EDUBIOLOGICA
Jurnal Penelitian Ilmu dan Pendidikan Biologi
Sekretariat: Jl. Pramuka No. 67 Kuningan 45512 Telepon/Fax. (1232) 878702

Meta-Analysis and Bibliographic Study: Effectiveness of Biological and Chemical Agents in Controlling *Spodoptera frugiperda* Based on Mortality Rate from Scopus-Indexed Journals (2019-2024)

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INFORMASI ARTIKEL

Article history
Received : 14 Nopember 2023
Revised : 30 Nopember 2023
Accepted : 14 Desember 2023
Published : 30 Desember 2023

Keywords
Spodoptera frugiperda
Mortality rate
Chemical
Biological

ABSTRACT

This meta-analysis and bibliographic study aims to compare the effectiveness of biological and chemical control methods against Spodoptera frugiperda, using the mortality rate percentage as the primary parameter. Data were pooled from studies indexed in Scopus from 2019 to 2024. Biological agents include species like Telenomus remus, Bacillus thuringiensis, and Trichogramma spp., while chemical agents include substances like emamectin benzoate, chlorpyrifos, and lambda-cyhalothrin. The research spans across multiple continents, highlighting significant contributions from China, Mexico, Brazil, Burkina Faso, Ethiopia, India, Indonesia, Pakistan, Ghana, Thailand, Cameroon, and Malawi, indicating a global effort to manage this pest. ANCOVA was employed to compare the efficacy of these control methods, controlling for covariates such as initial infestation levels and environmental conditions. The analysis confirmed the normality (sig. 0.51) and homogeneity of the data variances(sig.0.79), and linear relationships between covariates and the dependent variable were established. The final comparison revealed no significant difference between the effectiveness of biological and chemical agents in controlling Spodoptera frugiperda(sig. 0.279) This comprehensive assessment enhances the reliability and validity of the findings, providing insights for policymakers and agricultural practitioners to develop more effective pest management strategies and allocate resources efficiently.

APA Citation: Penulis Pertama, Penulis Kedua., & Penulis Ketiga. (2023). Judul. *Edubiologica: Jurnal Penelitian Ilmu dan Pendidikan Biologi* , *Vol 11*(2), xx-yy. doi: https://doi.org/10.22219/jpbi.vxiy.xxyy

Introduction

The fall armyworm, *Spodoptera frugiperda*, is a highly destructive pest that poses a significant threat to global agriculture, particularly affecting maize, sorghum, and other important crops. Native to the

Americas, this pest has rapidly spread to Africa, Asia, and other regions, causing extensive crop damage and economic losses. The control of *Spodoptera frugiperda* has become a critical issue for farmers and researchers worldwide.Traditional pest control methods have primarily relied on chemical insecticides, which, while effective in the short term, pose various environmental and health risks, and often lead to the development of resistance in pest populations. In response to these challenges, there has been growing interest in the use of biological control agents, such as natural predators, parasitoids, and microbial pathogens, which offer a more sustainable and environmentally friendly alternative.

Both chemical and biological control methods have been extensively studied and proven effective in managing *Spodoptera frugiperda*. However, there is a need to determine which of these two methods is more effective. To address this, our meta-analysis aims to compare the effectiveness of biological and chemical agents in controlling *Spodoptera frugiperda* based on mortality rates reported in Scopus-indexed journals from 2019 to 2024. Specifically, this study focuses on *Spodoptera frugiperda* infestations in maize, one of the most affected and economically significant crops.

Maize was chosen as the focal crop for this study due to several reasons. Maize is a staple food for millions of people around the world and is a critical component of global food security. The economic impact of *Spodoptera frugiperda* on maize is particularly severe, leading to significant yield losses and increased production costs. Furthermore, maize has a wide geographic cultivation range, making the findings of this study broadly applicable to various regions affected by the pest. To avoid bias, the unit of measurement used in this meta-analysis is the mortality rate. Mortality rate, in this context, refers to the proportion of *Spodoptera frugiperda* individuals that die as a result of exposure to a particular control agent within a specified period. It is a crucial metric that allows for a standardized comparison of the effectiveness of different control methods across various studies. By systematically reviewing and synthesizing data from multiple studies, this research seeks to provide a comprehensive assessment of the relative efficacy of these control strategies. The findings will contribute to a better understanding of the potential benefits and limitations of biological and chemical control methods, guiding future pest management practices and research initiatives.

