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Field evaluation of botanical and synthetic insecticides against fall armyworm in maize

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Abstract. *Siregar HM, Dadang, Sartiami D, Winasa IW, Zulkatri E. 2025. Field evaluation of botanical and synthetic insecticides against fall armyworm in maize. Biodiversitas 26: 5125-5131.* Fall armyworm (*Spodoptera frugiperda*) has emerged as a significant threat to maize production in Indonesia, leading to significant yield losses and ecological risks in control practices due to the overreliance on synthetic insecticides. This study aimed to evaluate the effects of botanical and synthetic insecticide applications on the population abundance and attack intensity of *S. frugiperda*, as well as their impact on parasitoid parasitism rate. The field experiment was conducted at the Sawah Baru Experimental Farm, IPB University, during the vegetative stage using a Randomized Block Design (RBD) with seven blocks and three treatments. These treatments include a botanical insecticide formulated as a 50 Emulsifiable Concentrate (EC) from a hexane extract mixture of *Piper retrofractum* fruits and *Annona squamosa* seeds (2:1 w/w), a synthetic insecticide (emamectin benzoate 30 EC), and a control. The data was analyzed using the Kruskal-Wallis test and Structural Equation Modeling (SEM) in R Studio version 4.4.2. The results showed that both insecticides effectively reduced the population abundance and attack intensity of *S. frugiperda*, with the synthetic insecticide exhibiting higher efficacy. However, the botanical insecticide was found to be relatively safer for parasitoids. These findings emphasize the potential of botanical insecticides as a promising and ecologically safer alternative for pest control, suitable for integration into Integrated Pest Management (IPM) strategies, thereby supporting a more sustainable approach to maize production.

Keywords: Emamectin benzoate, maize pest, parasitoid, *Spodoptera frugiperda*, sustainable pest management

Abbreviations: RBD: Randomized Block Design, EC: Emulsifiable Concentrate, IPM: Integrated Pest Management, SEM: Structural Equation Modeling

INTRODUCTION

Maize (*Zea mays* L.) is one of the most important agricultural commodities and plays an essential role in food security and farmers' livelihoods in many countries, including Indonesia. As the largest maize producer in Southeast Asia, Indonesia records an average annual growth of about 3% and ranks twelfth globally with a 1.1% share of world supply (USDA 2025). In 2024, national production reached 15.14 million tons, making maize the second most important staple crop after rice (BPS 2025). This production level underscores its strategic role in the national food system and its economic significance, as many farmers depend on maize cultivation for their income. It also serves as the main raw material for the animal feed industry, linking maize supply to livestock growth, national economic stability, and potential contributions through the export of feed raw materials. The increasing demand and utilization of maize highlight the need for sustainable productivity through good agricultural practices, including the adoption of high-yielding varieties, effective soil fertility management, and Integrated Pest Management (IPM), as pest infestation remains one of the main constraints contributing to yield losses in Indonesia (Sari et al. 2023).

The fall armyworm (*Spodoptera frugiperda* (J.E.Smith, 1797)) is recognized as one of the most destructive pests of maize, representing a serious threat to cultivation worldwide and a major concern for maize production in Indonesia. Since its first detection in 2019, this invasive pest originating from the Americas has rapidly spread across maize-producing regions of the country (Sartiami et al. 2020). Its high fecundity, strong migratory capacity, broad host range, and remarkable adaptability to diverse environments have enabled *S. frugiperda* to spread rapidly within a relatively short time (Westbrook et al. 2016; Early et al. 2018; Chen et al. 2022). The larvae can attack maize at all growth stages, causing severe damage to both leaves and cobs (Goergen et al. 2016). During the vegetative stage, infestations may reach up to 100%, leading to disruption of photosynthesis, stunted plant growth, and ultimately significant yield losses (Trisyono et al. 2019).

Effective pest management strategies are urgently needed to reduce the negative impacts of *S. frugiperda* outbreaks on maize yields. Current control methods mainly depend on synthetic insecticides because they work quickly, are highly effective, and are easy to apply. However, overusing and improper use of these insecticides can cause problems such as pest resistance, pest resurgence, environmental pollution, and a decline in beneficial organisms, especially natural enemies. This can upset ecosystem balance, weaken sustainable pest control, and increase dependence on chemicals. These issues highlight the need for developing alternative control methods that are effective and environmentally friendly.

