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Comparative performance of synthetic and bioinsecticides for controlling *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in maize fields in Egypt

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Abstract

The invasive fall armyworm *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae) poses a significant threat to maize production in Egypt, necessitating the development of effective pest management strategies. This two-season study (2023-2024) evaluated the comparative efficacy of insecticides (Ebenzoate and lufenuron) and biopesticides (*Beauveria bassiana* and *Bacillus thuringiensis* var. *kurstaki*) against *S. frugiperda* in Giza Governorate maize fields. Using a randomized complete block design, treatments were applied at three concentrations (15%, 20%, and 25% of the field rate) during early larval stages (L2-L4). Emamectin benzoate demonstrated superior efficacy (90.5-98.8% larval suppression), with near-complete larval suppression even at 15% concentration. Lufenuron showed dose-dependent effectiveness (70-90% suppression), while bio-pesticides exhibited moderate efficacy (25-52% larval suppression), with efficacy plateauing beyond 20% concentrations. The results highlight the dominance of emamectin benzoate for emergency control, the value of lufenuron in resistance management programs, and the complementary role of bio-insecticides in sustainable Integrated Pest Management (IPM). These findings support FAO-recommended economic threshold-based spraying strategies, combining targeted chemicals with microbial controls to balance efficacy and sustainability in Egyptian maize production systems.

Introduction

Spodoptera frugiperda (Smith) (Lepidoptera: Noctuidae), commonly known as the fall armyworm, is a destructive polyphagous pest infesting 353 host plants from 76 different families, leading to severe crop losses (Montezano *et al*., 2018). Currently, it poses a major agricultural threat, having invaded and damaged crops in over 20 African nations (Kumar and Murali, 2020). Maize (*Zea mays* L.) is a staple crop of critical economic importance worldwide, particularly in Egypt, where it contributes significantly to both human consumption and livestock feed, with an estimated annual production of 8.5 million tons (Shiferaw *et al*., 2011, and Tanumihardjo *et al*., 2020). The crop plays a vital role in the country's food security and agricultural economy, supporting livelihoods and driving rural development (Erenstein *et al*., 2022). However, maize production is increasingly threatened by the invasive fall armyworm (*S. frugiperda*), a highly destructive pest native to the Americas. Since its detection in Africa in 2016, *S. frugiperda* has caused severe outbreaks and significant yield losses in maize-growing regions, including Egypt, necessitating urgent and effective management strategies (FAO, 2023, and Sarr *et al*., 2023). Infestation rates can reduce maize yields by up to 50% in severe cases (CABI, 2022), highlighting the need for effective pest control measures.

Chemical insecticides have traditionally been the primary method for controlling *S. frugiperda* due to their rapid action and effectiveness in emergencies. Various classes of synthetic insecticides, such as emamectin benzoate and lufenuron, have demonstrated high efficacy in reducing larval populations and minimizing crop damage in both laboratory and field settings (Akhtar *et al*., 2022; Farag *et al*., 2023; and Idrees *et al*., 2023). However, overreliance on chemical control has led to several challenges, including the development of resistance in pest populations, negative impacts on non-target organisms, and environmental concerns (Gutiérrez-Moreno *et al*., 2019; Patil *et al*., 2022; and Lin *et al*., 2024).

In response to these challenges, there is increasing interest in microbial alternatives such as Beauveria bassiana (entomopathogenic fungi) and *Bacillus thuringiensis* (Bt) (Lacey *et al*., 2015; Fergani *et al*., 2022, 2023; and USDA-ARS, 2023). These bioinsecticides can be incorporated into pest management programs to reduce reliance on synthetic insecticides and minimize their associated risks. Despite the potential advantages of bio-pesticides, a significant knowledge gap remains regarding their effectiveness in North Africa. Limited field data on the performance of microbial control agents against *S. frugiperda* in this region hinder the development of effective Integrated Pest Management (IPM) strategies tailored to local agro-ecological conditions. Previous research has highlighted the need for region-specific studies to assess the effectiveness of biopesticides under varying environmental factors such as temperature and humidity, which can notably influence their performance (Lacey *et al*., 2015, and FAO, 2023). Addressing these gaps is essential for optimizing pest management practices and improving food security in maize production systems across North Africa.