The scope of this study includes evaluating the mortality rates of *Spodoptera frugiperda* in maize as influenced by various biological and chemical agents, identifying trends and patterns in the data, and discussing the implications of these findings for integrated pest management (IPM) programs. This research will also highlight any gaps in the current literature and suggest areas for further investigation. By integrating the latest evidence from 2019 to 2024, this meta-analysis aims to inform policymakers, researchers, and practitioners about the most effective and sustainable approaches to managing this pervasive agricultural pest in maize cultivation.

Method

This study evaluates the effectiveness of biological and chemical agents in controlling *Spodoptera frugiperda* by analyzing mortality rates through a meta-analysis and bibliometric study approach. The research focuses on experimental studies indexed in Scopus (Q1, Q2, Q3, and Q4) published between 2019 and 2024, with an emphasis on those reporting mortality rate parameters.

The meta-analysis presented in this study follows clearly defined and explained inclusion criteria and adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The selection process was designed in accordance with these guidelines.

The search for relevant literature was conducted using the Publish or Perish application and Scopus during the first week of July 2024. The search was restricted to publications from 2018 to 2024, using the keywords "*Spodoptera frugiperda*" and "mortality rate." Additional findings were sourced from Google Scholar using the same keywords.

10.22219/jpbi.vxiy
pISSN:2355-2352 eISSN:

The inclusion criteria applied to the search results were:

1. Data published between 2019 and 2024.
2. "*Spodoptera frugiperda*" or "Fall Armyworm" appears in the title, abstract, or keywords.
3. The articles are experimental studies providing data on *Spodoptera frugiperda* from maize.
4. The studies evaluate the efficacy of biological or chemical agents on *Spodoptera frugiperda* and provide mortality rate data in percentage.
5. The journal articles are indexed by Scopus (Q1, Q2, Q3, or Q4).