Considering these adverse effects, botanical insecticides have gained increasing attention as environmentally friendly alternatives. Botanical insecticides are generally safer for non-target organisms, biodegradable, and compatible with other components of IPM (Dadang 2023; Assalin et al. 2025). Many plants produce bioactive secondary metabolites, particularly terpenoids, which exhibit insecticidal, repellent, or growth-regulating activities. Among the most promising candidates are Javanese long pepper (*Piper retrofractum* Vahl) and sugar apple (*Annona squamosa* L.). Extracts of these plants have demonstrated significant insecticidal activity against several pests, including *S. litura* (Ratwatthananon et al. 2020; Muthu et al. 2023), *Crocidolomia pavonana* (Fabricius, 1794) (Prijono et al. 2020; Nenotek et al. 2022), and *S. frugiperda* (Bhosle et al. 2024; Siregar et al. 2025). Furthermore, a hexane extract mixture of *P. retrofractum* fruits and *A. squamosa* seeds (2:1 w/w) formulated as 50 EC was recorded to be effective against second-instar larvae of *S. frugiperda* (unpublished data).

Botanical insecticides are expected to reduce pest populations while conserving natural enemies, which represent essential components of biological control. Natural enemies such as parasitoids, predators, and other beneficial arthropods make important contributions to sustainable pest management, and their conservation is consistent with IPM principles. Therefore, evaluating both pest suppression efficacy and ecological safety is crucial for developing sustainable management strategies. In this context, this study aimed to evaluate the application of a botanical insecticide formulated as a 50 EC from a hexane extract mixture of *P. retrofractum* fruits and *A. squamosa* seeds (2:1 w/w) and a synthetic insecticide (emamectin benzoate 30 EC) on the population abundance and attack intensity of *S. frugiperda*, as well as their impact on parasitoid parasitism rate. This represents the first field evaluation in Indonesia comparing the effectiveness of a 50 EC botanical insecticide formulation with a synthetic insecticide in controlling *S. frugiperda*.

MATERIALS AND METHODS

Research location

This research was conducted at the Sawah Baru Experimental Farm, Institut Pertanian Bogor, Bogor, West Java, Indonesia. Rearing of *Spodoptera frugiperda* larvae for parasitism observations was carried out at the Insect Physiology and Toxicology Laboratory, Department of Plant Protection, Faculty of Agriculture, Institut Pertanian Bogor, Bogor, Indonesia.

Procedures

Land preparation

The field experiment was arranged in a Randomized Block Design (RBD) with seven blocks and three treatments. Treatments were a 50 EC botanical insecticide formulated from a hexane extract mixture of *P. retrofractum* fruits and *A. squamosa* seeds (2:1 w/w), a synthetic insecticide (emamectin benzoate 30 EC), and an untreated control. Each block consisted of one botanical, one synthetic, and one control plot, for a total of 21 plots. Plots measured 8 m × 3 m with 1 m inter-plot spacing (Figure 2).

The experiment began with land preparation across all plots. The field was plowed and loosened to a depth of 30 cm. Composted cattle manure was applied as a basal fertilizer at 20 kg per plot and incorporated into the soil, and the field was left for two weeks before planting. Maize variety NB Super F1 was planted at 70 × 45 cm spacing. Follow-up fertilization was applied at 2 and 5 Weeks After Planting (WAP), consisting of 2 kg per plot of nitrogen fertilizer and 2 kg per plot of multinutrient fertilizer (NPK 16:16:16), respectively.

Insecticide application

The botanical insecticide concentration was determined based on laboratory toxicity tests, equivalent to 2 × LC_{95} (2.4 mL/L), to ensure consistent efficacy under field conditions. This adjustment was necessary because environmental factors such as sunlight, rainfall, and temperature can degrade active compounds and reduce the effectiveness observed in laboratory tests. The 2 × LC_{95} concentration is expected to provide a safety margin to maintain insecticidal activity in the field, while the synthetic insecticide was applied at the recommended concentration (2 mL/L). Applications were made five times using a knapsack sprayer equipped with a flat fan nozzle at a spray volume of 2.5 L per plot, starting at 2 WAP and continuing at weekly intervals.