This study aims to compare the efficacy of selected synthetic lufenuron (A chitin synthesis inhibitor) and emamectin benzoate (a neurotoxic insecticide), and bioinsecticides, *B. bassiana* and *B. thuringiensis* var. *kurstaki*, for controlling *S. frugiperda* in maize fields in Egypt over two growing seasons (2023-2024). The findings will provide evidence-based recommendations for sustainable pest management strategies that align with FAO-recommended threshold-based spraying practices, combining targeted chemical use with microbial controls to balance efficacy and sustainability in Egyptian maize production systems.

Materials and methods

1. Field studies:

This research was conducted over two successive maize growing seasons (2023 and 2024) at Kerdassa center, Giza Governorate, Egypt (30.0086°N, 31.2089°E). A randomized complete block design (RCBD) with four replications was employed, using the maize cultivar (168 H.F. yellow), sown on April 10 each year. The total experimental area comprised one feddan (4200 m²), with each treatment assigned to four plots of 175 m² (quarter-feddan /qirat).

2. Crop establishment:

Maize seeds were sown at a rate of two seeds per hole with 15 cm inter-hole spacing to avoid interference. Treated plots and untreated control plots were separated by two unsprayed rows, following Egyptian Ministry of Agriculture recommendations **(Egyptian MoA, 2023).** Standard agronomic practices (irrigation, fertilization) were uniformly applied. Approximately one month after planting (30±2 days post-sowing), the infestation intensified. Subsequently, one quarter-Feddan (Qirat) plot was allocated for each insecticide concentration, with three replicate qirats per insecticide treatment.

3. Insecticide treatments:

Four insecticides were tested at three concentrations (15%, 20%, and 25% of the field rate): Lufenuron (Lofine® 10% CS), from Tinjin Highpoint Plant Protection Co., Ltd., China; emamectin benzoate (Alaska® 5.7% WG), from Ginangso Subin Agrochemical Co., Ltd., China; *B. bassiana* (Biossiana® 1×10 CFU/g); and *B. thuringiensis* var. kurstaki (Protecto® 9.4% WP). The bioinsecticide-formulated products were obtained from the Bio-insecticide Production Unit, Plant Protection Research Institute, Agricultural Research Centre, Dokki, Giza, Egypt.

Before insecticide application, baseline larval populations were established by carefully examining 20 randomly selected plants per plot. Tested insecticides were applied at early larval stages (L2–L4) when infestation reached 5–10% of plants with three concentrations. The insecticide solutions were applied using a microinjection technique, as described by Davis *et al*. (2020), which involved administering a volume of 0.5 mL of the insecticide solution directly into the stalk pith tissue where larval instars of *S. frugiperda* typically reside. This method enhances the targeted delivery of insecticide to the feeding sites of the larvae, improving efficacy (Davis *et al*., 2020). Control plots were treated with water only. Assessments were made at different intervals: five hours just after the initial insecticide application and two, three, five, seven, and 15 days after application.

4. Larval recovery and assessments:

Following treatment, larval recovery assessments were conducted at multiple time intervals to evaluate both immediate and prolonged effects. Short-term recovery measurements were taken at 5, 24, 48, and 72 hrs. post-application to monitor initial treatment impact. Long-term evaluations were conducted at 5, 7, and 15 days after application (DAA) to assess residual efficacy.

For comprehensive larval recovery, two complementary methods were employed. First, stalks were longitudinally dissected into 10 cm sections to extract pith-dwelling larvae, ensuring thorough examination of the primary feeding zone. Second, soil samples from the 0-5 cm depth beneath plants were systematically sieved to recover any escaped larvae, following established USDA-ARS (2023) protocols for field sampling of lepidopteran pests. This dual-method approach provided a complete assessment of larval populations across all potential habitats within the study plots.

5. Statistical analysis:

Larval suppression was calculated using the formula:

$$\text{Larval suppression\%} = \left\{\frac{\text{Control} - \text{Treated}}{\text{Control}}\right\} \times 100.$$

The control recovery: mean larvae in untreated plots (20 ± 2.1 larvae/plot).