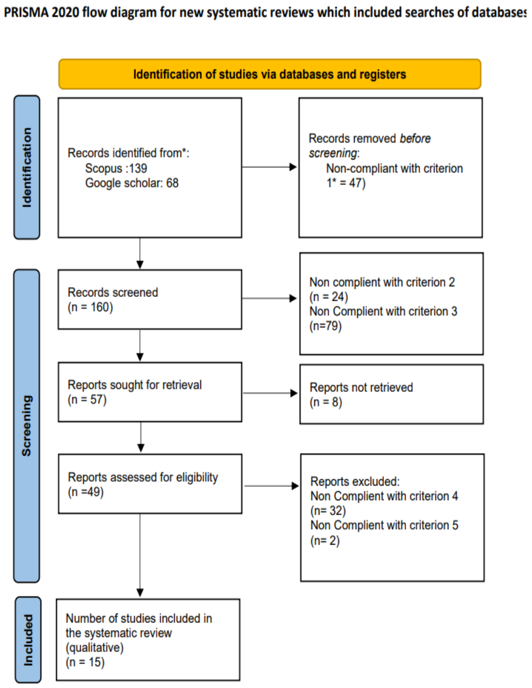


Figure 1 PRISMA FLOWDIAGRAM

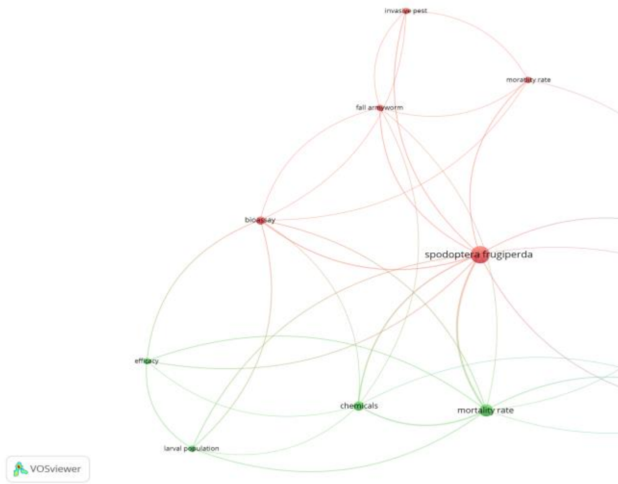
Result and Discussion

Bibliography analysis

The PRISMA flow diagram illustrates the process of identifying, screening, and including studies in the systematic review for this research on the effectiveness of biological and chemical agents in controlling *Spodoptera frugiperda*. Initially, 139 records were identified from Scopus and 68 records from Google Scholar. Before screening, 47 records were removed because they did not comply with the first inclusion criterion, which required the data to be published between 2019 and 2024. This left 160 records for screening.

During the screening process, 24 records were excluded for not complying with the second criterion (mentioning "*Spodoptera frugiperda*" or "Fall Armyworm" in the title, abstract, or keywords), and 79 records were excluded for not meeting the third criterion (being experimental studies providing data on *Spodoptera frugiperda* from maize). As a result, 57 records were sought for retrieval, but 8 reports could not be retrieved.

Of the 49 reports assessed for eligibility, 32 were excluded for not meeting the fourth criterion (evaluating the efficacy of biological or chemical agents on *Spodoptera frugiperda* and providing mortality rate data in percentage), and 1 was excluded for not meeting the fifth criterion (being indexed by Scopus in Q1, Q2, Q3, or Q4).



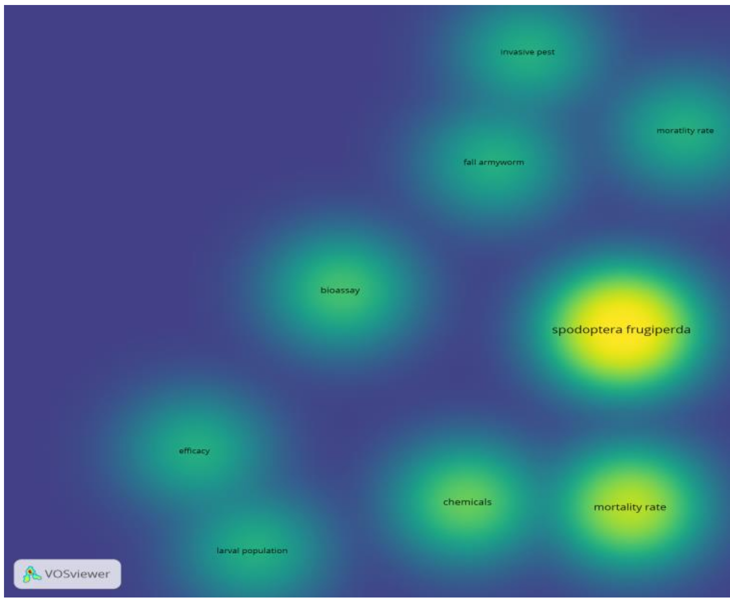


Figure.2 Vos-Viewer Visualization (A. Network and B. Density)

Ulti
mately, 15 studies were included in the systematic review, all of which met the inclusion criteria and provided qualitative data for the analysis. This thorough selection process ensures that only the most relevant and high-quality studies were considered for evaluating the effectiveness of biological and chemical agents on *Spodoptera frugiperda*.

The next step involves importing the selected articles into Mendeley to generate their RIS text. Subsequently, the RIS text file is uploaded to VOSviewer to analyze research trends. Using VOSviewer, visualizations and analyses are conducted to identify key clusters and patterns in the literature. The results of this analysis reveal the following research trends

The VOSviewer network visualization presented here shows the key research trends and relationships in studies on the effectiveness of biological and chemical agents in controlling *Spodoptera frugiperda*. This visualization was generated by importing the RIS text of the selected articles into VOSviewer. At the center of the network is *Spodoptera frugiperda*, indicating its central role in the research. The terms and concepts connected to it represent various aspects of the studies. For instance, there are strong connections to terms like "mortality rate," "biological control," "chemical control," and "efficacy," highlighting the primary focus areas of the research.