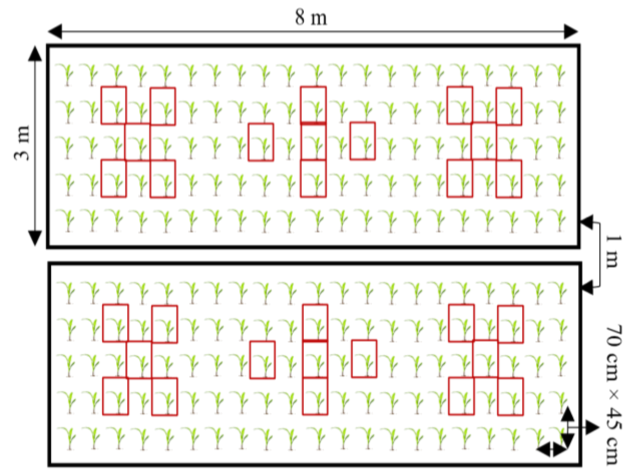

Figure 2. Experimental plot layout. Noted:  : Sample plants,  : Non-sample plants

Population abundance and attack intensity of Spodoptera frugiperda

Population abundance and attack intensity of *S. frugiperda* were observed weekly from the second to the sixth WAP. Each plot contained fifteen systematically selected sample plants that were used as observation units (Figure 2). Population abundance was determined by counting the larvae present on each sample plant. Attack intensity was evaluated based on leaf damage using the Davis scale (score zero for no damage to nine for severe damage), from the youngest unexpanded whorl leaf to the third leaf (Bagariang et al. 2020). The following formula was used to calculate attack intensity: AI (%) = $((\Sigma (n_i \times v_i)) / (N \times Z)) \times 100\%$, where AI: Percentage of attack intensity; n_i: Number of plants recorded at a specific damage scale; v_i: scale value according to the Davis scale; N: total number of plants observed; Z: highest damage scale value.

Parasitism rate of Spodoptera frugiperda *larvae*

Parasitism was evaluated by collecting ten larvae per plot from plants that were not sampled, totaling 70 larvae per treatment. The collected larvae were separated by treatment and reared in the laboratory under controlled conditions of 26±2°C and 65±5% RH. Each larva was reared individually in a 90 mL cup to ensure accurate observation and prevent cannibalism. The larvae were fed with fresh maize leaf pieces, which were insecticide-free. For each treatment, parasitoid emergence was recorded, and parasitism rate was measured using the following formula: Parasitism (%) = (Number of parasitized larvae / Total number of larvae collected) × 100%.

Data analysis

Data on population abundance, attack intensity, and parasitism rate of *S. frugiperda* were analyzed weekly and overall using the non-parametric Kruskal-Wallis test, followed by Dunn's test with Bonferroni correction when significant differences were detected (p<0.05). To assess causal relationships among variables, a Structural Equation Modeling (SEM) was performed using the *lavaan* package (version 0.6-19) in R Studio (version 4.4.2). Model fit was evaluated based on Root Mean Square Error of Approximation (RMSEA), Comparative Fit Index (CFI), and Tucker-Lewis Index (TLI), where acceptable fit was indicated by low RMSEA values and high CFI and TLI values (Efendi et al. 2025).

RESULTS AND DISCUSSION

Effect of insecticide applications on the population abundance of *Spodoptera frugiperda*

The application of both insecticides significantly affected the population abundance of *S. frugiperda* larvae. The lowest abundance was found in the synthetic insecticide treatment, followed by the botanical insecticide, both significantly lower than the control (p<0.01) (Figure 3).

The same trend was recorded in weekly measurements, where both insecticide treatments significantly reduced the population abundance of *S. frugiperda* larvae at all observation times (p<0.01) (Figure 4). The synthetic insecticide was consistently the most effective, suppressing larval populations near zero throughout the observation period. The botanical insecticide also lowered populations compared to the control, although its effectiveness was less than that of the synthetic insecticide.

