OPEN ACCESS Plant Protection, 10 (04) 2026. 765-776 DOI:10.33804/pp.010.04.6187

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Available Online at EScience Press
Plant Protection
ISSN: 2617-1287 (Online), 2617-1279 (Print)
http://esciencepress.net/journals/PP

Research Article

Evaluation of Selected Entomopathogenic Fungi and Pheromones for the Control of Fall Armyworm (*Spodoptera frugiperda*) on Maize in Baghdad

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ARTICLE INFO

Article history
Received: 18th May, 2026
Revised: 15th August, 2026
Accepted: 19th August, 2026

Keywords
Spodoptera frugiperda
Entomopathogenic fungi
Beauveria bassiana
Metarhizium anisopliae
Pheromone traps

ABSTRACT

Fall armyworm, *Spodoptera frugiperda*, is a major maize pest requiring effective and environmentally sustainable management strategies. This study evaluated the efficacy of *Beauveria bassiana*, *Metarhizium anisopliae*, pheromone traps, and their integration under field conditions in Iraq. Significant differences ($P \leq 0.05$) were observed among treatments for larval density, plant infestation, and damage severity. The untreated control recorded the highest larval density (3.46 larvae plant^{-1}), infestation (52.4%), and damage severity (2.86). In contrast, the combined application of *B. bassiana* + pheromone traps provided the greatest suppression, reducing larval density to 0.92 larvae plant^{-1} (73.4% reduction), infestation to 18.7% (64.3% reduction), and damage severity to 1.21 (57.7% reduction) relative to the control. Among individual treatments, *B. bassiana* was more effective than *M. anisopliae*, reducing larval density to 1.35 larvae plant^{-1}, infestation to 24.5%, and damage severity to 1.48. Pheromone traps alone provided moderate suppression, with corresponding values of 2.14 larvae plant^{-1}, 33.6%, and 1.94, respectively. The superior performance of the combined treatment was attributed to simultaneous suppression of larvae by fungal infection and adult males through pheromone trapping, although synergistic interaction was not statistically established. Overall, integrating entomopathogenic fungi with pheromone-based control showed strong potential for reducing *S. frugiperda* populations and maize damage while supporting sustainable integrated pest management under field conditions.

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Introduction

Maize (*Zea mays* L.) is one of the major cereal crops worldwide in terms of both harvested area and production. It is an instrumental crop for food security and a significant source of food for humans, feed for animals and raw materials to industry. In Iraq, maize is regarded as a cash crop due to the high demand by poultry and animal owners and its cultivation has seen a significant increase in the past 10 years. However, maize production is limited by many biotic and abiotic factors, among these; insect pests are the most devastating due to their direct effect on plant development, grain yield and subsequently the farmers, production profitability (FAO, 2018).

Among the insect pests of corn, the fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), has emerged as a highly damaging invasive species to agricultural production globally. Originating from tropical and subtropical areas of the Americas, this invasive pest has rapidly spread across Africa, Asia, and the Middle East within the last 10 years. Its extraordinary dispersal ability, high fecundity, broad host range (more than 350 plant species), and multivoltine nature have allowed the species to colonize new areas within a short time after introduction (Goergen et al., 2016; Day et al., 2017, 2021; CABI, 2024).

The concern regarding its introduction to Iraq is escalating due to suitable climatic conditions for its survival, reproduction and seasonal dispersal. These favorable environments such as warm climate, uninterrupted presence of host plants and the intensive cultivation of maize allow for rapid population build-ups and higher chances for extreme outbreaks. Thus, the pest has become a major challenge to maize production which demands effective, environmentally sustainable and economically viable management strategies that can be adapted to the local agroecological conditions.

The larvae of fall armyworm cause damage to crops. The freshly hatched larvae feed on leaf epidermal tissues while older instars usually feed on foliage causing typical window feeding, irregular elongated feeding holes, ragged margins and exposure of whorl leaves (Figure 1). Severe attacks of these tissues under heavy infestation leads to remarkable loss of plant vigor resulting in grain yield loss by 20 to 70% depending upon the crop growth stage, intensity of infestation and prevailing weather conditions (Harrison et al., 2019). Intensive studies on the biology and feeding nature of *S. frugiperda* have revealed that early larval control is critical for reducing yield losses and maintaining maize productivity (Sharanabasappa et al., 2018, 2020; Togola et al., 2018).