Abbott's correction is applied if control mortality is>5% (Abbott, 1925).

The data were analyzed using one-way ANOVA (α = 0.05) with Tukey's HSD in R v4.2.2. (Tukey's HSD test and R Core Team, 2022).

Results and discussion

The efficacy of four insecticides, lufenuron (Lofine® 10% CS), emamectin benzoate (Alaska® 5.7% WG), *B. bassiana* (Biossiana® 1×10 CFU/g), and *B. thuringiensis* var. *kurstaki* (Protecto® 9.4% WP), in controlling *S. frugiperda* larvae infestations in maize fields was evaluated over two consecutive growing seasons (2023 and 2024). The results demonstrated significant variations in larval suppression among treatments, concentrations, and seasons.

1. Larval recovery in response to insecticide treatments and treatment efficacy

Over the 2023 and 2024 growing seasons, all tested insecticides significantly reduced *S. frugiperda* larval populations compared to untreated controls (P < 0.05, Tukey's HSD). However, efficacy varied markedly between chemical and bioinsecticides treatments, as well as by concentration (Tables 1 and 3).

1.1. Season 2023:

In the 2023 season, all insecticides significantly reduced larval populations compared to untreated controls (P < 0.05, Tukey's HSD). Emamectin benzoate exhibited the highest efficacy, achieving 90.5–94.36 % larval reduction across concentrations (15-25%), with no significant differences between doses (P ≥ 0.05). Lufenuron, a chitin synthesis inhibitor, showed dose-dependent effects, with efficacy increasing from 75.3% (15%) to 85.26 % (25%). In contrast, the bio-insecticides, *B. bassiana* and *B. thuringiensis* (*Btk*), demonstrated moderate efficacy (37.5–51.1%), with no statistically significant differences among concentrations (Tables 1 and 2).

Table (1): Mean number of *Spodoptera frugiperda* larvae recovered per plot (±SE) after different insecticide treatments during the 2023 growing season.

Insecticides	Mean number of *Spodoptera frugiperda* larvae recovered per plot (±SE)		
	15%	20%	25%
Lufenuron	4.6±0.48	4.2±0.48	3.6± 0.25
Emamectin benzoate	5.9±0.48	5. ±0.48	3.8±0.48
Beauveria bassiana	3.5±0.29	2.7 ± 0.48	2.2± 0.48
Bacillus thuringiensis	4.7±0.25	4.2 ±0.48	3.2± 0.29
Control	20±0.25	20±1	20±0.50

-In a column, means followed by the same letters are non-significantly different, P≥0.05.

Table (2): Larval suppression (%) of the tested insecticides against *Spodoptera frugiperda* larvae at 15%, 20%, and 25% field rates (mean ± SE) in the 2023 growing season.

Insecticides	Larval suppression (%)		
	15%	20%	25%
Lufenuron	75.3±0.5%^{b}	80.5±0.3%^{b}	85.26±0.3%^{a}
Emamectin benzoate	90.5±0.3%^{a}	92.6±0.5%^{a}	94.36±0.3%^{a}
Beauveria bassiana	37.5±1.0%^{c}	45.8±0.5%^{c}	44.0±0.3%^{c}
Bacillus thuringiensis	45.3±0.5%^{c}	51.1±0.3%^{c}	50.77±0.5%^{c}
Control	0^{d}	0^{d}	0^{d}

Means within a column followed by the same superscript letter (a, b, c, d) are not significantly different (Tukey's HSD, P ≥ 0.05).

1.2. 2024 season:

In the 2024 season, emamectin benzoate outperformed other treatments, reaching 92.8% efficacy at 15% concentration and peaking at 98.8% at 25% concentration. Lufenuron's efficacy improved with higher doses, ranging from 70.3% to 90%, though it remained inferior to emamectin benzoate ($P < 0.05$). The bio-insecticides *B. bassiana* and Btk showed consistent but lower efficacy (25.8–52.2%), mirroring trends from the 2023 season (Tables 3 and 4).

