Journal of Applied and Natural Science
17(3), 1280 - 1289 (2025)
ISSN : 0974-9411 (Print), 2231-5209 (Online)
journals.ansfoundation.org

*Research Article*

# Evaluation of plant extracts as botanical insecticides for controlling *Spodoptera frugiperda* (Lepidoptera: Noctuidae)

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***Article Info***
https://doi.org/10.31018/jans.v17i3.6813
Received: May 13, 2025
Revised: August 23, 2025
Accepted: September 01, 2025

***How to Cite***
Siregar, H. M. *et al.* (2025). Evaluation of plant extracts as botanical insecticides for controlling *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Journal of Applied and Natural Science*, 17(3), 1280 - 1289. https://doi.org/10.31018/jans.v17i3.6813

**Abstract**
The increasing incidence of *Spodoptera frugiperda* resistance and the adverse effects of excessive synthetic insecticide use emphasize the need to develop safer and more environmentally sustainable alternative control strategies. One promising alternative is the use of botanical insecticides. This study aimed to evaluate the bioactivity of five plant extracts, namely spiked pepper (*Piper aduncum*), African marigold (*Tagetes erecta*), Mexican sunflower (*Tithonia diversifolia*), sugar apple (*Annona squamosa*), and soursop (*Annona muricata*), as candidates for botanical insecticide formulations against *S. frugiperda.* The experiments assessed toxicity, antifeedant, and ovicidal activities. Toxicity was tested using the leaf-dipping method with five concentration levels, equivalent to $LC_{15}$, $LC_{35}$, $LC_{55}$, $LC_{75}$, and $LC_{95}$. Antifeedant activity was tested using the choice method with three concentration levels, equivalent to $LC_{15}$, $LC_{35}$, and $LC_{55}$. Moreover, ovicidal activity was tested by spraying the extract on eggs with concentrations equivalent to $LC_{95}$ and $2\times LC_{95}$. The results showed a positive correlation between increasing test concentrations and higher larval mortality, antifeedant activity, and ovicidal activity. *P. aduncum* extract showed the highest toxicity, with $LC_{50}$ and $LC_{95}$ values of 0.11% and 0.70%, respectively. Among the tested extracts, *T. diversifolia* showed the highest antifeedant activity with moderate to strong effects, while the other showed very weak to moderate effects. In terms of ovicidal activity, all extracts showed strong inhibitory effects (>75%), particularly at a concentration of $2\times LC_{95}$, with *P. aduncum* being the most effective extract due to its highest inhibition rate. These findings indicate that each extract exhibited bioactivity in at least one parameter, supporting its potential as a botanical insecticide. *P. aduncum* emerged as the most promising candidate, with strong toxicity and ovicidal effects despite relatively weak antifeedant activity.

**Keywords:** Antifeedant, Choice method, Leaf-dipping method, Ovicidal, Toxicity

## INTRODUCTION

The fall armyworm (*Spodoptera frugiperda*) has continued to pose a serious threat to the success of corn cultivation in Indonesia, following the initial report in early 2019 (Sartiami *et al.,* 2020). The larvae of *S. frugiperda* attack corn at all growth stages, with the vegetative stage as the most vulnerable (Maharani *et al*., 2019). Infestations during this stage potentially cause up to 100% damage, leading to stunted growth (Trisyono *et al*., 2019). *S. frugiperda* infestations in several countries have been reported to significantly decline production. According to Harrison *et al*. (2019), in 2016, annual corn yield losses due to *S. frugiperda* infestations in 12 African countries were estimated at 18 million tons, with an economic loss of approximately US$13 million. In 2018, yield losses in Kenya were estimated at 883,000 tons (de Groote *et al*., 2020).

The significant potential for economic losses due to *S. frugiperda* infestations indicates the urgent need for effective control strategies. However, control measures to date have relied heavily on synthetic insecticides. Despite effectively controlling *S. frugiperda*, reliance on synthetic insecticides can also lead to several adverse effects, including resistance, mortality of non-target organisms, and hazardous toxic residues that pose risks to both human health and the environment (Dadang, 2023). Kumela *et al*. (2018) explained that improper use of synthetic insecticides may lead to the rapid development of resistance. In several countries, such as Brazil and Puerto Rico, genetic mutations have been identified that could lead to resistance against various insecticide active ingredients, particularly emamectin benzoate, diamides, organophosphates, spinosyns, and benzoylureas (Boaventura et al., 2020), as well as spinosad (Lira *et al*., 2020). Therefore, more environmentally friendly alternative control techniques are required than synthetic insecticides.

An environmentally friendly alternative technique for controlling *S. frugiperda* is the use of botanical insecticides, which offer several advantages, including selectivity toward target pests, rapid biodegradability, no inhibition of plant growth, and compatibility with other control technologies to enhance effectiveness (Dadang, 2023). Additionally, botanical insecticides contain various active compounds with different modes of action, which can slow the development of pest resistance (El-Wakeil, 2013).

As a megadiverse country, Indonesia has many plant species with potential as botanical insecticides. Several plant species, including *Piper aduncum, Tagetes erecta, Tithonia diversifolia, Annona squamosa*, and *Annona muricata*, have been reported to effectively control various insect pests. The fruit extract of *P. aduncum* reportedly showed strong antifeedant and toxic activities in controlling several pests, including *Nilaparvata lugens* (Nuryanti *et al*., 2018), *Crocidolomia pavonana* (Prijono *et al*., 2020), and *Helopeltis antonii* (Rohimatun *et al*., 2020). Similarly, the flower extracts of *T. erecta* and *T. diversifolia* have also shown potent insecticidal activity against *N. lugens* (Nuryanti *et al*., 2018) and *H. antonii* (Rohimatun *et al*., 2020). Meanwhile, the leaf and seed extracts of *A. squamosa* have shown strong toxicity against *S. litura* (Shiragave, 2018) and *C. pavonana* (Nenotek *et al*., 2022), whereas those of *A. muricata* have exhibited toxic effects against *Bactrocera* sp. (Ningrum *et al*., 2023) and *Aphis glycines* (Baldin *et al*., 2023).

Many studies have reported the use of various plant species as botanical insecticides, but the majority have primarily focused on the toxicity of the extracts. However, comprehensive studies on the bioactivity of plant extracts remain limited. Dadang (2023) explained that botanical insecticides caused insect mortality and functioned as antifeedants, oviposition deterrents, ovicidal agents, and growth regulators. Therefore, this study aimed to evaluate the bioactivity of five plant extracts, including *P. aduncum*, *T. erecta*, *T. diversifolia*, *A. squamosa*, and *A. muricata*, against *S. frugiperda*, with emphasis on assessing extract toxicity, antifeedant, and ovicidal activities.

## MATERIALS AND METHODS

### Study area

The study was conducted from January to November 2024 at the Laboratory of Insect Physiology and Toxicology, Department of Plant Protection, Faculty of Agriculture, IPB University, Bogor, West Java, Indonesia.