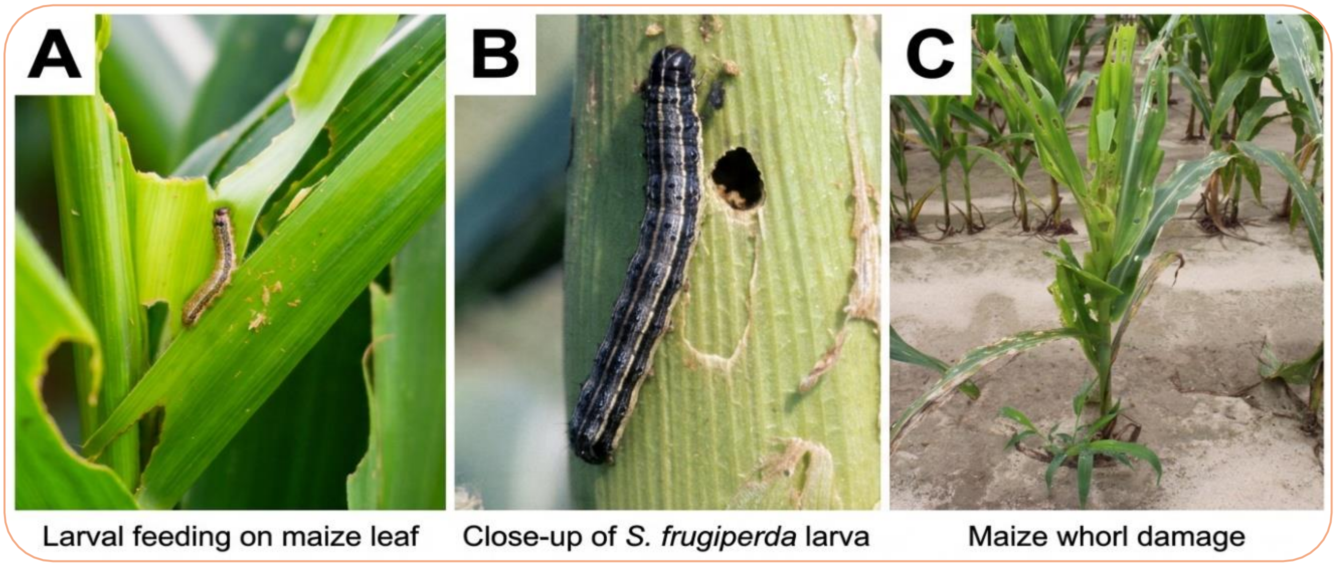

Figure 1. Typical damage caused by *S. frugiperda* on maize: (A) larvae feeding on maize leaves, (B) a fall armyworm larva under close-up, and (C) maize plants with typical whorl damage.

Fall armyworm control has been based on more or less intensive use of synthetic insecticides due to their fast knockdown action and rapid decrease in pest numbers. On the contrary, multiple and unplanned insecticide treatments are leading to a number of negative effects such as the development of insecticide resistance, pollution of soil and water, negative impact on beneficial arthropods and pollinators, pesticide residues on agricultural goods, and the increasing threat to human life and environmental sustainability (Sparks, 1979; Gutiérrez-Moreno et al., 2019). Populations of fall armyworm in the field have so far evolved resistance to a number of traditional insecticides in various parts of the world, thereby compromising the long-term utility of chemicals, highlighting the immediate requirement for durable options which can be incorporated in modern pest.

Thus, the IPM is considered as the best approach for sustainable management of fall armyworm. IPM provides a diverse suite of compatible pest control methods (biotic, behavioral, cultural, and chemical) to maintain pest populations at levels below economic injury levels that have the least impact on environment. United Nations agencies such as the Food and Agriculture Organization (FAO) advocate IPM-based programmes for sustainable management of *S. frugiperda* in maize production systems (FAO, 2018, 2020; Koffi et al., 2022).

Among the diverse biological control agents, entomopathogenic fungi have been extensively investigated as a potential alternative for the control of a wide range of insect pests. These fungi infect insects by direct penetration of the cuticle rather than by oral route as do chemical insecticides. After attachment to the insect host, fungal conidia are able to germinate and penetrate the cuticle, colonize the hemocoel, proliferate and kill the host by tissue colonization and toxin production (Goettel and Inglis, 1997; Vega et al., 2009). This novel mode of action confers entomopathogenic fungi a unique status among biological control agents and makes them extremely compatible for integration into environmentally friendly pest management programs.

Among the many fungal species tested against lepidopteran pests, *Beauveria bassiana* and *Metarhizium anisopliae* are regarded as two of the most potent microbial control agents due to their high virulence, wide host range, and efficacy in both laboratory and field application. Their capacity to decrease larval survival, feeding, and the population of *S. frugiperda*, thus leading to a reduction in crop damage and protection of plants, has been reported in numerous studies (Bateman et al., 2018; Lacey et al., 2015; Kuzhuppillymyal-Prabhakarankutty et al., 2021; Shahzad et al., 2021; Wakil et al., 2021; Liu et al., 2022; Bugti et al., 2024; Zalte et al., 2024). Their potential to serve as valuable elements of green pest management programs has also been confirmed by recent studies, due to their non-target safety and compatibility with other biological control approaches (Lacey et al., 2021; Abbas et al., 2022; Abbas, 2024).

Methods of behavioral control, including pheromone-based trapping systems, are now considered essential elements of IPM strategies for *S. frugiperda*. Synthetic sex pheromone traps are commonly used for monitoring adult male population, detecting the beginning of infestations, estimating the seasonal population trend, and predicting the timely application of control measures. Besides their role in monitoring, pheromone traps may be used as an active tool to reduce pest populations through mass trapping by decreasing male numbers and hence mating success, which may in turn reduce egg laying and subsequent larval population growth (Cork et al., 2001; Cruz et al., 2012; Meagher et al., 2016). Therefore, pheromone-based surveillance has evolved as an essential landscaping tool to sustain fall armyworm management strategies.

