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Bio-efficacy of Indigenous Weed-Derived Botanical Insecticides Against Fall Armyworm (FAW) *Spodoptera frugiperda* (J.E. Smith) (*Lepidoptera: Noctuidae)*

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ABSTRACT

The present study investigates the insecticidal properties and chemical composition of three native Philippine weeds, *Lantana camara*, *Chromolaena odorata*, and *Hyptis suaveolens* against *Spodoptera frugiperda*, a critical pest in maize cultivation. Through controlled lab bioassays, the effects of botanical extracts on larval mortality, pupation, and adult emergence were assessed. Phytochemical tests confirmed the presence of key bioactive substances, including flavonoids, phenols, tannins, and terpenoids, while saponins were notably absent in *H. suaveolens*. Using probit analysis, both LC_{50} and LT_{50} values were calculated. Among treatments, *L. camara* exhibited the most potent insecticidal effects, outperforming other botanicals in mortality and developmental disruption metrics. While cypermethrin remained most effective overall, findings suggest *L. camara* could be a practical, eco-friendly alternative. Further research should explore field applications and advanced formulations for sustainable pest control strategies.

Keywords: *Botanical insecticide; Mortality; LC_{50}; LT_{50}; Spodoptera frugiperda; Phytochemical screening*

INTRODUCTION

Maize is essential in the Philippines, serving as both a staple food and a primary ingredient in livestock feed, thus playing a crucial role in national food security and rural livelihoods. In recent years, however, several challenges, including climate variability and pest outbreak have contributed to a notable reduction in national rice maize yield (PSA, 2024). One of the most serious threats to production is the fall armyworm, *Spodoptera frugiperda,* an invasive species responsible for large-scale crop damage and economic loss across Asia and Africa. Annual yield losses are estimated at around 18 million tons, resulting in economic damage exceeding $13 million (De Groote et al., 2020).

Chemical insecticides are commonly used to control this pest, their continued use has brought environmental concerns and pest resistance into focus (Ratnakala et al., 2023). To address these ongoing issues, plant-based insecticide has merged as promising alternative solutions, valued for their selective toxicity and environmental compatibility (Abagli & Alavo, 2011; Acero, 2017; Duza et al., 2019; Sisay et al., 2019;). However, research on the insecticidal potential of locally abundant weed species in the Philippines remains limited. Most investigations have focused on introduced or cultivated species, leaving a significant gap in the exploration of indigenous flora.

This study aims to address this research gap by evaluating the insecticidal potential and phytochemical profiles of three commonly occurring weeds in the Philippines. These plants, often regarded as invasive or nuisance species, may offer an untapped source of bioactive compounds suitable for pest control. By assessing their efficacy against *S. frugiperda*, this study seeks to identify natural alternatives that are both locally accessible and environmentally sustainable, thereby reducing dependence on synthetic insecticides and contributing to integrated pest management strategies in maize production systems. Through this research, the study will contribute valuable insights toward the development of indigenous plant-based pest control solutions for sustainable agriculture in the Philippines.

Objectives of the Study

This study aims to assess the insecticidal efficacy and phytochemical composition of *Lantana camara*, *Chromolaena odorata*, and *Hyptis suaveolens* ethanolic extracts against *Spodoptera frugiperda* under controlled laboratory conditions, and to compare their effectiveness with selected synthetic insecticides. Specifically, the study seeks to identify the phytochemical constituents present in the botanical extracts; evaluate larval mortality of *S. frugiperda* at various time intervals (6 to 72 hours) following treatment; determine the median lethal concentration (LC_{50}) and median lethal time (LT_{50}) of each extract; and compare the insecticidal performance of the botanicals with commercial insecticides based on mortality rates, pupation, and adult emergence.

MATERIALS AND METHODS

Materials

The study utilized *Lantana camara*, *Chromolaena odorata*, *Hyptis suaveolens*, and maize (*Sweet Corn* variety) for extract preparation and feeding trials. Distilled water was used for soaking powdered plant materials. Third instar *Spodoptera frugiperda* larvae were maintained in an aerated plastic enclosures and storage boxes (4×15×21 cm) with absorbent paper place at the base. For bioassays, ventilated plastic cups were used for LC_{50} and LT_{50} tests, along with Petri dishes (35 mm), Whatman No. 1 filter paper, Parafilm, sterile cotton, wire mesh lids, and cheesecloth for filtration. Extract preparation required trays, pestle and mortar, and a digital weighing scale. Data were recorded using data sheets and analyzed using SPSS and PoloPlus 2.0. Safety and disposal materials included gloves, alcohol, pipettes, sealed containers, and waste bags. Terminated larvae were frozen at –20°C before incineration.

Area Description

Experimental trials/bioassay were conducted at the Insectary of the Crop Protection Laboratory, Old Building, CA, Cagayan State University, Piat Campus. The laboratory is situated at approximately 17.7885° N latitude and 121.4773° E longitude, within the municipality of Piat, Cagayan.