### Extraction of plant materials

The plant materials used for extraction were obtained from various locations in West Java Province, Indonesia. The fruits of *P. aduncum* were collected from the area around the IPB University Campus, Dramaga District, Bogor Regency (6°32'56.5"S, 106°42'57.9"E). Flowers of *T. diversifolia* were collected from Cipanas District, Cianjur Regency (6°42'42.9"S, 106°59'45.4"E), and *T. erecta* flowers were purchased from PT. Bina Usaha Flora (BUF), Sukaresmi District, Cianjur Regency (6°43'44.3 "S, 107°04'31.1"E). Seeds of *A. squamosa* were obtained from the collection of the Laboratory of Physiology and Toxicology, IPB University, while seeds of *A. muricata* were collected from Singaparna District, Tasikmalaya Regency (7°20'53.3"S 108° 06'40.4"E).

Extraction was conducted using the maceration method, beginning with the cutting of plant material and drying in the laboratory. All materials were dried in a room at 26 ± 2 ºC and 65 ± 5% RH for 7-14 days without direct sunlight exposure and continued with oven drying at 45 ºC. After drying, all materials were ground using a grinder (Retsch GmbH 5667 HAAN Type SK1 Nr. 37535) into a powder, then sieved using a 1 mm mesh, and soaked in a solvent at a ratio of 1:10 (w/v) for 48 hours (Sianturi *et al*., 2022). The solvents used were ethanol for *T. erecta* flowers (Rohimatun *et al*., 2020), methanol for *T. diversifolia* flowers (Firmansyah *et al*., 2017), and hexane for *P. aduncum* fruits (Heviyanti *et al*., 2024), *A. squamosa* seeds (Vetal and Pardeshi, 2019), and *A. muricata* seeds (Irwan *et al*., 2021). The resulting filtrate was filtered, evaporated using a rotary evaporator (RV 10 digital pro V Complete, Germany) at 50 ºC and 400–450 mmHg, and concentrated into a crude extract, which was then stored at 4 ºC until further use (Agustini *et al*., 2024).

### Insect rearing

The rearing of *S. frugiperda* followed the method described by Sianturi *et al*. (2022), starting with collecting

parental insects from field populations in a cornfield at the Sawah Baru Experimental Farm, IPB University (6° 33'48.4"S 106°44'06.0"E). The larvae were placed in rearing boxes measuring 36 cm × 28 cm × 7 cm and fed with baby corn, then transferred to cups containing sawdust upon reaching the final instar for pupation. The emerging adults were moved into cages (26 cm × 26 cm × 24 cm) lined with tissue paper on the walls to serve as oviposition substrates. The adults were fed a 10% honey solution absorbed in cotton and hung inside the cage. The eggs laid by adults in tissue paper were collected and transferred to rearing boxes, and the second-instar larvae from the second generation were used as test insects.

**Toxicity test**

The toxicity test of the plant extract was conducted in two stages, namely a preliminary and an advanced test. The experiment was arranged in a completely randomized design (CRD) with five concentration levels equivalent to $LC_{15}$, $LC_{35}$, $LC_{55}$, $LC_{75}$, and $LC_{95}$, determined from the preliminary test results (Nuryanti *et al*., 2018). The preliminary test used three replicates, and the advanced test used five replicates, with each replicate consisting of ten *S. frugiperda* larvae. Before testing, the plant extract was dissolved in 1% solvent (the same type of solvent as during extraction), then a mixture consisting of distilled water and 0.2% Alkyl-aryl polyglycol ether 400 L was added to reach a total volume of 100 mL (Agustini *et al*., 2024). Extract solutions were homogenized using a magnetic stirrer at 750 rpm for 30 minutes and then serially diluted to make lower concentrations. Control was distilled water added with solvent and Alkyl-aryl polyglycol ether 400 L at a ratio of 5:1 (v/v) (Sianturi *et al.*, 2022). The test was conducted using the leaf-dipping method, with each *S. frugiperda* larva placed individually in separate wells of a tray to prevent cannibalism and ensure accurate results. The test insect feed consisted of 2 cm × 2 cm pieces of fresh corn leaves, free of insecticide, sourced from corn plants cultivated without the use of insecticides. Initially, the corn leaf pieces were dipped into the extract solution according to the treatment concentration for approximately five seconds until evenly coated, then drained and placed in each tray well with a single *S. frugiperda* larva. After 48 hours, the treated leaves were replaced with fresh untreated leaves and larval mortality was observed at 24, 48, 72, and 96 hours after treatment (HAT) (Agustini *et al*., 2024).

**Antifeedant test**

The antifeedant test was conducted using the choice method in a residual feeding test. Extract concentrations tested were equivalent to $LC_{15}$, $LC_{35}$, $LC_{55}$, and control based on toxicity test results. The experiment was arranged in a CRD with five replications. Each tray well contained a single *S. frugiperda* larva, then one treated leaf, and one control leaf was provided and placed side by side. Observations were conducted by measuring the leaf area consumed 24 HAT using the *BioLeaf* application (Machado *et al*., 2016). The percentage of antifeedant activity (AP) was calculated using the formula:

$$AP = \left(\frac{CT - ET}{CT + ET}\right) \times 100\% \quad \text{Eq. 1}$$

CT and ET represent the leaf area consumed in the control and treatment groups.

**Ovicidal test**

The ovicidal test was conducted by spraying the extract solution onto groups of *S. frugiperda* eggs using a hand sprayer (Krinski *et al*., 2018). The egg criteria used were one day old after oviposition, normal morphology (intact shape and uniform color), and consisted of at least fifty eggs in a group. The spraying was carried out evenly until the entire egg surface was wet. Furthermore, the eggs were air-dried and placed in tissue-lined petri dishes, with one group per dish. The experiment was arranged using a CRD with three replications. Each replication consisted of one group of insect eggs. The extract concentrations tested were $LC_{95}$, $2\times LC_{95}$, and a control based on toxicity test results. These concentrations were chosen to assess the maximum effectiveness of the extract against insect eggs, which are more resistant than the larval stage due to the presence of a protective chorion. After treatment, the eggs were stored in a room maintained at 26 ± 2 ºC and 65 ± 5% RH. Observations were carried out daily until all eggs hatched or failed to hatch. The percentage of ovicidal activity (OP) was calculated using the formula:

$$OP = \left(\frac{\left(\frac{A}{N_1} \times 100\right) - \left(\frac{B}{N_2} \times 100\right)}{\left(\frac{A}{N_1} \times 100\right)}\right) \times 100\% \quad \text{Eq. 2}$$

A, B, $N_1$, and $N_2$ represent the number of eggs hatched in the control, the number of eggs hatched in the treatment, the total number of eggs in the control, and the total number of eggs in the treatment group, respectively.