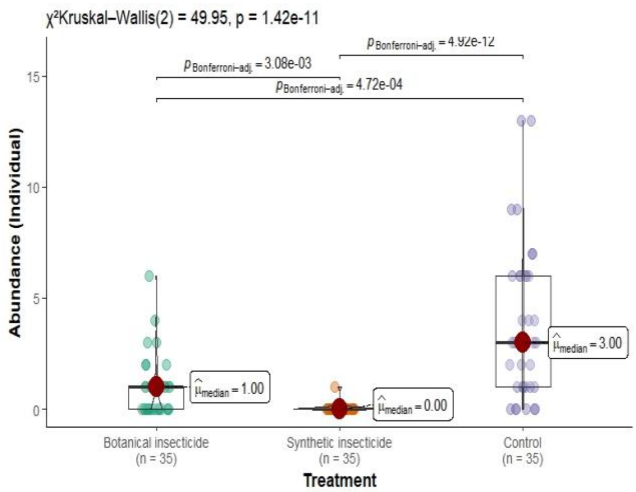

Figure 3. Population abundance of *Spodoptera frugiperda* larvae under different treatments

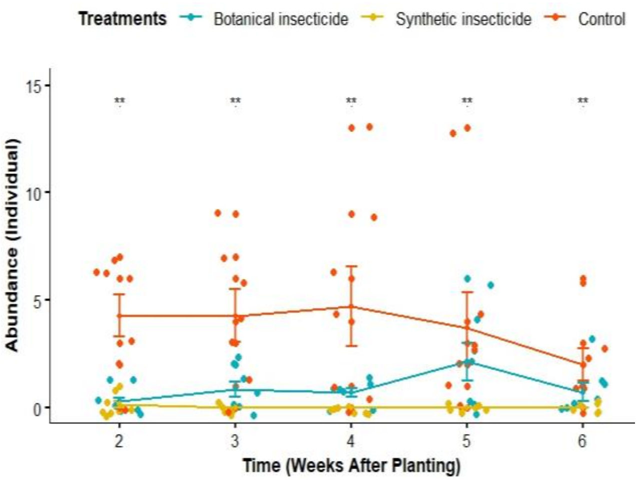

Figure 4. Weekly population abundance of *Spodoptera frugiperda* larvae under different treatments. Significance: *: p<0.05, **: p<0.01, ns: Not significant

Effect of insecticide applications on the attack intensity of *Spodoptera frugiperda*

The application of both insecticides significantly affected the attack intensity of *S. frugiperda*. The lowest intensity was recorded in the synthetic insecticide treatment, followed by the botanical insecticide, both significantly lower than the control (p<0.01) (Figure 5).

The same trend was recorded in weekly measurements, where both insecticide treatments significantly reduced attack intensity at all observation times (p<0.01) (Figure 6). The synthetic insecticide was consistently the most effective, maintaining attack intensity near zero throughout the observation period. The botanical insecticide also reduced attack intensity compared with the control, although its effectiveness was lower than that of the synthetic insecticide.

Effect of insecticide applications on the parasitism rate of *Spodoptera frugiperda*

The larval parasitoid species identified was *Microplitis manilae*. During the vegetative stage of maize, *M. manilae* parasitized *S. frugiperda* larvae with parasitism rates that differed significantly overall among treatments (p<0.01). The highest rate was recorded in the control, followed by the botanical insecticide, while no parasitism was recorded in the synthetic insecticide treatment. Further analysis showed a significant difference between the control and the synthetic insecticide (p<0.01). In contrast, no significant differences were found between the control and botanical insecticide or between the two insecticide treatments (p>0.05) (Figure 7).

Based on weekly measurements, the same trend was recorded, with higher parasitism rates in the control and botanical insecticide treatments compared to the synthetic insecticide, which showed no parasitism throughout the observation period. However, differences among treatments were not significant at all observation times (p>0.05) (Figure 8).