The network is divided into clusters, which represent different thematic areas within the research. The red cluster, for example, includes terms like "invasive pest," "fall armyworm," "mortality rate," and "bioassay," indicating studies focusing on the pest's invasiveness and the methods used to measure mortality rates. The blue cluster focuses on biological control methods, with terms such as "biological control," "generalist predators," and "biological agent." This suggests a significant amount of research is dedicated to exploring natural and biological methods for controlling *Spodoptera frugiperda*. The green cluster includes terms like "chemicals," "efficacy," "larval population," and "mortality rate." This cluster represents studies that examine the use of chemical agents and their effectiveness in controlling the pest, as well as their impact on larval populations. Overall, this network visualization helps in understanding the key research areas and trends in the literature, emphasizing the focus on both biological and chemical control methods for managing *Spodoptera frugiperda*. It also provides insights into the interconnectedness of various research topics, facilitating a comprehensive understanding of the current state of research in this field.

10.22219/jpbi.vxiy
pISSN:2355-2352 eISSN:

The image is a density visualization from VOSviewer, depicting key terms related to "*Spodoptera frugiperda*" (fall armyworm) in academic literature. The thicker and bigger the circle, the more frequently the term appears in the analyzed documents, highlighting its relevance or importance (Pinkie et al., 2021). The central and most prominent term is "*Spodoptera frugiperda*," indicating that it is the primary focus in the literature. Surrounding this central term are other significant terms such as "biological control," "chemicals," "mortality rate," "bioassay," "efficacy," and "larval population." These terms are essential to the research, which involves a meta-analysis of the effectiveness of biological and chemical agents in controlling *Spodoptera frugiperda*. The reason for choosing to meta-analyze the comparison of the effectiveness of biological and chemical agents is reflected in the visualization. "Biological control" and "chemicals" are both significant terms, suggesting that a substantial amount of research has been conducted in these areas. By focusing on "mortality rate," the research aims to provide a quantitative measure of the effectiveness of these control methods. The prominence of terms like "bioassay" and "efficacy" indicates that experimental and evaluative studies are common in the literature, supporting the approach to systematically compare and analyze these studies. In summary, the visualization supports the focus of the research by highlighting the key terms and their frequency in the literature. The meta-analysis seeks to provide a comprehensive comparison of the effectiveness of biological and chemical agents in controlling *Spodoptera frugiperda*, contributing valuable insights to the field.

This chart explaining the distribution of articles on *Spodoptera frugiperda* by year and journal scopus-index (Q1, Q2, Q3, or Q4) from 2020 to 2024. In 2020, there were two articles published in Q1 journals and two in Q2 journals. In 2021, four articles were published in Q1 journals and one in a Q4 journal. The year 2022 saw a similar pattern, with four articles in Q1 journals and one in a Q4 journal. In 2023, there was one article published in a Q1 journal. For 2024, one article was published in a Q4 journal. Overall, the chart indicates a total of eleven articles in Q1 journals, two in Q2 journals, and two in Q4 journals over this five-year period. The provided map illustrates the distribution of research locations concerning the study of *Spodoptera frugiperda*, an invasive pest affecting maize production. The map categorizes these locations into three distinct groups, indicated by different colors.