**Data analysis**

Data processing started with data tabulation using Microsoft Excel 2021. Extract toxicity was analyzed using probit analysis to determine the relationship between concentration and insect mortality based on $LC_{50}$ and $LC_{95}$ values through the *PoloPlus* software. Antifeedant

and ovicidal activities were classified according to specific criteria. Antifeedant activity was classified into five criteria: strong (AP ≥ 80%), moderate (60% ≤ AP < 80%), weak (40% ≤ AP < 60%), very weak (0% < AP < 40%), and no activity (AP = 0%) (Rohimatun *et al*., 2020). Similarly, ovicidal activity was also classified into five criteria: strong (OP ≥ 75%), moderate (50% ≤ OP < 75%), weak (25% ≤ OP < 50%), very weak (0% < OP < 25%), and no activity (OP = 0%) (Aprialty *et al*., 2021).

## RESULTS AND DISCUSSION

### Toxicity of extract against *Spodoptera frugiperda* larvae

The toxicity of the five plant extracts showed a positive correlation between increasing concentrations and the percentage of *S. frugiperda* larval mortality. During the assessment, larval mortality increased from the first observation at 24 HAT until 96 HAT. The highest mortality rates for each extract at 96 HAT, in order, were 100% *P. aduncum* (concentration 0.73%), 98% *A. squamosa* (1.47%), 88% *T. erecta* (1.87%), 74% *T. diversifolia* (5.79%), and 72% *A. muricata* (2.30%) (Fig.1).

The relationship between concentration and larval mortality percentage showed the toxicity level of each plant extract. According to probit analysis, the plant extract with the highest toxicity was *P. aduncum*, which had lower $LC_{50}$ and $LC_{95}$ values than the other extracts, at 0.11% and 0.70%, respectively. This was followed by *A. squamosa*, *T. erecta*, *A. muricata*, and *T. diversifolia* (Table 1). A previous study by Widayani *et al.* (2023) reported that the methanol extract of *P. aduncum* exhibited $LC_{50}$ and $LC_{95}$ values of 0.53% and 4.66%, respectively, against second-instar larvae of *S. frugiperda*. In comparison, the present study demonstrated significantly higher toxicity, with $LC_{50}$ and $LC_{95}$ values approximately 4.82 and 6.66 times lower, respectively, than previously reported values. Besides cultivar variation and geographical conditions, factors such as the specific plant parts used, tissue maturity, and postharvest handling practices (drying, grinding, and storage) can significantly influence the phytochemical composition and bioactivity of plant extracts (Raya *et al*., 2015; Firmansyah *et al*., 2017; Oszmiański *et al*., 2018). Moreover, the choice of solvent is also important, as it affects the polarity and determines the types of bioactive compounds that can be efficiently extracted (Tipsut *et al*., 2025). Numerous reports have shown that extracting plant materials with hexane solvent was more effective against test insects than other solvents such as dichloromethane, ethyl acetate, methanol, and ethanol (Lucena *et al*., 2017; Pumnuan *et al*., 2022; Wanna *et al*., 2023). The choice of solvent in plant material extraction determines the compounds obtained, depending on polarity (Pumnuan *et al*., 2022). The basic principle is "*like dissolves like*," meaning that when the target compounds are polar, a polar solvent should be used, and vice versa (Dadang, 2023). In general, plants of the Piperaceae family, including *P. aduncum*, have long been recognized as potential sources for botanical insecticides due to the abundance of potential phytochemicals with various insecticidal activities, including toxicity, antifeedant, and anti-oviposition effects (Dadang, 2023; Assunção *et al*., 2024). About 400 compounds with diverse structures and bioactivities have been isolated from this genus, primarily belonging to the alkaloid, lignan, flavone, chalcone, phenylpropanoid, and kava-pyrone groups (Xiang *et al*., 2016).

Dillapiol is a phenylpropanoid compound and a major component of *P. aduncum* (Morais *et al*., 2023). This compound is valuable and has great potential as an insecticide due to its strong insecticidal activity against various insect species (Lucena *et al*., 2017; Rohimatun *et al*., 2020; Heviyanti *et al*., 2024). It produces neurotoxic effects by inhibiting acetylcholinesterase enzymes and modulating octopamine synapses and GABA receptors, leading to loss of control over movement, seizures, paralysis, and ultimately, death (Fazolin *et al*., 2022). In addition, the presence of methylenedioxy rings in the dillapiol structure can also inhibit the activity of cytochrome P450 enzymes, which are responsible for xenobiotic metabolism, including insecticide detoxification (Fierascu *et al*., 2020). This mechanism increases insect susceptibility to insecticides while enhancing effectiveness.

Another extract that showed strong toxicity was *A. squamosa*. The strong insecticidal activity can be attributed to the presence of the main active compounds, namely, acetogenins (Durán-Ruiz *et al*., 2024). Several compounds classified as acetogenins include annonain, squamosin, annonacin, asimicin, cohibinsin, squamostatin-A, and bullatacin (Chen *et al*., 2012). Acetogenins act on a specific target by inhibiting mitochondrial respiration at NADH-ubiquinone oxidoreductase (mitochondrial complex I). This inhibition disrupts electron transfer, preventing the formation of a proton gradient and ultimately halting ATP production through oxidative phosphorylation (González-Coloma *et al*., 2002; Yabunaka *et al*., 2003; Durán-Ruiz *et al*., 2024). Consequently, cells experience energy deficiency, leading to metabolic disruption. In insects, this condition causes paralysis and physiological impairment, ultimately resulting in mortality due to the failure of ATP-dependent cellular systems.

### Antifeedant effects of the extracts on *Spodoptera frugiperda* larvae

All plant extracts showed variation in inhibiting the feeding activity of *S. frugiperda* larvae, with effectiveness depending on the type and concentration. Extracts of *P.*