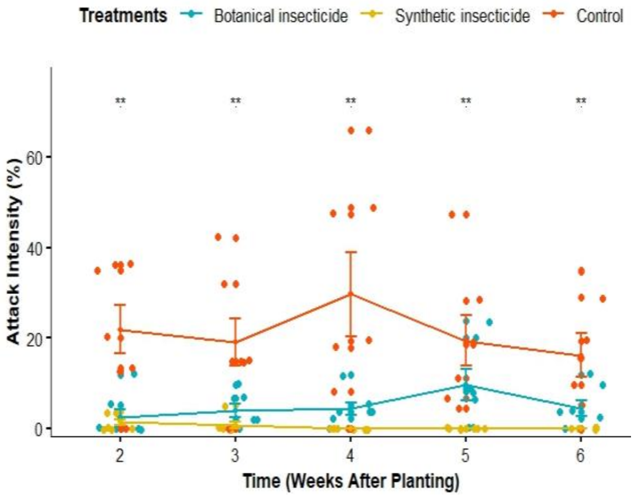

Figure 6. Weekly attack intensity of *Spodoptera frugiperda* under different treatments. Significance: *: p<0.05, **: p<0.01, ns: Not significant

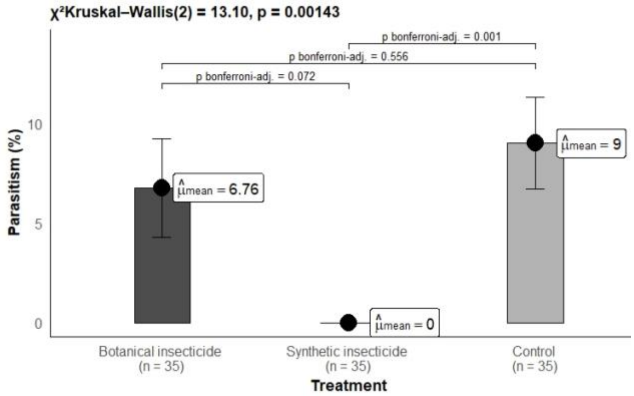

Figure 7. Parasitism rate of *Spodoptera frugiperda* larvae under different treatments

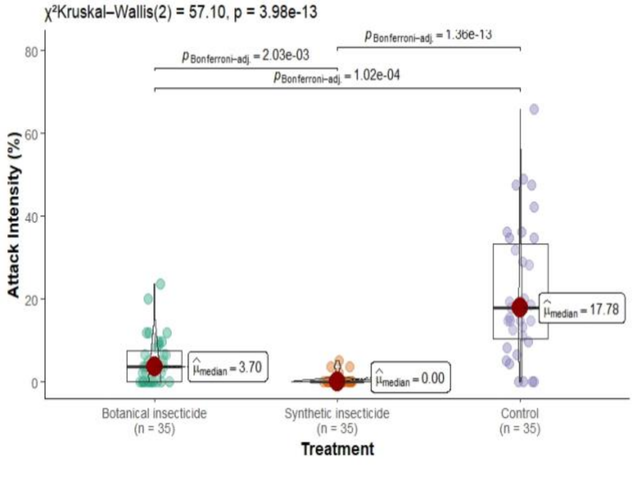

Figure 5. Attack intensity of *Spodoptera frugiperda* under different treatments

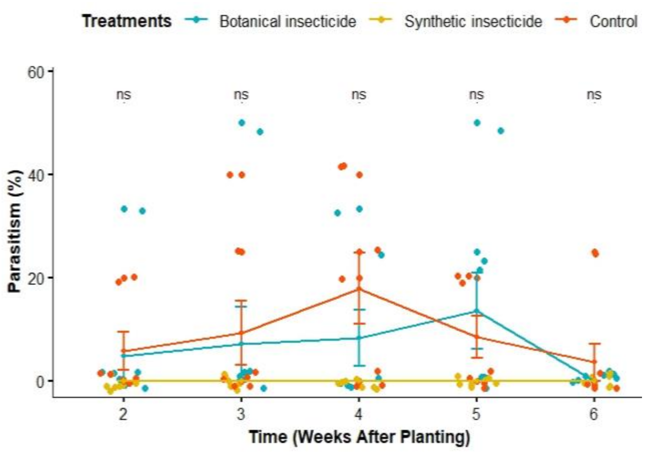

Figure 8. Weekly parasitism rate of *Spodoptera frugiperda* larvae under different treatments. Significance: *: p<0.05, **: p<0.01, ns: Not significant

