. (2007), who emphasized that minimizing overlap between push and pull stimuli enhances behavioral guidance.

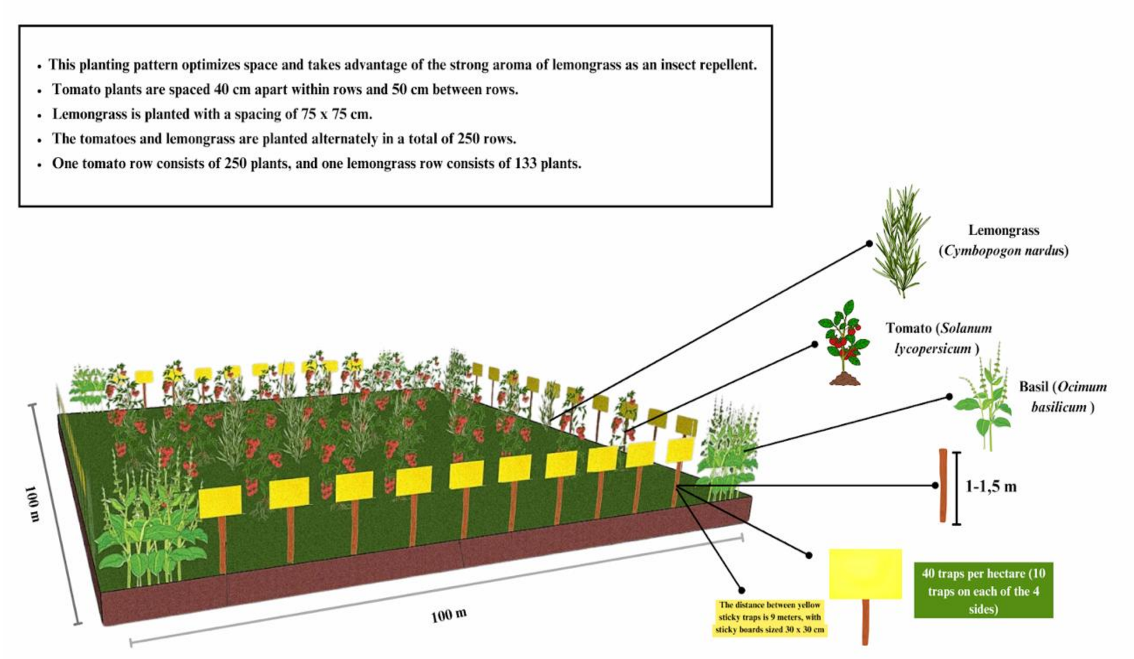

Fig. 3. Land layout of implementing the push-pull system

Unlike the combined push-pull implementation described by Meats et al. (2012), the present system prioritizes spatial optimization and sensory channel separation by placing lemongrass repellents around the perimeter, basil attractants at the corners, and yellow sticky traps adjacent to the attractants. This separation aims to reduce sensory interference and guide pest behavior more effectively, a spatial arrangement principle that is well-documented in Cook et al. (2007) and further supported by Khan et al. (2018), especially for pests with strong olfactory and visual navigation capabilities. The conceptual layout of this design includes basil as the primary pull crop planted at each corner of a 1-hectare field, with yellow sticky traps positioned evenly along each side, totaling 40 traps per hectare. This setup creates a defensive barrier where basil attracts female fruit flies for oviposition, diverting them from tomato crops, while surrounding yellow sticky traps intercept both male and female flies before reproduction occurs. Within the crop area, lemongrass emits strong VOCs to deter fruit flies, consistent with findings from Li et al. (2023) and supported by Legaspi et al. (2024), who reported a 40–60% reduction in fruit fly populations through lemongrass intercropping.

The integration of these elements establishes a multilayered, plant-based pest control system where each component is grounded in behavioral theory. The failure in Meats et al. (2012) due to signal interference is now understood as a neuroecological issue, where *Bactrocera* spp. simultaneously receive "approach" and "avoid" signals, leading to sensory dissonance. This proposed layout corrects for that by maximizing spatial and modal separation. The positioning of basil at the corners isolates attractant cues away from the tomato crop, reducing volatile overlap and guiding pests toward peripheral trap zones. This separation ensures that attractive volatiles are not masked by repellent ones. Pairing basil with yellow sticky traps creates a multimodal lure zone, where basil acts as a long-range olfactory lure and the traps offer close-range visual stimuli that trigger landing behavior, thereby amplifying the capture rate through complementary sensory channels. Lemongrass is positioned along the perimeter to act as a repellent wall, emitting volatiles that disrupt pest orientation before they encounter attractive cues. This "outer ring" discourages entry and establishes a behavioral funnel toward the corner traps, minimizing crop exposure. Collectively, the spatial configuration transforms the field into a guided behavioral system pushing pests away from sensitive areas while pulling them toward controlled capture zones representing a theory-informed enhancement to traditional IPM layouts.

3.5 Challenges and future prospects of push-pull technique in fruit fly management

The push-pull technique represents a significant advancement in integrated pest management (IPM), particularly for mitigating fruit fly (*Bactrocera dorsalis*) infestations in tomato cultivation. The system comprises two synergistic components: the “push” aspect, which utilizes repellent plants such as lemongrass (*Cymbopogon nardus*) to deter pests through volatile compounds like citronellal and geraniol, and the “pull” aspect, which attracts pests toward trap plants like basil (*Ocimum basilicum*) emitting lures such as methyl eugenol, linalool, and estragole. Legaspi et al. (2024) observed a 40–60% reduction in fruit fly populations when lemongrass was intercropped with tomatoes, as it interfered with the insects’ olfactory recognition systems. Complementarily, Niassy (2023) and Mefta & Fauzana (2021) demonstrated that basil-based attractant traps increased capture rates by up to 50% and decreased infestation by 35–55%, respectively. The addition of yellow sticky traps further strengthens the system by exploiting the flies’ visual preferences. Compared to synthetic pesticides, which can reduce pest populations by over 80% (Bughdady et al., 2020; Salam et al., 2023) but carry risks such as pest resistance, environmental degradation, and harm to non-target organisms (Conboy et al., 2020; Dimase et al., 2024), the push-pull method offers a more sustainable and ecologically grounded alternative.