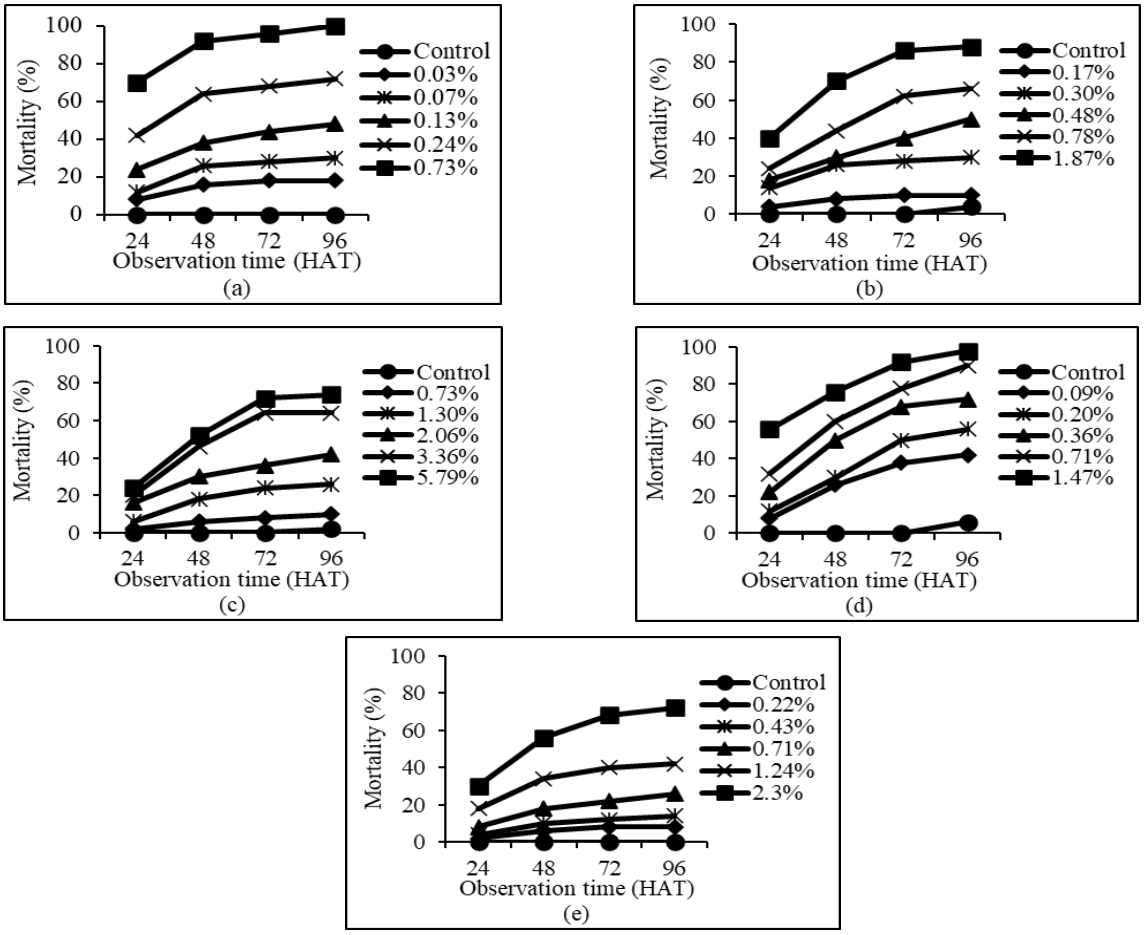


**Fig. 1.** *Mortality rate progression of second-instar larvae of Spodoptera frugiperda treated with five types of plant extract: a = Piper aduncum; b = Tagetes erecta; c = Tithonia diversifolia; d = Annona squamosa; e = Annona muricata*

**Table 1.** Toxicity of five plant extracts against second-instar larvae of *Spodoptera frugiperda*

| Plant extract | Observation time (HAT) | a ± SE | b ± SE | $LC_{50}$ (CI 95%) (%) | $LC_{95}$ (CI 95%) (%) |
|---|---|---|---|---|---|
| *Piper duncum* | 24 | 5.75 ± 0.18 | 1.55 ± 0.21 | 0.33 (0.25-0.48) | 3.80 (1.91-12.04) |
| | 48 | 6.44 ± 0.21 | 1.75 ± 0.21 | 0.15 (0,10-0.23) | 1.31 (0.63-6.34) |
| | 72 | 6.66 ± 0.22 | 1.85 ± 0.22 | 0.13 (0,08-0.20) | 0.98 (0.48-5.24) |
| | 96 | 6.97 ± 0.25 | 2.07 ± 0.24 | 0.11 (0,07-0.19) | 0.70 (0.34-5.73) |
| *Tagetes erecta* | 24 | 4.44 ± 0.11 | 1.25 ± 0.27 | 2.83 (1.67-9.33) | 59.09 (14.80-1798.90) |
| | 48 | 5.06 ± 0.11 | 1.70 ± 0.26 | 0.92 (0.72-1.28) | 8.57 (4.47-27.66) |
| | 72 | 5.51 ± 0.12 | 2.23 ± 0.28 | 0.59 (0.50-0.72) | 3.24 (2.19-6.03) |
| | 96 | 5.61 ± 0.13 | 2.42 ± 0.31 | 0.56 (0.47-0.67) | 2.67 (1.87-4.71) |
| *Tithonia diversifolia* | 24 | 3.38 ± 0.19 | 1.35 ± 0.36 | 15.91 (8.10-122.72) | 262.94 (52.77-44732.00) |
| | 48 | 3.86 ± 0.15 | 1.73 ± 0.30 | 4.55 (3.51-6.96) | 40.75 (19.37-180.41) |
| | 72 | 3.99 ± 0.14 | 2.25 ± 0.30 | 2.80 (2.35-3.44) | 15.05 (9.87-30.41) |
| | 96 | 4.04 ± 0.15 | 2.24 ± 0.31 | 2.69 (2.24-3.30) | 14.54 (9.49-30.01) |
| *Annona squamosa* | 24 | 4.82 ± 0.12 | 1.33 ± 0.23 | 1.36 (0.93-2.60) | 23.39 (8.44-180.54) |
| | 48 | 5.45 ± 0.12 | 1.16 ± 0.20 | 0.41(0.30-0.59) | 10.73 (4.39-63.45) |
| | 72 | 6.03 ± 0.14 | 1.36 ± 0.22 | 0.17 (0.11-0.24) | 2.81 (1.58-8.03) |
| | 96 | 6.43 ± 0.17 | 1.79 ± 0.26 | 0.16 (0.11-0.21) | 1.33 (0.88-2.64) |
| *Annona muricata* | 24 | 3.90 ± 0.11 | 1.61 ± 0.36 | 4.85 (2.88-16.51) | 50.93 (15.41-1023.04) |
| | 48 | 4.44 ± 0.09 | 1.79 ± 0.29 | 2.05 (1.54-3.23) | 16.93 (8.19-66.91) |
| | 72 | 4.64 ± 0.09 | 1.96 ± 0.28 | 1.54 (1.22-2.11) | 10.59 (5.96-28.85) |
| | 96 | 4.72 ± 0.09 | 2.01 ± 0.28 | 1.38 (1.11-1.83) | 9.03 (5.31-22.37) |

HAT = hours after treatment; a = intercept of probit regression line; b = probit regression slope; SE = standard error; LC = lethal concentration; CI = confidence interval.