Relationship between insecticides, population abundance, attack intensity, and parasitism rate of *Spodoptera frugiperda*

Both insecticides have significant negative direct relationships with the population abundance of *S. frugiperda* larvae, with the synthetic insecticide exhibiting a stronger effect (coefficient = −3.771, SE = 0.586, p<0.01) than the botanical insecticide (coefficient = −2.857, SE = 0.627, p<0.01). Population abundance has a significant positive relationship with attack intensity (coefficient = 4.117, SE = 0.334, p<0.01), indicating that higher larval populations lead to greater crop damage. In contrast, population abundance has no significant relationship with parasitism rate (coefficient = 1.441; SE = 1.392; p = 0.301). Meanwhile, the botanical insecticide has a positive but non-significant direct relationship with the parasitism rate (coefficient = 1.590; SE = 3.811; p = 0.677), whereas the synthetic insecticide has a negative but non-significant direct relationship (coefficient = –3.935; SE = 3.226; p = 0.222) (Figure 9).

Discussion

The 50 EC botanical insecticide formulated from a hexane extract mixture of *P. retrofractum* fruits and A. *squamosa* seeds was effective in reducing *S. frugiperda* populations and attack intensity in maize fields from 2 to 6 WAP. Its application significantly suppressed pest population abundance and attack intensity compared to the control, although its effectiveness was slightly lower than that of the synthetic insecticide. This effectiveness is attributed to the combined action of bioactive compounds in both extracts. *P. retrofractum* contains piperamides that act as neurotoxins by inhibiting cytochrome P450 enzymes (Scott et al. 2008), whereas *A. squamosa* contains acetogenins that inhibit complex I of the mitochondrial electron transport chain, thereby disrupting ATP production (Durán-Ruiz et al. 2024). These different modes of action allow the mixture to work synergistically against the pest. Such combined action has been widely reported, with mixtures of plant extracts often exhibiting higher insecticidal activity than single-extract applications (Nuryanti et al. 2022; Heviyanti et al. 2024).

The botanical insecticide treatment exhibited a gradual effect in suppressing the larval population of *S. frugiperda*. Although fluctuations occurred, the overall abundance consistently remained lower than that of the control, with the lowest population recorded at 4 WAP, coinciding with the control's peak. This indicates that the maximum impact was achieved after repeated applications. This effectiveness is closely related to the EC formulation, which helps protect bioactive compounds from environmental degradation and ensures more even deposition on leaf surfaces, thereby improving efficacy compared to crude extracts, as also reported by Ibrahim and Sammour (2024). Although less persistent than synthetic insecticides, the gradual effect of EC formulations may reduce selection pressure for resistance while maintaining populations below economic threshold levels. In contrast, the synthetic insecticide emamectin benzoate 30 EC provided rapid and strong suppression, with larval populations remaining very low throughout the observation period, reflecting the high toxicity and rapid mode of action of the active ingredient. Acting as a group 6 neurotoxin, emamectin benzoate activates chloride channels, leading to ion influx, membrane depolarization, disruption of nerve impulses, and ultimately muscle paralysis, feeding cessation, and insect death (El-Sheikh 2015). However, this high efficacy also poses a risk of resistance development, particularly when applied repeatedly (Muraro et al. 2022).

The reduction in *S. frugiperda* larval population abundance was followed by a decrease in attack intensity under both insecticide treatments. The synthetic insecticide consistently maintained attack intensity at very low levels throughout all observation periods, while the botanical insecticide also significantly lowered attack intensity compared with the control. The strong positive relationship between larval population abundance and attack intensity demonstrates that effective suppression of larval populations directly contributes to reduced crop damage (Figure 9). This finding is consistent with Mukanga et al. (2024), who reported that effective field control of *S. frugiperda* not only reduced larval population but also decreased crop damage, ultimately contributing to higher yields.