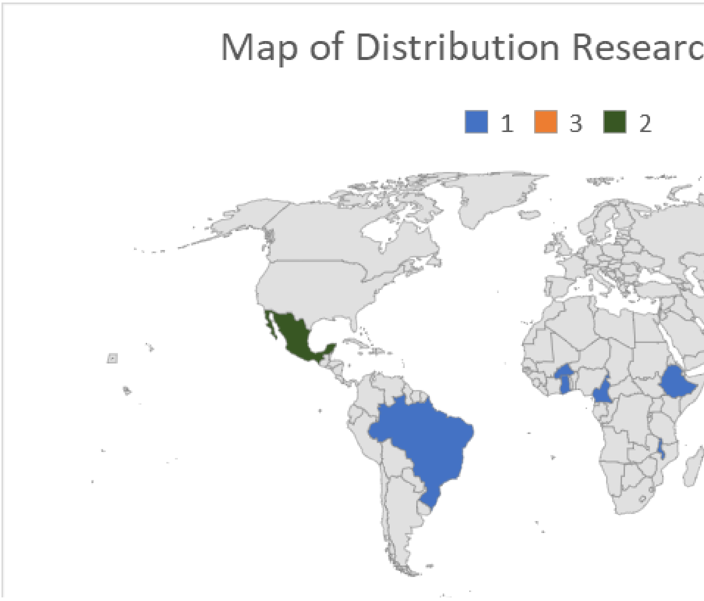


Figure.3 Map of Distribution Research Location

Meta-analysis

Meta-analysis is a statistical technique that combines the results of multiple scientific studies addressing the same question, with the aim of synthesizing findings to derive more robust conclusions (Oh, 2020). In the context of this research, the meta-analysis focuses on comparing the effectiveness of biological and In detail, China stands out with the highest number of research studies, totaling three, represented by the orange color on the map. Mexico follows with two studies, highlighted in green. The remaining countries, each contributing to one study, are shown in blue. These countries include Brazil, Burkina Faso, Ethiopia, India, Indonesia, Pakistan, Ghana, Thailand, Cameroon, and Malawi.

This distribution highlights a global effort to tackle the pest, with significant contributions from both developed and developing nations. The research spans across multiple continents, reflecting the widespread impact of *Spodoptera frugiperda* and the concerted efforts required to manage it effectively. The map provides a visual representation of the global research landscape, underscoring the importance of international collaboration in addressing agricultural challenges (Tepa-yotto et al., 2021)

chemical control methods against *Spodoptera frugiperda* using the parameter of mortality rate percentage. This approach allows for determining which method is more effective in reducing the population of this pest.

10.22219/jpbi.vxiy
pISSN:2355-2352 eISSN:

Table 1. Data Source

Variabel	Mortality Rate (%)		Article code	Citation
	Control	Experiment		
Biology				
Telenomus remus	8.7	23.1	A2	(Abang et al., 2021)
Bacillus thuringiensis Solution	8	49	A3	(dos Santos et al., 2021)
***Bacillus thuringiensis* Wet Powder**	8	58	A3	
Beauveria bassiana	0.1	22.7	A4	(Herlinda et al., 2021)
Trichogramma chilonnis	0	15.87	A6	(L. Yang et al., 2022)
Trichogramma dendrolimi	0	29.98	A6	
Trichogramma pretiosum	0	25.73	A6	
Chelonus insularis	0	16.60	A9	(García-González et al., 2020)
Mermithide Nematode	7.4	8.20	A10	(Ahissou et al., 2021)
Lespesia	0	13.29	A11	(Cabrera-Asencio et al., 2023)
Archytas marmoratus	0	15.58	A12	(Deshmukh et al., 2020)
Azadirachtin	8.06	30	A13	(Fiaboe et al., 2023)
PrGV + Btk	8.06	27.87	A13	
Lippia javanica	0	62	A14	(Kelita Phambala & Philip C Stevenson, 2020)
Nicotiana tabacum	0	60	A14	
A. indica	1.7	82.7	A15	(Sisay et al., 2019)
S. molle	1.7	78.33	A15	
M. abyssinica	1.7	61.6	A15	
M. ferruginea	1.7	46.6	A15	
P. dodecandra	1.7	81.1	A15	
J. curcas	1.7	77.8	A15	
C. macrostachyus	1.7	48.3	A15	
N. tabacum	1.7	25	A15	
L. camara	1.7	21.1	A15	
E. globulus	1.7	3.3	A15	
C. ambrosoids	1.7	9.46	A15	
Chemical				
ZnO 500 ppm	2.5	11.25	A1	(Pittarate et al., 2021)
Emamectin Benzoate	16.67	61.54	A5	(Liu, 2022)
Chlorpyrifos	0	40.00	A7	(Smith et al., 2022)
Chlorantraniliprole	0	38.00	A7	
Broflanilide	4.7	71.00	A8	(Idrees et al., 2022)
Abemectin	4.7	68.00	A8	
Spinoteram	4.7	67.00	A8	