Table (3): Mean number of *Spodoptera frugiperda* larvae recovered per plot (±SE) after different insecticide treatments during the 2024 growing season.

Insecticides	Mean number of *Spodoptera frugiperda* larvae recovered per plot (±SE)		
	15%	20%	25%
Lufenuron	5.6±0.48	5.1±0.48	4.2±0.25
Emamectin benzoate	6.5±0.48	6.2 ±0.48	4.8±0.48
Beauveria bassiana	3.9±0.25	2.5 ± 0.48	2.1± 0.42
Bacillus thuringiensis	4.9±0.25	4.2 ±0.48	3.4± 0.26
Control	20±0.25	20±0.25	20±0.50

Table (4): Larval suppression (%) of the tested insecticides against *Spodoptera frugiperda* larvae at 15%, 20%, and 25% field rates (mean ± SE) in the 2024 growing season.

Insecticides	Larval suppression (%)		
	15%	20%	25%
Lufenuron	70.3±0.8%^{b}	73.8± 1.5%^{b}	90±0.5%^{a}
Emamectin benzoate	92.8±0.5%^{a}	95.6±0.5%^{a}	98.8±0.3%^{a}
Beauveria bassiana	25.8±0.5%^{c}	39.3±0.5%^{c}	45.7±0.8%^{c}
Bacillus thuringiensis	34.3±0.5%^{c}	45.8±0.5%^{c}	52.2±0.8%^{c}
Control	0^{d}	0^{d}	0^{d}

-Means within a column followed by the same superscript letter (a, b, c, d) are not significantly different (Tukey's HSD, $P \geq 0.05$).

2. Concentration-dependent effects and residual activity:

The data in Figure (1) demonstrates the concentration-dependent efficacy of the tested insecticides across both seasons (2023-2024). Emamectin benzoate achieved near-complete larval suppression (>90%) even at 15% concentration, with no significant improvement at higher doses. In contrast, lufenuron exhibited a linear increase in efficacy (70–90%), while the bio-insecticides plateaued at 20% concentration, suggesting an optimal threshold for field applications.