**Table 2.** Inhibition of the feeding activity of five plant extracts against second-instar larvae of *Spodoptera frugiperda*

| Plant extract | Concentration (%) | Antifeedant activity (%) ± SE | Criteria |
|---|---|---|---|
| *Piper aduncum* | $LC_{15}$ (0.04) | 15.24 ± 2.91 | Very weak |
| | $LC_{35}$ (0.07) | 43.54 ± 3.99 | Weak |
| | $LC_{55}$ (0.13) | 54.25 ± 3.36 | Weak |
| *Tagetes erecta* | $LC_{15}$ (0.21) | 43.02 ± 5.25 | Weak |
| | $LC_{35}$ (0.39) | 64.33 ± 2.01 | Moderate |
| | $LC_{55}$ (0.63) | 70.95 ± 3.61 | Moderate |
| *Tithonia diversifolia* | $LC_{15}$ (0.93) | 78.54 ± 3.73 | Moderate |
| | $LC_{35}$ (1.81) | 84.81 ± 1.30 | Strong |
| | $LC_{55}$ (3.06) | 87.22 ± 4.47 | Strong |
| *Annona squamosa* | $LC_{15}$ (0.04) | 38.49 ± 13.06 | Very weak |
| | $LC_{35}$ (0.10) | 46.35 ± 10.98 | Weak |
| | $LC_{55}$ (0.19) | 65.46 ± 2.44 | Moderate |
| *Annona muricata* | $LC_{15}$ (0.42) | 34.57 ± 4.12 | Very weak |
| | $LC_{35}$ (0.89) | 44.94 ± 3.90 | Weak |
| | $LC_{55}$ (1.59) | 53.86 ± 3.71 | Weak |

LC = lethal concentration; SE = standard error.

**Table 3**. Inhibition of *Spodoptera frugiperda* egg hatching by treatment with five plant extracts

| Plant extract | Concentration (%) | Ovicidal activity (%) ± SE | Criteria |
|---|---|---|---|
| *Piper aduncum* | $LC_{95}$ (0.70) | 87.62 ± 9.99 | Strong |
| | 2 x $LC_{95}$ (1.40) | 98.61 ± 0.70 | Strong |
| *Tagetes erecta* | $LC_{95}$ (2.67) | 57.55 ± 17.09 | Moderate |
| | 2 x $LC_{95}$ (5.34) | 91.64 ± 4.18 | Strong |
| *Tithonia diversifolia* | $LC_{95}$ (14.54) | 68.22 ± 11.95 | Moderate |
| | 2 x $LC_{95}$ (29.08) | 89.66 ± 4.56 | Strong |
| *Annona squamosa* | $LC_{95}$ (1.33) | 81.53 ± 11.89 | Strong |
| | 2 x $LC_{95}$ (2.66) | 92.69 ± 4.92 | Strong |
| *Annona muricata* | $LC_{95}$ (9.03) | 73.47 ± 7.46 | Moderate |
| | 2 x $LC_{95}$ (18.06) | 92.92 ± 1.55 | Strong |

LC = lethal concentration; SE = standard error.

*aduncum* and *A. muricata* showed relatively low antifeedant activity percentages, with inhibition criteria ranging from very weak to weak. In contrast, *A. squamosa* and *T. erecta* extracts showed higher antifeedant activity, particularly at higher concentrations, with moderate inhibition criteria. Although most extracts caused relatively weak feeding inhibition, the potential as antifeedants became stronger at higher concentrations. This shows that antifeedant activity increases with treatment concentration (Rohimatun *et al*., 2020). Several previous studies reported that increasing the test concentration significantly inhibited the feeding activity of *S. frugiperda* larvae. *P. aduncum* extract at the highest concentration (0.25%) showed strong antifeedant activity against second-instar *S. frugiperda* larvae, reaching 94.35% (Lina *et al*., 2023). Similarly, *A. squamosa* extract at the highest concentration (16%) also showed strong antifeedant activity, reaching 82.37% (Bhosle *et al*., 2024).

Among all the tested extracts, *T. diversifolia* showed the highest effectiveness in inhibiting the feeding activity of second-instar *S. frugiperda* larvae, with $LC_{35}$ and $LC_{55}$ concentrations treatments, reaching 84.81% and 87.22%, respectively (Table 2). The presence of antifeedant compounds influences the high feeding inhibition of *T. diversifolia* extract. Antifeedant compounds are chemical substances that inhibit or suppress insect feeding activity by affecting specific sensory receptors, leading to deterrent or suppressant effects on plant consumption (Purrington, 2017). Furthermore, Mossa (2016) explained that antifeedant compounds influence insect feeding behavior through peripheral sensilla, ultimately reducing food intake. A review by Kerebba *et al.* (2019) identified several antifeedant compounds present in *T. diversifolia*, including 6-methoxyapigenin, tagitinins (A, B, C, and F), diversiform, tirotundin, tithonine, sulphurein, hispidulin, and sesquiterpene lactones.

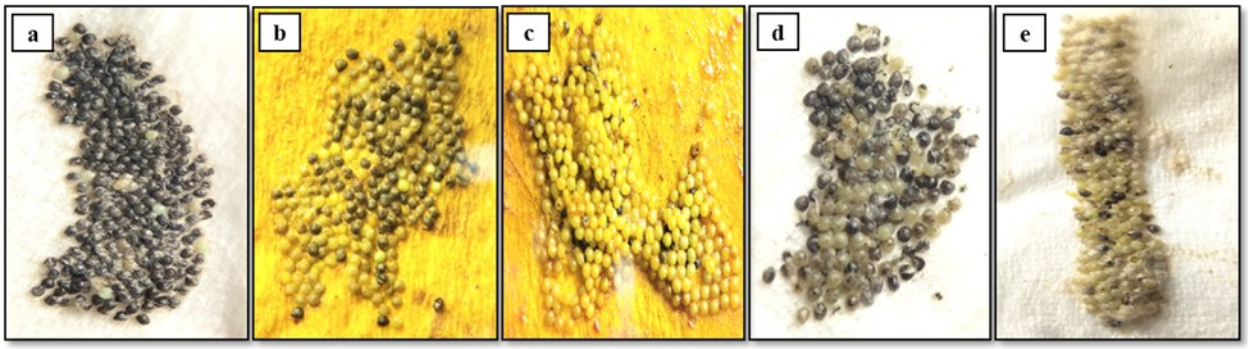


**Fig. 2.** *Ovicidal effects of the five plant extracts on Spodoptera frugiperda eggs at six days after treatment. a = Piper aduncum; b = Tagetes erecta; c = Tithonia diversifolia; d = Annona squamosa; e = Annona muricata.*

These results showed that *T. diversifolia* extract has potential as a candidate for botanical insecticide development despite the relatively lower toxicity compared to other plant extracts. Blessing *et al.* (2010) explained that plant extract with strong feeding inhibition activity can cause insects to gradually suffer mortality from starvation, thereby reducing feeding activity and minimizing damage to cultivated plants. Therefore, the use of botanical insecticides should not rely solely on toxicity, but also apply alternative approaches that effectively suppress insect activity, such as antifeedant compounds (Pavela *et al.*, 2025).

**Ovicidal effects of the extracts on *Spodoptera frugiperda* eggs**

Ovicidal activity of all tested plant extracts was in the strong category, particularly at a concentration of 2×$LC_{95}$ (Table 3). Extracts of *P. aduncum* and *A. squamosa* showed strong ovicidal activity at both tested concentrations. At $LC_{95}$, these two extracts had ovicidal percentages of 87.62% and 81.53%, respectively, which significantly increased to 98.61% and 92.69% at 2×$LC_{95}$. Meanwhile, extracts of *A. muricata*, *T. erecta*, and *T. diversifolia* showed moderate ovicidal activity at $LC_{95}$, with values of 73.47%, 57.55%, and 68.22%, respectively. At 2×$LC_{95}$, these three extracts showed a significant increase in effectiveness, falling into the strong category, with ovicidal percentages of 92.92%, 91.64%, and 89.66%, respectively. This increase showed that higher concentrations can enhance the ovicidal potential of plant extract, thereby improving the inhibition of egg development.