Variabel	Mortality Rate (%)		Article code	Citation
	Control	Experiment		
Chlorantraniliprole	21.74	85.90	A12	(Deshmukh et al., 2020)
Flubendiamide	21.74	53.1	A12	
Lambda-cyhalothrin	21.74	28.1	A12	
Acetamiprid + Indoxacarb	8.06	26.79	A13	(Fiaboe et al., 2023)
Acetamiprid + ʎ-Cyhalothrin	8.06	26.42	A13	
Ethyl palmitate	8.06	34.33	A13	
Coragen 200 SC	0	40	A15	(Sisay et al., 2019)
Radiant 120 SC	0	36.65	A15	
Dimethoate 40%	0	46.65	A15	
Tracer 480 SC	0	23.35	A15	
Karate 5 EC	0	46.65	A15	
Ampligo 150 SC	0	26.65	A15	
Imidacloprid	0	33.35	A15	
Carbaryl	0	6.7	A15	
Malathion 50% EC	0	3.35	A15	

By pooling data from studies indexed in Scopus from 2019 to 2024, the meta-analysis synthesizes evidence to provide a clearer picture of the overall effectiveness of different control strategies. This synthesis helps in identifying consistent patterns and variations across different studies, offering a comprehensive understanding of the effectiveness of these control methods. Furthermore, the meta-analysis helps generalize findings across different contexts, such as geographical regions, environmental conditions, and crop types, which is crucial for developing broadly applicable recommendations for controlling *Spodoptera frugiperda*. Through this analysis, gaps in the current research can also be identified, highlighting areas where data may be lacking or where further research is needed to clarify uncertainties. This includes identifying the need for more studies on certain biological agents or chemicals. Additionally, the results of the meta-analysis can guide future research by identifying which control methods show the most promise and inform policymakers and agricultural practitioners on the most effective strategies for pest control. This can lead to better resource allocation and management practices. This method needs to incorporating data from multiple studies, the meta-analysis enhances the reliability and validity of the findings, mitigating biases and limitations inherent in individual studies and providing a more comprehensive assessment of control methods. In summary, conducting a meta-analysis within the scope of this research on the control methods for *Spodoptera frugiperda*, focusing on the comparison between biological and chemical agents using mortality rate percentage, will provide a detailed and statistically robust evaluation, aiding in the development of more effective pest management strategies (Yan et al., 2022).

ANCOVA (Analysis of Covariance) is employed to determine if there is a significant difference between the efficacy of chemical and biological agents in controlling *Spodoptera frugiperda*. This test compares the mean effectiveness of these two groups while controlling for one or more covariates that might affect the outcome, such as initial infestation levels or environmental conditions (Papadimit ropoulou et al., 2020). The test involves several key assumptions that must be met for valid results. First, the residuals (errors) of the model should be normally distributed, which can be assessed using normality tests such as the Kolmogorov-Smirnov test. Second homogeneity of variances, which means the variance within each group should be approximately equal, must be verified with Levene's test. Third, the relationship between the covariates and the dependent variable should be linear, ensuring that the covariates have a consistent effect across all levels of the independent variable, Fourth, homogeneity of regression slopes must be checked, indicating that the relationship between the covariates and the dependent variable is the same across all groups (Qi et al., 2022). The normality test is conducted using the Kolmogorov-Smirnov test.

Table 2. Komolgorov-smirnov test result

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for Mortality_rate	.109	45	.200*	.950	45	.051

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Based on the table above, the significance value is 0.051, while the alpha (α) level is 0.05. Since the significance value (sig.) is greater than α, we accept the null hypothesis (H0). This indicates that the data is normally distributed, thereby satisfying the first requirement. Following this, the statistical analysis proceeds to the second requirement, which is to determine if the data variance is homogeneous. This assessment is conducted using Levene's test.