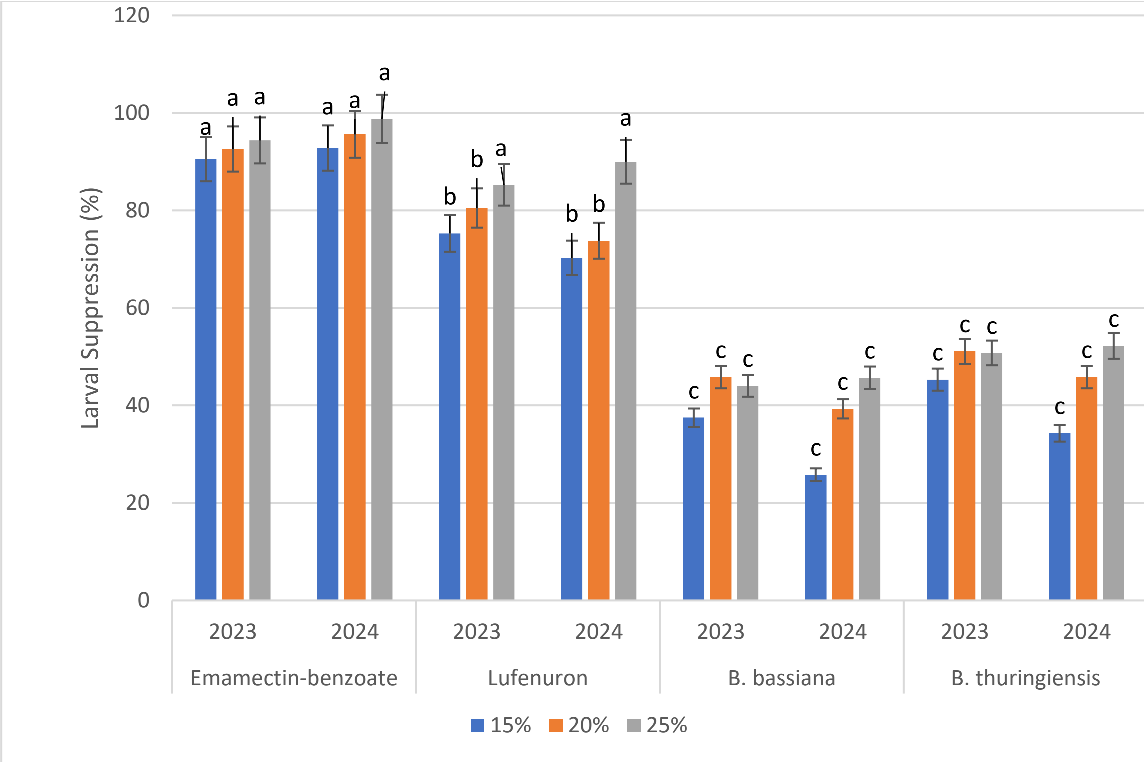

Figure (1): Concentration-dependent efficacy of insecticides (2023-2024).
- In each chart, means followed by the same superscript letter (a, b, c, d) are not significantly different (Tukey's HSD, P ≥ 0.05).

Short-term assessments (5-72 hrs. post-application) revealed rapid knockdown effects for emamectin benzoate (neurotoxic action), while lufenuron and microbial agents required longer (5-15 days) to achieve peak efficacy. Residual activity was strongest for emamectin benzoate, maintaining >90% suppression for 15 days, whereas bio-insecticides showed a gradual decline after 7 days. Both seasons confirmed the superiority of emamectin benzoate but also highlighted the reliability of lufenuron under high larval pressure. However, less effective bio-insecticides provided consistent suppression without the resistance risks associated with synthetic insecticides.

This two-season field study (2023-2024) conducted in Giza Governorate, Egypt, provides valuable insights into the comparative efficacy of chemical insecticides (emamectin benzoate, lufenuron) and bioinsecticides (*B. bassiana*, *B. thuringiensis* var. *kurstaki*) for managing *S. frugiperda* infestations in maize fields. Our findings consistently demonstrated the superior performance of the neurotoxic insecticide emamectin benzoate in rapidly suppressing larval populations across both the 2023 and 2024 growing seasons, even at the lowest concentration tested (15% of the field rate). This high level of efficacy underscores its potential as a critical tool for emergency control situations when rapid pest knockdown is essential to prevent significant yield losses. This high efficacy aligns with its neurotoxic mode of action and rapid knockdown effects (Idrees *et al*., 2023, and Akhtar *et al*., 2022). Also, consistent with findings from other regions where emamectin benzoate remained effective against *S. frugiperda* even in resistance-prone areas (Gutiérrez-Moreno *et al*., 2019, and CABI, 2022). On the other hand, the superior efficacy of emamectin benzoate (90.5-98.8% suppression) may be attributed to its neurotoxic action combined with targeted delivery via stalk microinjection, a technique shown to enhance pesticide translocation to larval feeding sites (Davis *et al*., 2020). However, overreliance on this insecticide risks accelerating resistance development, as documented in Puerto Rico and Mexico (Gutiérrez-Moreno *et al*., 2019). While less potent, Lufenuron, a chitin synthesis inhibitor, exhibited a clear dose-dependent response, with its efficacy increasing with higher concentrations. Our results revealed the 15-day residual efficacy of emamectin benzoate, which matches the findings of Davis *et al*. (2020), who attributed prolonged activity to its systemic translocation in maize tissues. While consistently less effective than emamectin benzoate, lufenuron achieved substantial larval suppression (up to 90% at the highest concentration). This characteristic makes lufenuron a valuable component of resistance management programs through rotation with insecticides possessing different modes of action, thereby mitigating the selection pressure for resistance development against highly effective compounds like emamectin benzoate. The slower mode of action of lufenuron, affecting larval molting, likely contributes to the observed delay in achieving peak efficacy compared to the rapid neurotoxic effects of emamectin benzoate (Lin *et al*., 2024).