In general, all tested plant extracts were effective as ovicidal agents, inhibiting at least 75% of egg hatching, particularly at the 2×$LC_{95}$ concentration (Krinski *et al*., 2018). An ovicidal effect was demonstrated by the darkening of eggs, which failed to hatch beyond the normal incubation period (Bhosle *et al*., 2024) (Fig. 2). Russianzi *et al*. (2021) explained that *S. frugiperda* eggs generally hatch simultaneously within each egg group, occurring 2–3 days after oviposition. Meanwhile, observations showed that up to six days after treatment (DAT), most eggs did not hatch, and a few hatched within 2–3 DAT.

One of the causes of egg-hatching failure was the presence of essential oils (EOs) in the extract, which can suppress the respiratory rate. The ovicidal properties of EOs were due to their ability to block oxygen supply to the developing embryo or to the toxicity of specific chemical compounds, thereby inhibiting development and causing egg mortality (Riedl *et al*., 1995). Krinski *et al*. (2018) reported that several EOs from the Piperaceae, suspected to have bioactivity against *Anticarsia gemmatalis* eggs, were asaricine, myristicin, spathulenol, (E)-caryophyllene, germacrene B, dillapiol, (E)-ß-ocimene, limonene, (E)-nerolidol, piperitone, 1-epi-cubenol, cadalene, 4,6-dimethyl-5-vinyl-1,2-benzodioxide, eudesm-7(11)-en-4-ol, cyclocolorenone, α-copaene, (E, E)-α-farnesene, and allo-aromadendrene.

## Conclusion

All plant extracts showed varying effectiveness against *S. frugiperda*, depending on the type and concentration tested. Increasing the concentration was positively correlated with higher larval mortality as well as antifeedant and ovicidal activity. *P. aduncum* extract showed the highest toxicity, while *T. diversifolia* showed the strongest antifeedant activity. Furthermore, all extracts effectively acted as ovicidal agents, inhibiting more than 75% of egg hatching at the highest concentration (2×$LC_{95}$). *P. aduncum* was the most effective, due to its highest inhibition rate.

## Conflict of interest

The authors declare that they have no conflict of interest.

## REFERENCES

1. Agustini, M., Sartiami, D., & Dadang. (2024). Effectiveness of soursop leaves, yam bean seeds, and Javanese long pepper fruits extracts against larvae of fall armyworm (*Spodoptera frugiperda* (Smith)) (Lepidoptera: Noctuidae).