Contemporary IPM strategies are now aimed at the integration of biologically and behaviorally compatible control methods to enhance pest control and reduce reliance on conventional insecticides. Entomopathogenic fungi and pheromone traps act differently but complementary ways: fungal pathogens infect immature stages of insect directly and kill them, but pheromone traps intercept adult males, allowing for the continued monitoring of the dynamics of pest populations. The combination of the two options has proven to enhance the efficacy of pest management systems, to refine timing for interventions in control and to decrease insecticide dosing without jeopardizing protection of the crop (Prasanna et al., 2018; Sisay et al., 2019; Silva et al., 2021; Zhou et al., 2021), as previously reported for other studies on combining biological control agents and pheromone-based monitoring. Combined laboratory and field studies with *B. bassiana* and *M. anisopliae* confirmed more recently their high virulence against *S. frugiperda*, with drastic decreases of larval survival, feeding, and associated crop damage after fungal treatment (Jeon and Kim, 2024; Mekonnen et al., 2024; Tessari et al., 2024; Ramos et al., 2025). These data support the integration of microbial agents into environmentally friendly management programs for invasive lepidopteran pests (Khamis et al., 2023).

Many studies have been conducted on entomopathogenic fungi or pheromone traps alone, but there are only a few that have dealt with their integration especially under Middle Eastern agroecological conditions and in Iraq, in which *S. frugiperda* is currently considered an invasive pest for the production of maize. In addition, there is limited data on the relative efficacy of these green options in the climate of the study site. This absence of field validation constitutes a significant gap in knowledge, which impedes the formulation of location-specific IPM recommendations for the Iraqi maize production system.

Hence, the current study was performed to investigate the efficacy of two entomopathogenic fungi, *B. bassiana* and *M. anisopliae*, combined or alone with pheromone traps against the population of *S. frugiperda* in open field maize production at Baghdad, Iraq. The study was focused on their impact on the density of larvae, incidence of infestation and severity of plant damage to find out environment-friendly management options that could be recommended in integrated pest management packages for maize under Iraqi conditions.

Materials and Methods

Experimental site

The field study was carried out in the fall season of 2025 at the Farm of Plant Protection, College of Agricultural Engineering Sciences, University of Baghdad (Al-Jadriya Campus), Baghdad, Iraq. The study site is situated in the heart of Iraq (33°16′ N, 44°23′ E) and lies in a semi-arid zone characterized by very hot, dry summer and cool winter. The experimental soil was a clay loam with medium fertility. Prior to planting, the land was prepared by using conventional methods of ploughing and harrowing followed by levelling and making of the seedbeds for uniform soil condition across the field.

All the agronomic practices such as irrigation, fertilization, weed control and other cultural practices were uniformly applied to all treatments based on the recommendations for the maize by the Iraqi Ministry of Agriculture for the production of commercial maize. To prevent disturbance of the biological control formulations under evaluation, no chemical insecticides were used during the experimental trial.

Crop establishment

The commercial maize hybrid IBA 5018 was chosen for this study based on its high potential yield, suitability for Iraqi agroecology, and popularity among local farmers. The seeds were sown by hand in rows 75 cm apart, and with 25 cm between the seeds in each row. Every trial plot consisted of five rows, each roughly 5 m long, and covered a total area of 4 × 5 m (20 m^2). There were about 80 plants established in each of these plots. The experimental field was surrounded by guard rows and two-meter buffer zones between adjacent plots were left to prevent treatments interfering with each other and to avoid spray drifts.

Experimental design

The study was conducted in a Randomized Complete Block Design (RCBD) with three replicates and five treatments (Table 1). Treatments were randomly assigned within blocks, for a total of 15 experimental plots. The field layout employed in the present study is depicted in Figure 2, displaying the RCBD design, treatment layout and the location of pheromone traps within the plots of the experiment.

Preparation of entomopathogenic fungal suspensions

The biological control agents evaluated were the commercial formulations: *B. bassiana* (strain GHA) as a wettable powder formulation and *M. anisopliae* (strain F 52) as a wettable powder formulation. The fungal products were purchased from a commercial agricultural supplier and kept at the temperature recommended by the manufacturer until used.

Fungal suspensions were freshly made before each application by suspending the formulated product in distilled water with 0.05% Tween-80 as a surfactant to a final concentration of 1×10^8 conidia mL^{-1}. The suspensions were stirred constantly by mechanical stirring to ensure homogeneous distribution of the conidia and to avoid settling during processing and application. The viability of conidia was evaluated by conventional germination tests before field application and was found higher than 90%, which indicated good biological activity.