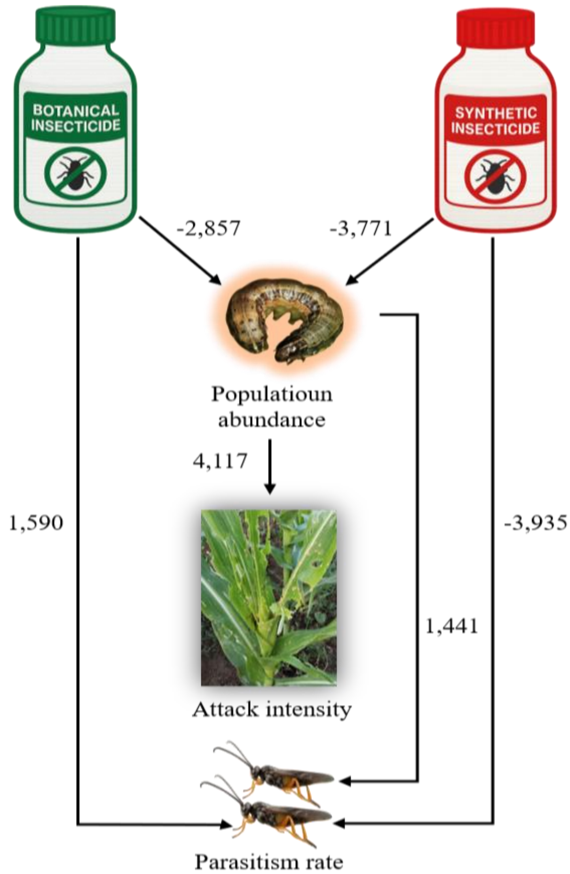

Figure 9. Causal relationships between insecticide treatments and response variables

In addition to suppressing pest populations, the treatments differed in their effects on the parasitism rate of *M. manila*. Higher parasitism was observed in the control and botanical insecticide treatments, whereas no parasitism occurred under the synthetic treatment. This suggests that the botanical insecticide was relatively safe for parasitoids during 2 to 6 WAP and supports the conservation of natural enemies under field conditions, although sublethal and behavioral effects were not assessed. The direct effect was not significant, but the positive coefficient for the botanical insecticide indicates compatibility with biological control, whereas the synthetic insecticide showed a negative coefficient, reflecting its potential to reduce parasitoid activity (Figure 9). Emamectin benzoate, although often reported as selective for non-target organisms (Govindan et al. 2024), has also been classified as a high-risk insecticide for parasitoids. Previous studies showed that its exposure may threaten survival, reduce adult emergence, prolong host handling time, and decrease parasitism efficiency (Li et al. 2024; Zhu et al. 2025).

The relevance of this study to Integrated Pest Management (IPM) is evident from the different control patterns of the treatments. The botanical insecticide significantly reduced *S. frugiperda* larval abundance with a gradual effect, keeping numbers low during the observation period. This pattern is consistent with IPM principles, which focus on reducing pest populations rather than completely eradicating them, thereby lowering the risk of resistance development. Besides that, its safety for natural enemies, especially parasitoids, further supports the goals of sustainability and conservation in IPM. As emphasized in IPM principles, effective pest management is measured not only by reducing pest populations but also by preserving ecosystem functions and biodiversity in the long term (Zhou et al. 2024). In contrast, the synthetic insecticide, although providing more rapid control with higher efficacy, tended to reduce parasitoid populations, making it less suitable for long-term IPM strategies.

In conclusion, the 50 EC botanical insecticide formulation is a suitable component of IPM in maize cultivation, as it effectively reduces *S. frugiperda* populations and attack intensity while remaining safe for parasitoids. The synthetic insecticide also plays an important role due to its high efficacy; however, its use should be limited to prevent ecological impacts on natural enemies. Nevertheless, these findings provide only an initial indication of the potential and effectiveness of the botanical insecticide for controlling *S. frugiperda*. Results may differ across locations or seasons; therefore, future studies should adopt more comprehensive designs with larger sample sizes to ensure adequate sensitivity to detect ecologically meaningful differences. Sustainable pest management is most effectively achieved by combining botanical insecticides with the selective rotation of synthetic insecticides and the preservation of natural enemies. This strategy not only ensures consistent pest control and reduces ecological risks but also strengthens agroecosystem resilience and supports the long-term goals of sustainable agriculture.

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