*Jurnal Entomologi Indonesia, 21*(3), 224-233. doi.org/10.5994/jei.21.3.224

2. Aprialty, A. S., Sjam, S., Dewi, V. S., & Agustina, Y. E. (2021). The synergy of *Calotropis gigantea* and *Cresscentia cujete* plant extract as an inhibitor of egg hatching and antifeedant against *Spodoptera frugiperda*. *IOP Conference Series: Earth and Environmental Science*, *807*, 022086. doi.org/10.1088/1755-1315/807/2/022086
3. Assunção, J. A. E. S., Machado, D. B., Felisberto, J. S., Chaves, D. S. A., Campos, D. R., Cid, Y. P., Sadgrove, N. J., Ramos, Y. J., & Moreira, D. L. (2024). Insecticidal activity of essential oils from *Piper aduncum* against *Ctenocephalides felis felis*: a promising approach for flea control. *Brazilian Journal of Veterinary Parasitology, 33*(3), e007624. doi.org/10.1590/S1984-29612024050
4. Baldin, E. L. P., Soares, M.C.E., Santana, A. S., Hunt, T. E., McMechan, J., Arango, A. M. V., & Louis, J. (2023). Efficacy of ethanolic seed extracts of *Annona* spp. against *Aphis glycines*. *Crop Protection, 170*, 106268. doi.org/10.1016/j.cropro.2023.106268
5. Bhosle, D., Thulasy, S., Thiyagarajan, E., Sankaran, S. P., Sampathrajan, V., & Kolanchi, P. (2024). Insecticidal activity and phytochemical profiling of *Annona squamosa* (L.) leaf extract against the fall armyworm, *Spodoptera frugiperda* (J.E. Smith). *Plant Science Today, 11(sp4)*, 1–8. doi.org/10.14719/pst.5770
6. Blessing, L. D. T., Colom, O. A., Popich, S., Neske, A., & Bardón, A. (2010). Antifeedant and toxic effects of acetogenins from *Annona montana* on *Spodoptera frugiperda*. *Journal of Pest Science, 83*, 307-310. doi.org/10.1007/s10340-010-0299-0
7. Boaventura, D., Martin, M., Pozzebon, A., Mota-Sanchez, D., & Nauen, R. (2020). Monitoring of target-site mutations conferring insecticide resistance in *Spodoptera frugiperda*. *Insects, 11*(8), 545. doi.org/10.3390/insects11080545
8. Chen, Y., Xu, S., Chen, J., Wang, Y., Xu, H., Fan, N., & Li, X. (2012). Anti-tumor activity of *Annona squamosa* seeds extract containing annonaceous acetogenin compounds. *Journal of Ethnopharmacology, 142*(2), 462-466. doi.org/10.1016/j.jep.2012.05.019
9. Dadang. (2023). Pengembangan insektisida nabati untuk pertanian. IPB Press, Bogor, Indonesia.
10. de Groote, H., Kimenju, S. C., Munyua, B., Palmas, S., Kassie, M., & Bruce, A. (2020). Spread and impact of fall armyworm (*Spodoptera frugiperda* J.E. Smith) in maize production areas of Kenya. *Agriculture, Ecosystems & Environment, 292*, 106804. doi.org/10.1016/j.agee.2019.106804
11. Durán-Ruiz, C. A., González-Esquinca, A. R., & de-la-Cruz-Chacón, I. (2024). Annonaceous acetogenins: A comparative analysis of insecticidal activity. *Revista Brasileira de Fruticultura, 46*, e-508. doi.org/10.1590/0100-29452024508
12. El-Wakeil, N. E. (2013). Botanical pesticides and their mode of action. *Gesunde Pflanzen, 65*(4), 125-149. doi.org/10.1007/s10343-013-0308-3
13. Fazolin, M., Monteiro, A. F. M., Bizzo, H. R., Gama, P. E., Viana, L. d. O., & Lima, M. É. C. d. (2022). Insecticidal activity of *Piper aduncum* oil: variation in dillapiole content and chemical and toxicological stability during storage. *Acta Amazonica, 52*(3), 179-188. doi.org/10.1590/1809-4392202102292
14. Fierascu, R. C., Fierascu, I. C., Dinu-Pirvu, C. E., Fierascu, I., & Paunescu, A. (2020). The application of essential oils as a next-generation of pesticides: Recent developments and future perspectives. *Zeitschrift fur Naturforschung. C, Journal of Biosciences, 75*(7-8), 183-204. doi.org/10.1515/znc-2019-0160
15. Firmansyah, E., Dadang., & Anwar, R. (2017). Insecticidal activity of extracts of *Tithonia diversifolia* (Hemsl.) A. Gray (Asteraceae) against the diamondback moth *Plutella xylostella* (L.) (Lepidoptera: Yponomeutidae). *Journal of Tropical Plant Pests and Diseases*, *17*(2), 185-193. doi.org/10.23960/j.hptt.217185-193
16. González-Coloma, A., Guadaño, A., de Inés, C., Martínez-Díaz, R., & Cortes, D. (2002). Selective action of acetogenin mitochondrial complex I inhibitors. *Zeitschrift fur Naturforschung. C, Journal of Biosciences*, *57*(11-12), 1028-1034. doi.org/10.1515/znc-2002-11-1213
17. Harrison, R. D., Thierfelder, C., Baudron, F., Chinwada, P., Midega, C., Schaffner, U., & van den Berg, J. (2019). Agro-ecological options for fall armyworm (*Spodoptera frugiperda* JE Smith) management: providing low-cost, smallholder friendly solutions to an invasive pest. *Journal of Environmental Management*, *243*, 318–330. doi.org/10.1016/j.jenvman.2019.05.011
18. Heviyanti, M., Dadang., Sartiami, D., Kusumah, R. Y. M., & Purwantiningsih. (2024). Joint action of the extract mixture of *Piper aduncum* and *Aglaia odorata* against *Plutella xylostella* (L.) (Lepidoptera: Plutellidae). *Journal of International Society for Southeast Asian Agricultural Sciences, 30*(2), 113-129.
19. Irwan, Z., Kamarudin, W. F. W., Korish, U. A. S. A., N A Z, Rusli, A. S., & Sallehuddin, S. (2021). Effectiveness of *Annona Squamosa* and *Annona Muricata* seed extract as ingredients in bio-pesticides spray. *IOP Conference Series: Materials Science and Engineering, 117*, 012007. doi.org/10.1088/1757-899X/1176/1/012007
20. Kerebba, N., Oyedeji, A. O., Byamukama, R., Kuria, S. K., & Oyedeji, O. O. (2019). Pesticidal activity of *Tithonia diversifolia* (Hemsl.) A. Gray and *Tephrosia Vogelii* (Hook f.); phytochemical isolation and characterization: a review. *South African Journal of Botany, 121*, 366-376. doi.org/10.1016/j.sajb.2018.11.024
21. Krinski, D., Foerster, L.A., & Deschamps, C. (2018). Ovicidal effect of the essential oils from 18 Brazilian Piper species: controlling *Anticarsia gemmatalis* (Lepidoptera, Erebidae) at the initial stage of development. *Acta Scientiarum. Agronomy, 40*(1), e35273. doi.org/10.4025/actasciagron.v40i1.35273
22. Kumela, T., Simiyu, J., Sisay, B., Likhayo, P., Mendesil, E., Gohole, L., & Tefera, T. (2018). Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm *(Spodoptera frugiperda)* in Ethiopia and Kenya. *International Journal of Pest Management, 65*(1), 1-9. doi.org/10.1080/09670874.2017.1423129
23. Lina, E. C., Hidayatullah, M. S., Nurbailis., Reflin, R., & Nelly, N. (2023). The activity of spiked pepper fruit essential oil against fall armyworm larvae. *IOP Conference Series: Earth and Environmental Science*, *1228*, 012001. doi.org/10.1088/1755-1315/1228/1/012001
24. Lira, E. C., Bolzan, A., Nascimento, A. R., Amaral, F. S.,

Kanno, R. H., Kaiser, I. S., & Omoto, C. (2020). Resistance of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) to spinetoram: inheritance and cross-resistance to spinosad. *Pest Management Science, 76*(8), 2674-2680. doi.org/10.1002/ps.5812