Despite its proven efficacy, several practical challenges hinder the widespread adoption of the push-pull system, particularly among smallholder farmers. The initial investment for seeds, trap installation (approximately 40 traps per hectare), and land configuration adjustments may be cost-prohibitive. Furthermore, the technique requires technical competency in spatial arrangement, trap positioning, and maintenance. Irregular land topographies, such as terraced or fragmented fields, can further complicate proper implementation (Suprehatin, 2019). Environmental factors also pose constraints; basil’s attractant efficiency tends to diminish under humid or rainy conditions due to the degradation of volatile compounds (Meats et al., 2012). Beyond these logistical barriers, a more profound socio-economic and psychological dimension affects farmer adoption. Smallholder farmers often operate within narrow economic margins and short-term planning horizons, which make them naturally risk-averse. The push-pull system requires upfront investment and a waiting period before the companion plants mature and deliver visible benefits—conditions that contrast sharply with the immediate and predictable outcomes associated with conventional chemical pesticides. This temporal mismatch introduces economic uncertainty, which amplifies farmers’ hesitation. Moreover, many farmers lack visible role models in their local networks who have succeeded with the system, which reinforces skepticism. Addressing this challenge requires more than technical training; it calls for a transformation in mindset—from reactive pest control (spraying upon infestation) to proactive, ecology-based prevention. To shift this paradigm, outreach strategies must include demonstration plots that showcase the system's financial viability over a full growing cycle and incorporate tailored risk communication to build trust in the long-term value of agroecological approaches.

From a conceptual standpoint, the push-pull strategy exemplifies core principles of agroecology, which emphasize plant diversity, ecological balance, and minimal reliance on external inputs. By integrating functional biodiversity into agricultural systems, farmers harness natural pest regulation mechanisms that contribute to resilient and sustainable production outcomes (Eigenbrode et al., 2015). The technique also aligns with the framework of chemical ecology, wherein plant-emitted volatile organic compounds engage with insect olfactory systems to modify behavior (Benton, 2022; Mallick et al., 2025). Understanding these interactions enables the refinement of biologically targeted and environmentally benign pest control strategies. Thus, the system represents not only an ecologically sound approach but also a scientifically grounded innovation in the field of pest management.

Beyond ecological advantages, the push-pull system presents considerable economic opportunities. Lemongrass and basil, the main intercrops in this system, hold commercial value as sources of essential oils, culinary herbs, or herbal teas, allowing farmers to diversify their income and reduce economic dependence on a single crop. This added economic layer increases the overall resilience of farming households. Furthermore, the integration of this technique into national agricultural policy can contribute to broader goals of food sovereignty and environmental sustainability. Policy interventions such as farmer education, initial subsidies, and locally adapted research and development are essential to unlock its full potential (Pawlak & Kołodziejczak, 2020).

Ultimately, the push-pull approach provides a comprehensive, scientifically validated, and ecologically responsible pest management solution that aligns with key national and global agendas. Its implementation supports Sustainable Development Goals, especially SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), by promoting local, safe, and environmentally conscious agricultural practices. With adequate support and participatory implementation, the push-pull system can become a foundational pillar in the transition toward more sustainable, inclusive, and productive agroecosystems—particularly in tropical regions like Indonesia.

Beyond its ecological benefits, the push-pull system also enhances economic resilience by enabling farmers to diversify income sources through the commercial use of lemongrass and basil derivatives. These crops can be processed into essential oils, herbal teas, or culinary products, providing added value and reducing dependence on a single commodity. In sum, the push-pull technique not only provides a scientifically validated and ecologically sustainable solution to pest control but also serves as a strategic pillar in the transition toward more resilient, inclusive, and productive agricultural systems in tropical regions such as Indonesia.

4. Conclusions

The push-pull system, which synergistically integrates repellent plants like lemongrass with attractant components such as basil and yellow sticky traps, represents a scientifically validated and efficacious strategy for suppressing fruit fly (*Bactrocera dorsalis*) populations in tomato cultivation. This agroecological approach manipulates the pest's olfactory behavior to significantly reduce crop infestation, thereby diminishing reliance on synthetic pesticides and mitigating their adverse environmental impacts. In turn, this strategy is shown to promote agricultural biodiversity and support food security. This review therefore concludes that the push-pull technique is a viable and holistic alternative to conventional pest control in tomato farming, offering significant ecological and productive benefits.

While the push-pull technique is a promising solution, its transition from research to widespread practice necessitates a concerted, multi-stakeholder effort. To facilitate this, several aspects should be prioritized. Future research trajectories should focus on quantitative meta-analyses to ascertain precise effect sizes, field studies to assess the system's adaptability across diverse Indonesian agroecologies, and investigations into its integration with emerging agricultural technologies. Concurrently, a supportive policy framework is essential; government agencies can foster adoption by championing funded training programs, offering financial incentives to mitigate initial investment barriers, and strategically embedding this approach within national food security policies.

Ultimately, effective implementation at the farm level is contingent upon the active engagement of farmers. This includes their initiation of small-scale trials to tailor the system to specific local contexts, and their strategic capitalization on the economic diversification opportunities presented by the companion crops, such as lemongrass and basil.

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