Table 3. Levene's test result

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Mortality rate

F	df1	df2	Sig.
3.244	1	43	.079

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Category + Control + Category * Control

According to the table above, the significance value is 0.079, while the alpha level (α) is 0.05. Since the significance value (sig.) is greater than α, the null hypothesis (H0) is accepted. This implies that the variance in the data is homogeneous, thereby fulfilling the second requirement. Next, the statistical test proceeds to the third requirement, which involves checking the linearity of the covariance with the dependent variable. This is evaluated using a scatter plot to observe the distribution of values and the regression line equation.

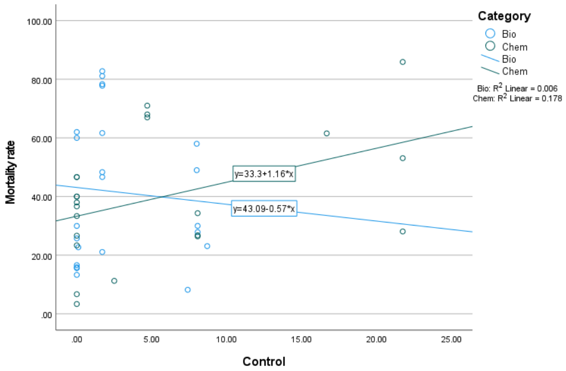


Figure 4. Data Source

Both lines in the graph exhibit linear regression, as indicated by the lines generated from the data and the regression equations shown. For the "Biological" agent the regression equation is y = 43.09 + 0.57x, while for the "Chemical", it is y = 33.3 + 1.16x. This demonstrates that the third requirement is fulfilled. The statistical test then moves on to the final requirement, which is the homogeneity of regression coefficients test.

Table 4. ANCOVA Results

Tests of Between-Subjects Effects

Dependent Variable: Mortality rate

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1835.304[a]	3	611.768	1.194	.324
Intercept	40855.889	1	40855.889	79.736	<.001
Category	671.732	1	671.732	1.311	.259
Control	70.566	1	70.566	.138	.712
Category * Control	616.682	1	616.682	1.204	.279
Error	21008.063	41	512.392		
Total	97301.327	45			
Corrected Total	22843.367	44			

a. R Squared = .080 (Adjusted R Squared = .013)

the table indicates a significance value of 0.279 with an alpha level (α) of 0.05. Since the significance value (sig.) is greater than α, the null hypothesis (H0) is accepted. This suggests that the regression coefficients of the data are homogeneous. The table further reveals that the differences among all treatment groups are homogeneous, indicating no significant differences between them.

Efficacy Comparison between Biological and Chemical Agents to Spodoptera frugiperda.

The efficacy comparison between biological and chemical agents in controlling *Spodoptera frugiperda*, based on the results of the ANCOVA test, indicates that there is no significant difference between the two types of treatments. This means that the effectiveness of biological agents, such as bacteria, fungi, and other insects(dos Santos et al., 2021; Herlinda et al., 2021), is not significantly different from that of chemical agents like emamectin benzoate and ZnO(Liu, 2022; Pittarate et al., 2021). In the studies used as sources for this meta-analysis, both biological and chemical agents have individually demonstrated significant efficacy in controlling *Spodoptera frugiperda*. Each agent, whether biological or chemical, has been proven effective in various contexts and experimental setups. However, this analysis aimed to determine which type of agent is more significantly effective when compared directly.

The ANCOVA test was used to control for potential covariates and ensure that the comparison between the two types of agents

10.22219/jpbi.vxiy
pISSN:2355-2352 eISSN:

was fair and unbiased. Despite the individual proven efficacy of both biological and chemical agents, the results show that neither type of agent has a significantly greater effect on controlling *Spodoptera frugiperda* than the other. This finding suggests that both biological and chemical methods can be considered viable options for pest control, offering flexibility in choosing an approach based on other factors such as environmental impact, cost, and availability.