The microbial control agents, *B. bassiana* and *B. thuringiensis* (*Btk*), demonstrated moderate levels of efficacy against *S. frugiperda* larvae, with suppression rates ranging from 25% to 52%. Notably, their efficacy appeared to plateau beyond a 20% concentration, suggesting a threshold effect. While their overall efficacy was lower than that of chemical insecticides, these microbial agents offer significant advantages in terms of environmental safety and reduced risk to non-target organisms (Lacey *et al*., 2015, and USDA-ARS, 2023). Their efficacy plateaued beyond 20% concentrations, suggesting a threshold effect likely caused by environmental factors (UV exposure, humidity) or larval behavioral avoidance (Patil *et al*., 2022). In addition, their consistent, moderate suppression highlights their potential as key components of sustainable Integrated Pest Management (IPM) strategies, particularly in situations where lower pest pressure was anticipated or in combination with other control methods. These microbial agents require repeated applications for optimal control. Sarr *et al*. (2023) suggested that the slower action of these biopesticides, relying on infection and pathogenesis, likely contributes to their lower initial efficacy compared to chemical options. However, their minimal non-target effects and compatibility with beneficial arthropods make them essential for sustainable agriculture (FAO, 2023).

The dose-response relationships (Figure 1) underscore the trade-offs between chemical and bio-insecticides. Emamectin benzoate's flat curve aligns with its neurotoxic mode of action, but its minimal dose-dependence risks overuse in the field. Conversely, the plateau effect observed for *B. bassiana* and *Btk* highlights environmental or physiological constraints that warrant further formulation research. Our findings align with the FAO-recommended threshold-based spraying strategies, emphasizing the importance of targeted insecticide applications based on pest scouting and economic thresholds. In situations exceeding economic thresholds and requiring immediate action, emamectin benzoate appears to be the most effective option. In addition, it is crucial to implement effective resistance management strategies by limiting the application of emamectin benzoate to 1–2 applications per season and rotating it with other insecticides that have different modes of action, such as lufenuron. This approach can help reduce selection pressure on pest populations and prolong the efficacy of these insecticides.

However, for proactive management and resistance mitigation, the integration of lufenuron and bio-insecticides into IPM programs offers a more sustainable approach. This integrated approach could involve the strategic rotation of chemical insecticides with different modes of action and the utilization of microbial agents as stand-alone treatments or in conjunction with chemical controls to enhance overall pest suppression while minimizing environmental impact (Lin *et al*., 2024).

Further research could explore the long-term impacts of these different insecticide regimes on non-target arthropod populations (Egyptian MoA, 2023) and the development of insecticide resistance (CABI, 2022) in *S. frugiperda* under Egyptian field conditions. Additionally, investigating the economic feasibility and farmer adoption rates of IPM strategies incorporating microbial control agents would be crucial for promoting their widespread use in maize production in Egypt.

This two-season study evaluated the efficacy of chemical and bio-insecticides for controlling *S. frugiperda* in Egyptian maize fields. Emamectin benzoate demonstrated the highest efficacy, achieving 90.5–98.8% larval suppression, but poses resistance risks with prolonged use. To mitigate these risks, we recommend limiting the application of emamectin benzoate to 1–2 applications per season and rotating it with other insecticides, such as lufenuron, which showed substantial efficacy (70–90%) and can serve as a suitable rotational alternative. While microbial agents (*B. bassiana* and *B. thuringiensis*) exhibited moderate efficacy (25–52%), their role in sustainable pest management remains vital. The observed plateau in their effectiveness beyond 20% concentration suggests the need for further research, including studies on UV-shielded formulations to enhance their performance under field conditions. The findings underscore the importance of integrating chemical and microbial controls into a comprehensive Integrated Pest Management (IPM) strategy. We propose a structured IPM calendar that involves applying biopesticides during early infestations and escalating to chemical controls when pest thresholds exceed 10%. This approach not only optimizes pest suppression but also minimizes environmental impact and promotes the sustainability of maize production systems in Egypt. Overall, this study provides evidence-based recommendations for adopting Integrated Pest Management strategies that combine targeted chemical applications with microbial controls, ensuring effective and economically viable pest control.

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