Application of entomopathogenic fungi

Suspensions of fungi were applied with a 20-L knapsack sprayer which was calibrated to deliver 350 L ha^{-1}, and this was considered to be sufficient for uniform coverage of the maize leaves. The initial application was made when the first *S. frugiperda* larva was found in the experimental field. Two further applications were made at 10-day intervals, giving three applications in total during the crop season. Applications were made in the early morning when environmental conditions were favorable to prevent ultraviolet degradation of fungal propagules and to optimize the rate of infection.

Table 1. Description of the experimental treatments used for the management of *S. frugiperda* in maize under field conditions.

Treatment	Description
T1	Application of *B. bassiana* at 1×10^8 conidia mL^{-1}.
T2	Application of *Metarhizium anisopliae* at 1×10^8 conidia mL^{-1}.
T3	Installation of Delta pheromone traps baited with species-specific synthetic sex pheromone lures for *S. frugiperda*.
T4	Integrated treatment consisting of *B. bassiana* application combined with Delta pheromone traps.
T5	Untreated control receiving distilled water only.

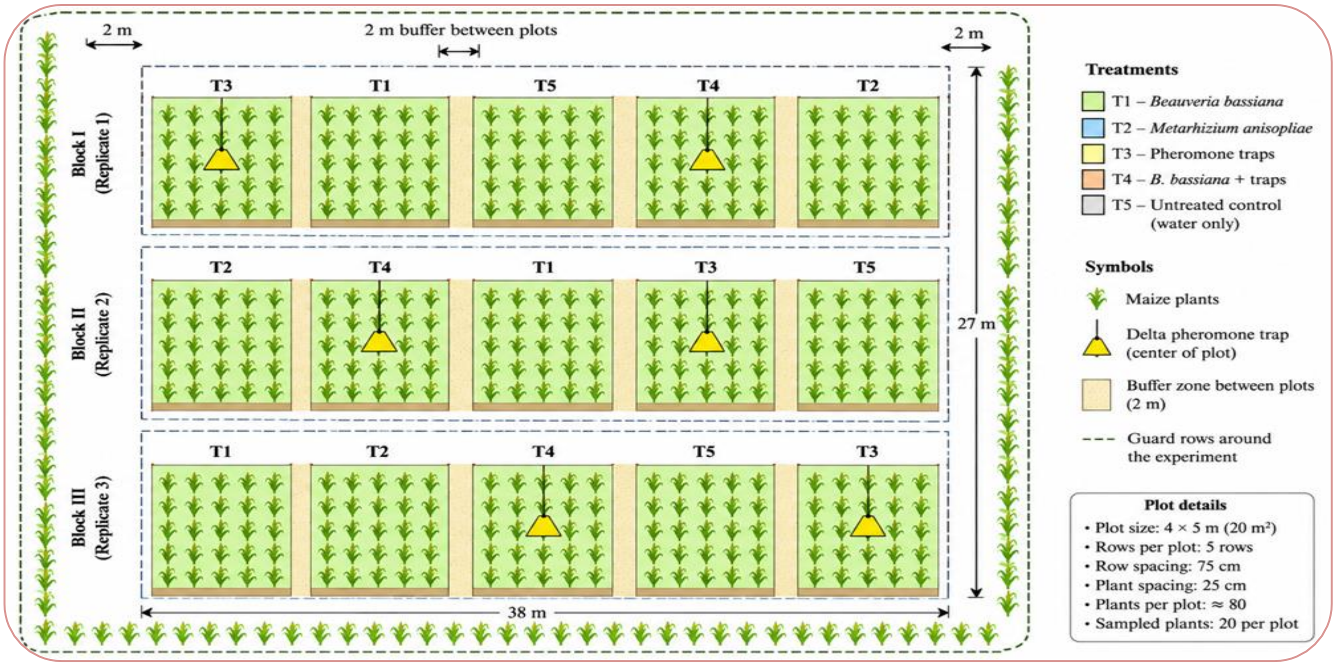

Figure 2. Experimental layout of the field trial showing RCBD, treatment allocation, and pheromone trap positions.

Installation of pheromone traps

Commercial Delta pheromone traps with species-specific synthetic sex pheromone lures for *S. frugiperda* were used to monitor adult males and for mass trapping. Immediately after plot establishment, one trap was hung at the center of each plot. Traps were held at the height of the maize canopy during the experimental period and evaluated as the crop growth increased. To reduce the interference of the traps, the neighboring traps were separated at a distance of about 25-30 m. Pheromone lures were changed after every four weeks following the manufacturer's instructions, while sticky inserts were changed when found necessary for maintaining efficiency. Male moths caught were counted weekly and removed after each observation. The properties of the biological control agents and the pheromone trapping used in this study are given in Table 2.

Data collection

Daily field observations started 14 days after seedling emergence and continued until the physiological maturity of the crop. From each plot, 20 plants were randomly selected and tagged enabling observations over time. The following parameters were taken into account:

Larval density

Density of larvae was estimated by visual observation of the plants and all *S. frugiperda* larvae found were counted. The data was shown as the mean larvae per plant.

Adult male capture

The total number of adult male moths captured in each Delta trap baited with pheromone was counted weekly and reported as number of moths per trap per week.