These research findings are actually encouraging because they provide flexibility and options for pest management strategies based on mortality rates. Since both biological and chemical agents have proven to be similarly effective in controlling *Spodoptera frugiperda*, with comparable mortality rates, farmers and agricultural professionals can choose the method that best suits their needs and circumstances. For instance, those who prioritize environmental sustainability and want to minimize chemical usage can opt for biological agents like bacteria, fungi, or parasitic insects. These biological agents have shown substantial mortality rates while generally having a lower environmental impact. On the other hand, in situations where rapid pest control is critical, chemical agents like emamectin benzoate and ZnO can be employed for their quick and broad-spectrum action, achieving high mortality rates swiftly.

This versatility allows for integrated pest management approaches that can combine both methods. For example, biological agents can be used to maintain long-term control and prevent pest populations from building up, while chemical agents can be applied for immediate pest suppression when necessary. This integrated approach ensures effective control of *Spodoptera frugiperda* with high mortality rates, balancing efficacy and sustainability. Ultimately, this flexibility can lead to more effective and environmentally responsible pest management strategies, benefiting both agricultural productivity and ecological health. Given that the efficacy of biological and chemical agents in controlling *Spodoptera frugiperda* is not significantly different, choosing between the two should take into account several other factors. Here are some considerations:

a. Environmental Impact:

- Biological Agents: These tend to have a lower environmental impact compared to chemical agents. They are often more specific to the target pest and do not harm non-target species, making them more environmentally friendly. However, there is a potential risk that some biological agents, if not properly managed, could become pests themselves or disrupt local ecosystems(Perier et al., 2022).
- Chemical Agents: While effective, chemical agents can have a broader impact, potentially affecting non-target species, including beneficial insects, and can lead to environmental contamination. The long-term use of chemicals can also lead to soil and water pollution(Guan et al., 2023).

b. Resistance Development:

- Biological Agents: There is generally a lower risk of pests developing resistance to biological control agents because these agents often involve complex interactions that pests find harder to overcome. However, the risk is not zero, and continuous monitoring is necessary to ensure long-term efficacy(Yang et al., 2022).
- Chemical Agents: Pests can develop resistance to chemical agents more quickly due to the simpler mode of action. This can lead to the need for higher doses or the development of new chemicals, which can be costly and unsustainable(Garlet et al., 2021).

C. Cost:

The initial development and implementation of biological control can be more expensive. However, once established, they can provide long-term control with lower recurring costs.These can be cheaper to apply in the short term but may require repeated applications, leading to higher long-term costs. Additionally, the development of resistance can further increase costs due to the need for new products (Lee et al., 2024).

d. Potential for Becoming Pests:
There is a risk that some biological agents could become pests themselves if not carefully managed. This requires thorough research and monitoring to ensure that introduced biological agents do not disrupt local ecosystems. While chemical agents do not become pests, over-reliance on chemical agents can lead to secondary pest outbreaks by eliminating natural enemies of other pests(Stenberg et al., 2021).

Conclussion

In conclusion, the comparison between biological and chemical agents in controlling *Spodoptera frugiperda* reveals that both methods are similarly effective, as indicated by the comparable mortality rates. However, choosing between these two methods should take into account additional factors beyond mere efficacy. Environmental impact, resistance development, cost, the Allee effect, and potential damage to maize are crucial considerations.

Biological agents, while environmentally friendly and less likely to cause resistance, may carry risks such as becoming pests themselves or being less effective under certain conditions. Chemical agents, though effective and fast-acting, can lead to environmental contamination and pest resistance over time. The damage caused by *Spodoptera frugiperda*, particularly to maize, underscores the importance of effective control methods to prevent significant agricultural losses. An integrated pest management (IPM) approach that combines both biological and chemical methods can provide a balanced solution. This strategy allows for the strengths of each method to be utilized while mitigating their weaknesses, offering flexibility and sustainability in pest control practices. By considering all these factors, farmers and agricultural professionals can make informed decisions to effectively manage *Spodoptera frugiperda*, ensuring both agricultural productivity and ecological health.

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