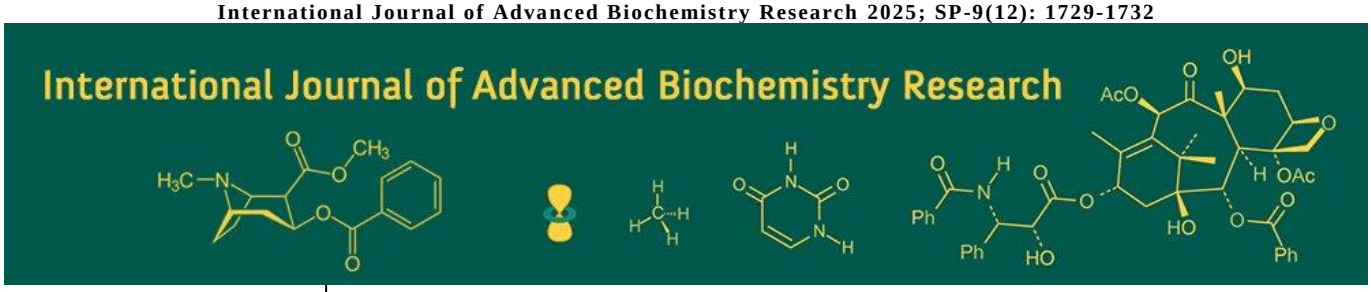

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Meta-analysis of biological control strategies for fall armyworm (*Spodoptera frugiperda*) in maize cultivation

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Abstract
The fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), is a major invasive pest posing a serious threat to global maize production. The present study conducted a meta-analysis to evaluate the effectiveness of biological control strategies against fall armyworm. A total of 86 observations from selected studies were analyzed to estimate the overall pest reduction efficiency of different biocontrol approaches. The meta-analysis was performed in R Studio using the meta and metafor packages. The heterogeneity statistic (I^2 = 94.01%) with a *p*-value < 0.01 indicated highly significant variability among studies, reflecting differences in biocontrol agents, environmental conditions, and integration methods. Given this high heterogeneity, a random-effects model was employed, yielding a pooled mean pest reduction of 64.52%, which was slightly higher than the fixed-effects model estimate of 60.08%. These findings suggest that biological control measures exhibit moderately high efficacy in suppressing fall armyworm populations. However, the substantial heterogeneity underscores the need for further investigation to determine the most effective biocontrol agents and management practices under varying agroecological contexts. Standardized experimental designs and reporting practices are recommended to enhance comparability and accuracy in future meta-analyses.

Keywords: Fall armyworm, *Spodoptera frugiperda*, meta-analysis, biological control, heterogeneity, R studio, random effects model

Introduction
The fall armyworm (*Spodoptera frugiperda* J. E. Smith) (Lepidoptera: Noctuidae) has emerged as one of the most destructive invasive pests affecting maize and several other crops worldwide. Native to the tropical and subtropical regions of the Americas, it was first reported in Africa in 2016 and has since rapidly spread across Asia and other parts of the world, causing severe economic losses to maize cultivation. Its polyphagous feeding behavior, high reproductive potential, and migratory ability have made its management a major challenge for farmers and agricultural researchers alike.

Chemical insecticides have been widely used as a primary control strategy; however, their excessive and indiscriminate use has led to problems such as pest resistance, resurgence, environmental contamination, and negative impacts on non-target organisms. In response to these challenges, biological control has gained increasing attention as an environmentally sustainable alternative. Biological control strategies involve the use of natural enemies—including parasitoids, predators, entomopathogenic fungi, bacteria, and viruses—to suppress pest populations. These approaches are not only eco-friendly but also align with the principles of Integrated Pest Management (IPM), contributing to long-term pest suppression and agroecosystem stability.

Despite numerous studies evaluating the performance of individual biocontrol agents against fall armyworm, their reported effectiveness varies considerably due to differences in experimental conditions, agroecological settings, and application methods. Therefore, synthesizing the available evidence through a meta-analysis provides a quantitative and comprehensive understanding of their overall efficacy.

The present study aims to systematically assess and quantify the effectiveness of biological control strategies against fall armyworm in maize cultivation using a meta-analytical approach. By integrating results from multiple independent studies and employing statistical analysis in R Studio using the *meta* and *metafor* packages, this research provides pooled estimates of pest reduction and explores the degree of heterogeneity among studies. The findings are expected to inform researchers, policymakers, and practitioners about the potential and limitations of biological control in managing fall armyworm infestations, thereby supporting the development of more effective and sustainable pest management strategies.

Methodology

Data Collection and Literature Search

A comprehensive literature search was conducted to identify studies that evaluated the effectiveness of biological control strategies against fall armyworm in maize cultivation. Relevant peer-reviewed articles published between 2020 and June 2025 were retrieved from Google Scholar, using a combination of keywords such as "Fall armyworm," "Spodoptera frugiperda," "biological control," "natural enemies," "maize," and "pest management." Additional references were identified from the bibliographies of selected studies to ensure inclusion of all relevant data.

Inclusion and Exclusion Criteria

Studies were screened based on defined inclusion and exclusion criteria. Only studies that (i) reported the use of biological control agents such as parasitoids, predators, entomopathogenic fungi, bacteria, or viruses against fall armyworm in maize; (ii) provided quantitative results in terms of pest reduction or mortality percentage; and (iii) contained sufficient statistical information for effect size calculation were included. Studies focusing solely on chemical, mechanical, or cultural control methods, or lacking quantitative data, were excluded from the analysis.