Infestation percentage

The infestation percentage was calculated according to the following equation:

$$\text{Infestation (\%)} = \frac{\text{Number of infested plants}}{\text{Total number of examined plants}} \times 100$$

Where plants showing typical feeding symptoms or with live larvae were deemed infested.

Damage severity assessment

S. frugiperda larvae leaf and whorl feeding damage was visually evaluated based on the following 0–5 scale of damage severity:

0 = No feeding damage visible to the naked eye,
1 = Very superficial feeding scars or pinholes,
2 = Small patches of injury,
3 = Moderate feeding damage incorporating uniform perforations and whorl injuries,
4 = Attack on the majority of leaves, and whorl,
5 = The whorl is largely eaten away, resulting in complete plant death,

The mean damage score for each plot was calculated from the assessed plants. The entire experimental procedure (field preparation, application of treatments, weekly observations, harvesting, data collection, and statistical analysis), which was consistent throughout the study, is depicted in Figure 3.

Statistical analysis

All the recorded data were subjected to ANOVA using RCBD. The assumptions of normality and homogeneity of variance were satisfied prior to analysis. Percentage data were arcsine-square-root transformed as necessary prior to analysis; however, original means were presented in the tables for clarity. Treatment means were compared using the least significant difference (LSD) at 5% level of probability ($P \leq 0.05$). Analyses were performed with the SAS software (Version 9.4, SAS Institute, Cary, NC, USA).

Table 2. Characteristics of the biological control agents and pheromone trapping system used in the study.

Parameter	*Beauveria bassiana*	*Metarhizium anisopliae*	Pheromone traps
Biological agent	Entomopathogenic fungus	Entomopathogenic fungus	Delta trap
Formulation	Wettable powder (WP)	Wettable powder (WP)	Sticky Delta trap
Fungal strain	GHA	F 52	Species-specific lure
Working concentration	1×10^8 conidia mL^{-1}	1×10^8 conidia mL^{-1}	—
Spray volume	350 L ha^{-1}	350 L ha^{-1}	—
Application frequency	Three applications	Three applications	Continuous
Application interval	Every 10 days	Every 10 days	Weekly inspection
Trap density	—	—	One trap per plot
Trap height	—	—	Maize canopy height
Lure replacement	—	—	Every four weeks