25. Lucena, D. C., Bertholdo-Vargas, L. R., Silva, W. C., Machado, A. F., Lopes, T. S., Moura, S., & Barros, N. M. (2017). Biological activity of *Piper aduncum* extract on *Anticarsia gemmatalis* (Hübner) (Lepidoptera: Erebidae) and *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae). *Anais da Academia Brasileira de Ciencias, 89* (3), 1869-1879. doi.org/10.1590/0001-3765201720170194
26. Machado, B. B., Oruê, J. P. M., Arruda, M. S., Santos, C. V., Sarath, D. S, Gonçalves, W. N., Silva, G. G., Pistori, H., Roel, A. R., & Rodrigues-Jr, J.F. (2016). BioLeaf: a professional mobile application to measure foliar damage caused by insect herbivory. *Computers and Electronics in Agriculture, 129*, 44-55. doi.org/10.1016/j.compag.2016.09.007
27. Maharani, Y., Dewi, V. K., Puspasari, L. T., Rizkie, L., Hidayat, Y., & Dono, D. (2019). Cases of fall armyworm *Spodoptera frugiperda* J. E. Smith (Lepidoptera: Noctuidae) attack on maize in Bandung, Garut, and Sumedang District, West Java. *Cropsaver: Jurnal of Plant Protection, 2*(1), 38-46. doi.org/10.24198/cropsaver.v2i1.23013
28. Morais, V. P., Cabral, F. V., Fernandes, C. C., & Miranda, M. L. D. (2023). Brief review on *Piper aduncum* L., its bioactive metabolites and its potential to develop bioproducts. *Brazilian Archives of Biology and Technology*, *66*(3), e23220314. doi.org/10.1590/1678-4324-2023220314
29. Mossa, A. H. (2016). Green pesticides: Essential oils as biopesticides in insect-pest management. *Journal of Environmental Science and Technology, 9*(5), 354–378. doi.org/10.3923/jest.2016.354.378
30. Nenotek, P. S., Londingkene, J. A., Ludji, R., Harini, T. S., Kapa, M. J., Nguru, E. S. O., Roefaida, E., & Konanin, M. (2022). The toxicity of *Annona squamosa* seeds and *Anacardium occidentale* seed shells from East Nusa Tenggara, Indonesia, against cabbage caterpillar *(Crocidolomia pavonana). International Journal of Tropical Drylands, 6* (1), 39-44. doi.org/10.13057/tropdrylands/t060105
31. Ningrum, P. T., Ekaningrum, Y., & Pujiati, R. S. (2023). Soursop leaf extract (*Annona muricata* L) as a biochemical pesticide against fruit flies (*Bactrocera* sp). *Pharmacy Education*, *23*(4), 99-104. doi.org/10.46542/pe.2023.234.99104
32. Nuryanti, N. S. P., Martono, E., Ratna, E. S., & Dadang. (2018). The bioactivities of selected Piperaceae and Asteraceae plant extracts against brown plant hopper (*Nilaparvata lugens* Stål.). *Journal of International Society for Southeast Asian Agricultural Sciences, 24*(2), 70-78.
33. Oszmiański, J., Lachowicz, S., Gorzelany, J., & Matłok, N. (2018). The effect of different maturity stages on phytochemical composition and antioxidant capacity of cranberry cultivars. *European Food Research & Technology*, *244* (4), 705–719. doi.org/10.1007/s00217-017-2994-z
34. Pavela, R., Kovaříková, K., & Novák, M. (2025). Botanical antifeedants: An alternative approach to pest control. *Insects, 16*, 136. doi.org/10.3390/insects16020136
35. Prijono, D., Wulan, R. D. R., Ferdi, F., & Saryanah, N. A. (2020). Insecticidal activity of the extract of *Piper retrofractum* fruit and *Tephrosia vogelii* leaf and their mixtures against *Crocidolomia pavonana*. *Cropsaver: Journal of Plant Protection, 3*(2), 68-75. doi.org/10.24198/cropsaver.v3i2.31305
36. Pumnuan, J., Namee, D., Sarapothong, K., Doungnapa, T., Phutphat, S., Pattamadilok, C., & Thipmanee, K. (2022). Insecticidal activities of long pepper *(Piper retrofractum* Vahl) fruit extract against seed beetles (*Callosobruchus maculatus* Fabricius, *Callosobruchus chinensis* Linnaeus, and *Sitophilus zeamais* Motschulsky) and their effects on seed germination. *Heliyon, 8*(12), e12589. doi.org/10.1016/j.heliyon.2022.e12589
37. Purrington, C. B. (2017). Antifeedant substances in plants. *Encyclopedia of Applied Plant Sciences (Second Edition), 2,* 364–367. doi.org/10.1016/B978-0-12-394807-6.00068-X
38. Raya, K. B., Ahmad, S. H., Farhana, S. F., Mohammad, M., Tajidin, N. E., & Parvez, A. (2015). Changes in phytochemical contents in different parts of *Clinacanthus nutans* (Burm. f.) lindau due to storage duration. *Bragantia, 74*(4), 445-452. doi.org/10.1590/1678-4499.0469
39. Riedl, H., Halaj, J., Kreowski, W. B., Hilton, R. J., & Westigard, P. H. (1995). Laboratory evaluation of mineral oils for control of codling moth (Lepidoptera: Tortricidae). *Journal of Economic Entomology, 88*(1), 140–147. doi.org/10.1093/jee/88.1.140
40. Rohimatun., Yuliani, S., Winasa, I. W., & Dadang. (2020). Efficacy of selected Piperaceae, Asteraceae, and Zingiberaceae plant extract against *Helopeltis antonii* Sign. *Journal of International Society for Southeast Asian Agricultural Sciences, 26*(2), 145-157.
41. Russianzi, W., Anwar, R., & Triwidodo, H. (2021). Biostatistics of fall armyworm *Spodoptera frugiperda* in maize plants in Bogor, West Java, Indonesia. *Biodiversitas*, *22* (6), 3463-3469. doi.org/10.13057/biodiv/d220655.
42. Sartiami, D., Dadang, D., Harahap, I. S., Kusumah, Y. M., & Anwar, R. (2020). First record of fall armyworm *(Spodoptera frugiperda)* in Indonesia and its occurrence in three provinces. *IOP Conference Series: Earth and Environmental Science*, *468*, 012021. doi.org/10.1088/1755-1315/468/1/012021
43. Sianturi, Y. P. P. A., Dadang., & Sartiami, D. (2022). Bioactivity of extract from *Syzygium aromaticum, Annona muricata*, and *Piper retrofractum* against *Spodoptera frugiperda* J. E. Smith (Lepidoptera: Noctuidae). *IOP Conference Series: Earth and Environmental Science, 1083*, 012075. doi.org/10.1088/1755-1315/1083/1/012075
44. Shiragave, P. (2018). Effect of leaf and seed extract of custard apple (*Annona squamosa* L.) on ovicidal activity against *Spodoptera litura* F. *Journal of Entomology and Zoology Studies*, *6*(6), 1196–1198.
45. Tipsut, N., Kumrungsee, N., Pimsawang, L., Changkeb, V., Pluempanupat, W., Chaisan, T., & Bullangpoti, V. (2025). Extraction solvents and geographical origins of *Piper retrofractum* on the control efficiency of *Spodoptera litura* and *Spodoptera frugiperda* in laboratory and greenhouse conditions. *Journal of Natural Pesticide Research, 11,* 100112. doi.org/10.1016/j.napere.2025.100112
46. Trisyono, Y. A., Suputa, S., Aryuwandari, V. E. F., Hartaman, M., & Jumari, J. (2019). Occurrence of heavy infestation by the fall armyworm *Spodoptera frugiperda*, a new alien invasive pest, in corn Lampung Indonesia. *Jurnal Perlindungan Tanaman Indonesia, 23*(1), 156-160.

doi.org/10.22146/jpti.46455

47. Vetal, D. S., & Pardeshi, A. B. (2019). Insecticidal potential of ethanol and hexane solvent seed extract of *Annona squamosa* against *Spodoptera litura* Fab. *Journal of Pharmacognosy and Phytochemistry, 8*(3), 842-845.
48. Wanna, R., Bunphan, D., & Wongsawas, M. (2023). Chemical composition and bioactivity of essential oils from *Piper nigrum* L. and *Piper retrofractum* Vahl. against *Callosobruchus maculatus* (F.). *Australian Journal of Crop Science, 17*(8), 664–670. doi.org/10.21475/ajcs.23.17.08.p3940
49. Widayani, N., Dono, D., Hidayat, Y., Ishmayana, S., & Syahputra, E. (2023). Toxicity of *Calophyllum soulattri, Piper aduncum, Sesamum indicum* and their potential mixture for control *Spodoptera frugiperda*. *Open Agriculture*, *8*(1), 20220213. doi.org/10.1515/opag-2022-0213
50. Xiang, C. P., Shi, Y. N., Liu, F. F., Li, H. Z., Zhang, Y. J., Yang, C. R., & Xu, M. (2016). A survey of the chemical compounds of *Piper* spp. (Piperaceae) and their biological activities. *Natural Product Communications, 11*(9), 1403–1408. doi.org/10.1177/1934578X1601100948
51. Yabunaka, H., Abe, M., Kenmochi, A., Hamada, T., Nishioka, T., & Miyoshi, H. (2003). Synthesis and inhibitory activity of ubiquinone-acetogenin hybrid inhibitor with bovine mitochondrial complex I. *Bioorganic & Medicinal Chemistry Letters, 13*(14), 2385-2388. doi.org/10.1016/s0960-894x(03)00439-6.