Data Extraction

For each eligible study, key information such as author, year of publication, type of biological control agent, experimental design, sample size, location, and reported percentage of pest reduction or mortality was extracted. When multiple treatments were evaluated within the same study, each treatment was considered as a separate observation. This process resulted in 86 observations included in the final meta-analysis dataset.

Statistical Analysis

The meta-analysis was performed using R Studio with the meta and metafor packages. Percentage pest reduction was used as the primary effect size metric. To account for variability among studies, both fixed-effects and random-effects models were computed. The Cochran's Q-test and I^2 statistic were used to assess heterogeneity across studies, with I^2 values greater than 75% indicating substantial heterogeneity.

Results

The effectiveness of biological control strategies against fall armyworm was assessed through a meta-analysis of 86 observations derived from selected published studies (Table 1). The analysis revealed a very high level of heterogeneity (I^2 = 94.01%, p<0.01), indicating significant variability among the included studies. This variability can be attributed to differences in biological control agents, environmental conditions, experimental designs, and integration methods used across the studies. Considering this substantial heterogeneity, the random-effects model was applied as the most appropriate approach for estimating the overall effect size. The pooled mean pest reduction under the random-effects model was 64.52%, slightly higher than the fixed-effects model estimate of 60.08%, both of which were statistically significant at the 1% level (p < 0.01). The forest plot illustrated wide confidence intervals among studies but showed consistent positive effects of biological control, while the funnel plot indicated a largely symmetrical distribution, suggesting minimal publication bias and reliable pooled estimates.

Overall, the results demonstrate that biological control measures exhibit a moderately high efficacy in reducing fall armyworm infestations in maize cultivation. However, the high heterogeneity highlights that the effectiveness of these strategies varies depending on the type of biocontrol agent, geographical region, and mode of application. Parasitoids, entomopathogenic fungi, bacteria, and viruses all showed potential but with differing levels of success under varying field conditions. These findings emphasize the need for further research to identify the most effective biocontrol agents and combinations suitable for specific agroecological contexts. Future studies with standardized experimental methodologies and consistent reporting will be crucial to reduce variability and strengthen evidence for large-scale adoption of biological control as a sustainable component of IPM for fall armyworm.

Table 1: Effectiveness of biological management strategies to control fall armyworm: a meta-analysis using different statistical methods from selected studies

Statistical method	Estimate value (% pest reduction)	P value
Fixed effect model	60.08**	<0.01
Random effect model	64.52**	<0.01
Heterogeneity statistics	94.01**	<0.01

** indicates significant at 1% level

Discussion

The findings of this meta-analysis demonstrate that biological control strategies are a crucial component of sustainable fall armyworm management in maize cultivation. The pooled pest reduction estimate of 64.52% under the random-effects model indicates that biological control provides a moderately high level of suppression. Although this is lower than the control achieved with chemical insecticides, it aligns with the principles of ecological pest management, offering advantages such as reduced pesticide resistance, preservation of beneficial organisms, and environmental safety (Prasanna *et al.*, 2018) [25]. The high heterogeneity observed (I^2 = 94.01%) suggests that the success of biological control is context-dependent, influenced by the diversity of natural enemies, environmental conditions, and integration methods used in different studies (Day *et al.*, 2017) [9].

Previous studies have reported variable effectiveness among different biocontrol agents. Egg parasitoids such as *Telenomus remus* and *Trichogramma pretiosum* have been shown to achieve high parasitism rates under controlled and

field conditions (Agboyi *et al.*, 2020; Kenis *et al.*, 2019) [1, 18], while entomopathogenic fungi like *Metarhizium anisopliae* and *Beauveria bassiana* have demonstrated promising larval mortality, particularly under humid tropical conditions (Durocher-Granger *et al.*, 2020; Yashaswini *et al.*, 2023) [11, 30]. Likewise, entomopathogenic nematodes (*Steinernema* spp., *Heterorhabditis* spp.) and baculoviruses have shown potential when incorporated into integrated pest management (IPM) programs (Behle *et al.*, 2019; Kamali *et al.*, 2022) [4, 17]. However, inconsistencies in experimental designs, climatic variability, and biocontrol application methods across studies contribute to the significant heterogeneity detected in this meta-analysis.

These results reinforce the notion that no single biological control method can consistently achieve complete suppression of fall armyworm under all conditions. Instead, integrating compatible biological agents within a holistic IPM framework, in combination with cultural, mechanical, and host plant resistance methods, offers the most sustainable and resilient approach to fall armyworm management (Bateman *et al.*, 2021; Shylesha *et al.*, 2020) [3, 27]. Strengthening farmer awareness, promoting field-level validation of promising biocontrol agents, and encouraging standardized experimental and reporting protocols are essential to improving reliability and adoption. Future meta-analyses incorporating larger datasets, regional stratification, and standardized response metrics will help clarify the performance of different biological agents and enhance evidence-based pest management recommendations for sustainable maize production systems.

Conclusion

This meta-analysis quantitatively evaluated the effectiveness of biological control strategies against fall armyworm in maize cultivation, integrating data from 86 observations across published studies. The overall pooled pest reduction estimate of 64.52% under the random-effects model indicates that biological control provides moderately high efficacy, reinforcing its potential as a sustainable alternative to chemical control. However, the high heterogeneity (I^2 = 94.01%) observed among studies suggests that the success of biocontrol measures depends on factors such as agent type, environmental conditions, and integration with other management practices. To enhance consistency and applicability, future research should focus on identifying the most effective biological agents and standardizing experimental methodologies. Overall, biological control remains a key component of IPM and contributes significantly to the sustainable management of fall armyworm in maize ecosystems.

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