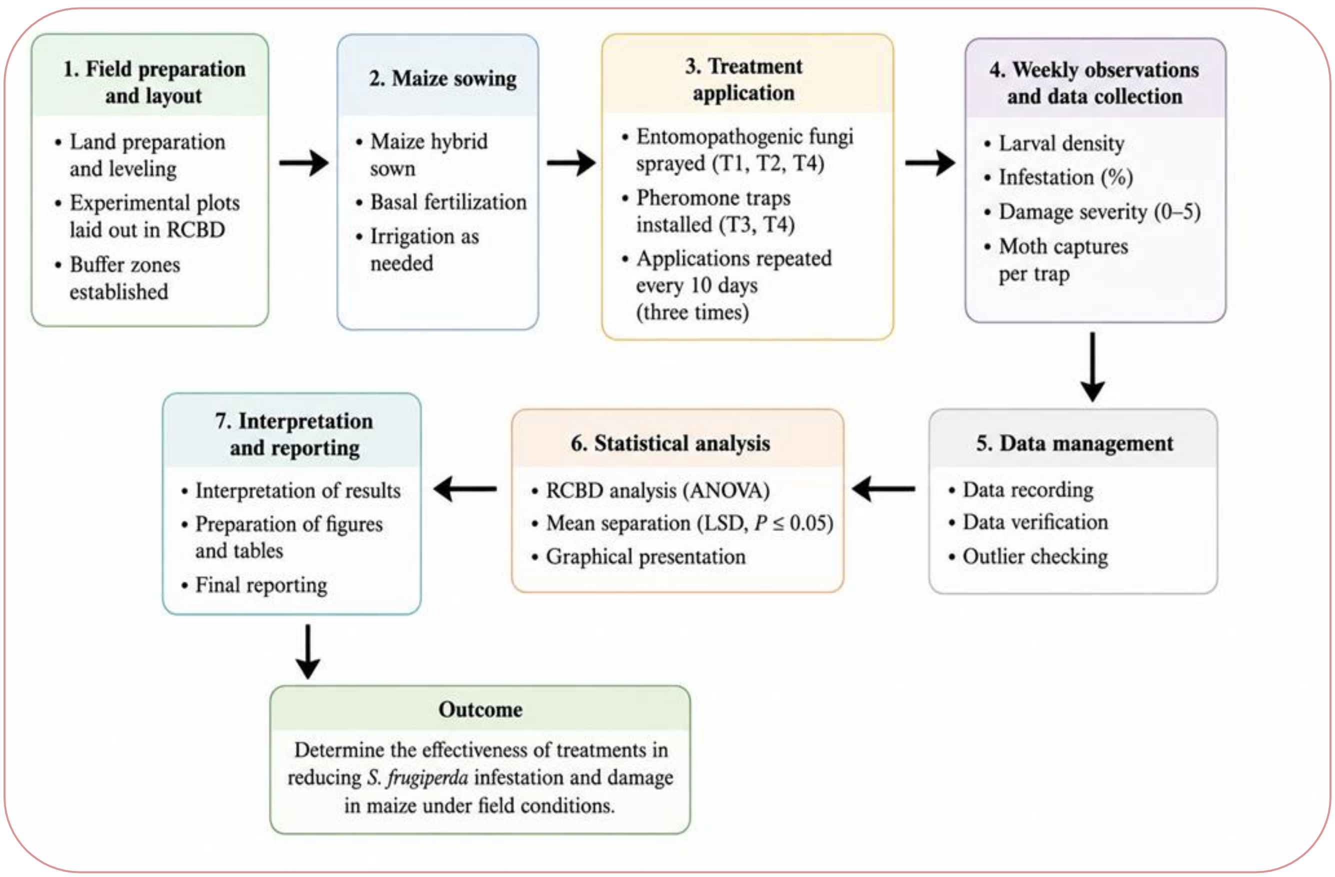

Figure 3. Experimental workflow illustrates maize cultivation, treatment application, weekly observations, and statistical analysis.

Results and Discussion

Effect of treatments on larval density of *S. frugiperda*

The larval density of *S. frugiperda* under different management options is given in Table 3. The ANOVA indicated the existence of significant differences ($P \leq 0.05$) among the applied treatments. The highest larval density was recorded in the untreated control, with an average of 3.46 larvae plant^{-1}, suggesting a fast establishment and population increase of the pest in the field without the application of any control measures. On the other hand, the integrated treatment *B. bassiana* + pheromone traps was the best for suppressing pest population and density of larvae to 0.92 larvae plant^{-1}, which was showed about 73.4% reduction compared to untreated control.

Among the tested entomopathogens, *B. bassiana* caused the highest reduction in larval density to 1.35 larvae plant^{-1}, followed by *M. anisopliae* with 1.58 larvae plant^{-1}. Although the number of larvae was drastically reduced by the pheromone traps alone in comparison to the untreated control, and was less effective treatment than the fungus treatments, with 2.14 larvae plant^{-1}. These results suggest that biological agents delivered superior direct suppression of the immature stages compared to behavioral control via pheromone trapping alone.

Table 3. Effect of treatments on larval density of *S. frugiperda* on maize plants.

Treatment	Larval density (larvae plant^{-1})
B. bassiana	1.35 ± 0.09^{c}
M. anisopliae	1.58 ± 0.11^{c}
Pheromone traps	2.14 ± 0.13^{b}
B. bassiana + pheromone traps	0.92 ± 0.07^{d}
Untreated control	3.46 ± 0.18^{a}
LSD ($P \leq 0.05$)	0.42

Values are presented as mean ± standard error (SE). Means within the same column followed by different superscript letters differ significantly according to the Least Significant Difference (LSD) test at $P \leq 0.05$.

The integrated control has superior efficacy and can be explained by additive or synergistic effect of the two strategies. Entomopathogenic fungi infect susceptible larval stages directly through the insect cuticle, grow inside the haemocoel and kill the host by tissue destruction and the production of toxic metabolites, causing reduction in larval survival and feeding activity (Vega et al., 2009; Lacey et al., 2015). At the same time, pheromone traps are continuously used to catch adult males and chase them away from mating, so the number of viable eggs gets lower, resulting in less production of new larval generations. It cannot be confirmed that there existed a true synergistic interaction. However, under the present experimental design, the joint application clearly provided better pest control than either of the two individual control measures tested under field conditions.

The superiority of *B. bassiana* over *M. anisopliae* might be due to the difference in virulence, the rate of conidial germination, environmental fitness, and host pathogen compatibility as a result of the weather conditions in central Iraq. Temperature, relative humidity, solar radiation, and fungal propagule persistence are considered to be key determinants for the efficacy of entomopathogenic fungi under field conditions (Vega et al., 2009; Lacey et al., 2021). *B. bassiana* frequently caused the fastest infection and highest mortality in the field and sometimes under laboratory conditions, although both fungal species were highly pathogenic to lepidopteran larvae (Liu et al., 2022). Similar results were obtained by Liu et al. (2022). *B. bassiana* and *M. anisopliae* were frequently found associated with highest larval mortality (Shahzad et al., 2021; Wakil et al., 2021; Bugti et al. 2024). Kuzhuppillymyal-Prabhakarankutty et al. (2021) also reported significant reductions in larval survival and feeding behavior after fungal infection.

Pheromone traps by themselves yielded a modest suppression of larval populations. This is not surprising since pheromone-based control targets adult male moths and not the larvae which are feeding on the maize plants. Therefore, pheromone traps disrupt the future population growth by reducing successful mating and only have indirect effect on the current larval population. However, pheromone trapping is still a crucial aspect of integrated pest management programs as it ensures continuous monitoring of pest density, enables prompt control measures at the right time, and enhances population reduction through mass trapping (Cruz et al., 2012; Meagher et al., 2016).

In summary, our results indicate that the combination of biological control with pheromone trapping is a more efficient and environmentally friendly management strategy than either method alone. These findings are consistent with earlier field studies suggesting that the combination of compatible biological and behavioral control measures provides one of the most dependable means of achieving sustained reduction of *S. frugiperda* populations with minimized reliance on chemical insecticides (Prasanna et al., 2018; Sisay et al., 2019; FAO, 2020; Silva et al., 2021; Zhou et al., 2021).

Effect of treatments on infestation percentage of *S. frugiperda*

The percentage of maize plants infested with *S. frugiperda* in each management treatment is shown in Table 4. There were significant differences (P ≤ 0.05) among the tested treatments, as revealed by analysis of variance. The highest infestation rate was observed in the untreated control (52.4%), which confirmed the quick development and dispersion of *S. frugiperda* populations in the field in the absence of control measures. By contrast, the integrated treatment of *B. bassiana* + pheromone traps had the minimum infestation rate (18.7%), which was equivalent to a decrease of 64.3% over the control.

The treatment with *B. bassiana* alone was the most effective in reducing plant infestation, resulting in 24.5% of the plants being infested, whereas *M. anisopliae* gave 27.8%. The pheromone trap treatment also reduced infestation significantly compared to the untreated control but was still less effective than both the fungal treatments, with an average infestation rate of 33.6%.

Table 4. Effect of treatments on the infestation percentage of maize plants by *S. frugiperda*.

Treatment	Infestation (%)
Beauveria bassiana	24.5 ± 1.21^{c}
Metarhizium anisopliae	27.8 ± 1.43^{c}
Pheromone traps	33.6 ± 1.58^{b}
B. bassiana + pheromone traps	18.7 ± 1.05^{d}
Untreated control	52.4 ± 2.02^{a}
LSD (P ≤ 0.05)	5.12

Values are presented as mean ± standard error (SE). Means within the same column followed by different superscript letters differ significantly according to the Least Significant Difference (LSD) test at P ≤ 0.05.

The decrease in infestation percentage after application of fungi is the result of the pathogenic nature of these entomopathogenic fungi on the larvae of the pest. Fungal conidia, after attachment to the cuticle of an insect, germinate, and through enzymatic and mechanical actions, invade the integument, then proliferate in the haemocoel and, finally, lead to mortality of the host. As a result, survival of the larvae on the plant, their feeding and movement from plant to plant, are all dramatically reduced leading to a diminished infestation of the whole field (Goettel and Inglis, 1997; Vega et al., 2009; Lacey et al., 2015).

Among the fungal treatments, *B. bassiana* had higher suppression than *M. anisopliae,* which could be attributed to the variations in the virulence of the fungus, its ability to infect, persist in the environment, and adapt to the local climate. Related observations have been found by Liu et al. (2022), who confirmed that both fungi are highly pathogenic to lepidopteran pests, although it is often reported that *B. bassiana* infects faster and is more effective in the field. Similar decreases in feed damage and larval infestation after fungal treatment were also recorded by Jeon and Kim (2024), Mekonnen et al. (2024), Tessari et al. (2024), and Ramos et al. (2025).

Although fungal formulations proved more effective than pheromone traps used alone, these traps also caused a notable decline in infestation when compared to untreated control. This is not surprising, as pheromone traps are designed to capture adult males and not the larvae that are feeding on the maize crops. However, the ongoing removal of males reduces the chances for mating, egg laying and the appearance of new larval populations. In addition, information obtained from pheromone trapping is useful for monitoring population dynamics of the pest and timely adoption of management options in integrated management programmes (Cruz et al., 2012; Meagher et al., 2016).

The integrated treatment always resulted in the lowest level of infestation among all the treatments tested. This indicates that a dual suppression of the larval population via fungal infection and the adult male population by pheromone traps is a more holistic management strategy than the use of any single of these methods. Our current investigation was not set out to estimate the magnitude of such an interaction effect statistically, but the combined treatment was undeniably the best treatment in the field under the climatic conditions of Iraq. Comparable observations have been made in earlier reports on integrated pest management, indicating the synergistic nature of integrated biologically and behaviorally based control methods in improving the sustainability and the efficacy of fall armyworm management solutions (Prasanna et al., 2018; Sisay et al., 2019; FAO, 2020; Silva et al., 2021; Zhou et al., 2021).

Effect of treatments on the severity of damage caused by *S. frugiperda*

The magnitude of foliar feeding damage caused by *S. frugiperda* to maize plants in the field among different management treatments is shown in Table 5. There were highly significant (P ≤ 0.05) differences among the treatments as revealed by analysis of variance. The untreated control suffered the most damage, so it had the highest damage severity index (2.86), showing extensive feeding injury and complete destruction of maize whorls without pest control. On the other hand, the integrated treatment of *B. bassiana* + pheromone traps led to the minimum damage severity (1.21), which was approximately 57.7% lower than the untreated control.

The use of *B. bassiana* alone led to a decrease in the severity of damage index to 1.48, and with *M. anisopliae* it was 1.63. Pheromone traps alone also reduced damage versus the untreated control, receiving a damage severity index of 1.94, but they were still less effective than either fungal treatment.

Table 5. Effect of treatments on the damage severity caused by *S. frugiperda* on maize plants.

Treatment	Damage severity index
Beauveria bassiana	1.48 ± 0.08^{c}
Metarhizium anisopliae	1.63 ± 0.10^{c}
Pheromone traps	1.94 ± 0.12^{b}
B. bassiana + pheromone traps	1.21 ± 0.07^{d}
Untreated control	2.86 ± 0.15^{a}
LSD (P ≤ 0.05)	0.37

Values are presented as mean ± standard error (SE). Means within the same column followed by different superscript letters differ significantly according to the Least Significant Difference (LSD) test at P ≤ 0.05.

The decrease in severity of damage was in close accordance with the similar decreases in larval density and percentage of infested plants recorded in this study. Since the larval stage accounts for almost all of the economically important feeding injury in maize, the reduction of larval populations invariably also translates into reduced foliar damage and better crop protection. The parallel treatment responses observed for larval density, infestation level, and damage intensity further support the idea that effective control of immature stages is crucial for the reduction of yield losses caused by *S. frugiperda*. Similar results were reported by Harrison et al. (2019) and Nonci et al. (2020), who found that larval populations significantly reduced the feeding injury and protected yields of maize.

Combined use of the entomopathogenic fungi and the pheromone traps showed the best result in the damage severity reduction. This result is explained by the complementary roles of the two control measures. Entomopathogenic fungi suppress the larvae directly by infecting and killing them, while pheromone traps limit the number of adult males and thus restrict the mating and oviposition. As a result, the simultaneous suppression of both established and newly produced pest populations are essential for a continuous protection of maize plants from the incursive pest over the entire growing season. Nevertheless, a combined treatment apparently was better in field performance than each of the single applications, even though interaction effects were not statistically tested in this study.

The higher efficacy of *B. bassiana* compared to *M. anisopliae* was in accordance with the results of the larval density and the infestation percentage recorded in the respective treatments. Variations in fungal pathogenicity, survival in the field, conidial germination, and environmental tolerance are considered as the major factors affecting the efficacy of biological control (Vega et al., 2009; Lacey et al., 2015). Similar decrease in feeding damage after fungal treatment against fall armyworm was reported by Tessari et al. (2024) who also noted significant reduction in both larval movement and crop damage with application of entomopathogenic fungi.

Although the pheromone traps by themselves were less efficient than the fungal treatments in reducing the damage intensity, they are still the good components in integrated pest management as they help in monitoring the population, reducing the number of adult males, better scheduling of control measures, and lowering the risk of future infestations (Cruz et al., 2012; Meagher et al., 2016). Their importance is particularly pronounced when combined with biological control agents that can directly attack the destructive larval stage.

Overall, the combined application of an entomopathogenic fungus and pheromone trapping provided the greatest suppression of *S. frugiperda*, reducing larval density, plant infestation, and feeding damage under field conditions in Iraq. These findings agree with reports indicating that the integration of biological and behavioral control is central to sustainable IPM programmes for fall armyworm in maize-based systems (FAO, 2020; Prasanna et al., 2020; Silva et al., 2021; Zhou et al., 2021).

Conclusion

In the present research, it was observed that the density of the population, the percentage of infestation, and the feeding damage caused by *S. frugiperda* on maize were significantly lowered by all the tested management treatments as compared to untreated control. Of the single treatments, the fungal *B. bassiana* was more suppressive to the pest than *M. anisopliae*, while pheromone traps provided marginal control by decreasing adult males and, hence reducing subsequent infestations. The combined treatment of *B. bassiana* and pheromone traps generally gave the best protection, with the minimum larval density, infestation percent, and damage severity at harvest in the field. The results suggest that a combination of biological and behavioral control approaches is a powerful and environmentally benign fall armyworm control alternative. Hence, an integration of entomopathogenic fungi and pheromone trapping is advisable as the technological tools of IPM strategy for a safe maize production in Iraq reducing dependence on synthetic insecticides for sustainable crop protection and better future of agriculture.

Authors' Contributions

SMS conceptualized and designed the experiment and contributed to methodology, supervision, and validation. ZZHA conducted the investigation, curated and analyzed the data, and performed the visualization. ZZHA prepared the initial manuscript draft, while SMS provided critical review and editorial refinement. Both authors critically reviewed and revised the manuscript, verified the data and analyses, and approved the final version for submission.

Research Funding

This research did not receive any grant from funding agencies.

Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 12: Responsible Consumption and Production
SDG 15: Life on Land

Policy Addressed

The study supports policies promoting integrated pest management, sustainable crop protection, biological control and biopesticide adoption, pesticide-risk reduction, invasive pest surveillance, and environmentally responsible maize production. It also highlights the need for region-specific management guidelines and farmer extension programs for sustainable management of *S. frugiperda* in Iraq.

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