Corn as feed materials

Maize (*sweet corn* variety) was grown in pots at the Crop Protection Nursery, with two seeds sown per pot and thinned to a single healthy seeding two weeks after emergence. Vegetative-stage leaves were collected and used as a food source for the insect specimens.

Sourcing of Indigenous Weeds

Three indigenous weed species—*Lantana camara*, *Chromolaena odorata*, and *Hyptis suaveolens*—were selected based on their reported insecticidal properties. These were collected from CSU–Piat Integrated Farm and maintained in the Crop Protection Nursery. Morphological features such as growth habit and leaf structure were documented. Collected samples were later subjected to phytochemical screening to identify bioactive compounds contributing to their insecticidal potential.

Phytochemical Screening methods

All botanical extracts were submitted to the Bioanalytical Laboratory of CSU–Andrews Campus, Tuguegarao City, for phytochemical assay, Alkaline Reagents test for Alkaloids, the method described by Muñoz et al (2021) for coumarins, the Shido Test for Flavonoids, the ferric Chloride Test for Phenols, the Froth test for Saponins, the Liebermann-Burchard Test for steroids, Braymer's Test for Tannins, and the Salkowski Test for Terpenoids. The analysis did not involve quantification of their concentration.

FAW Insect colony

The starter colony approximately 100 fourth instar larvae of fall armyworm (FAW) was collected from the cornfield of Baung, Piat, Cagayan. Each larva was kept individually in aerated plastic jar to prevent cannibalism and was provided a natural diet consisting of sweet corn leaves 15–30-day-old. Once the larvae reached the pupal stage, they were transferred to moistened Petri dishes inside modified oviposition cages containing corn plants. After 2 to 3 days, egg masses were carefully collected from the modified oviposition cages and transferred into sterile plastic containers. The eggs were observed until hatching, and upon emergence of the first- instar larvae, they were fed with fresh and young maize leaves as their food source. FAW larvae were reared in transparent conical plastic container measuring 11 cm x 8.5 cm x 5.5 cm, the containers were lined with tissue paper, and each larva was provided with minimum of 2 grams of maize leaves as food source. Rearing was done at room temperature (24–26 °C) and 81±13% relative humidity (RH). Larvae from the second laboratory- reared generation were utilized for the experiment.

Preparation and Extraction of Bio-insecticides

Leaves of *Lantana camara*, *Chromolaena odorata*, and *Hyptis suaveolens* were air-dried separately under sunlight and ground into fine powders. Each botanical powder was soaked in distilled water at a concentration of 400 g/L. This rate was based on existing literature for *L. camara*, and similarly applied to *C. odorata* and *H. suaveolens* due to the lack of established concentrations. The mixtures were soaked for 24 hours, filtered through cheesecloth, and the resulting extracts were stored for seven days prior to use in bioassays.

Bioassay of Botanicals Against FAW

Fresh maize leaves (60g), collected from 30–45 days after planting (DAP) maize plants at the Crop Protection Nursery, were cut into 4–5 pieces (3–5 cm length each) and placed in plastic containers. Based on Sisay et al. (2019), 60 g of maize leaves can sustain about 10–15 larvae for 2–3 days. For each treatment, 20 mL of botanical extract was mixed with 80 mL of water to obtained a 100ml working solution. The maize leaf was soaked in the diluted extract for 10 minutes, then air-dried on plastic trays for 15 minutes to remove excess moisture. Control leaves were soaked in sterile distilled water following the same procedure. Each treated leaf was placed into individual ventilated cups containing 10 fourth-instar *S. frugiperda* larvae. Treatments were replicated three times, totaling 30 larvae per treatment. Larvae were observed at 6, 12, 24-, 36-, 48-, and 72-hours post-exposure, and mortality along with other parameters were recorded.

Experimental Treatments

The experiment followed a Completely Randomized Design (CRD) with three replicates per treatment. Larvae were provided with natural diets as their food source, which were replaced every other day or sooner if largely consumed. The bioassay was conducted in three trials, to ensure reliability of the results. Observation on the larval mortality were made at 6, 12, 24, 36, 48, and 72 hours after treatment application.

The following treatments were used in this study.

Treatments	Description	Active Ingredient
Treatment 1	**No Application**	**Distilled Water**
Treatment 2	**Commercial Insecticide**	**Carbonsulfan**
Treatment 3	**Devil Weed (*Chromolaena Odorata*)**	**Phyto-complex**
Treatment 4	**Bush Mint (*Hypis Suaveolens*)**	**Phyto-complex**
Treatment 5	**Lantana (*Lantana camara*)**	**Phyto-complex**

Note: 20 mL of botanical extract was mixed with 80 mL of water to obtained a 100mL working solution

Phytochemical Screening

Phytochemical screening of *Lantana camara, Chromolaena odorata,* and *Hyptis suaveolens* extracts was conducted at the Bioanalytical Laboratory, CSU-Andres Campus, Tuguegarao City. For the phytochemical assay, Alkaline Reagents test for Alkaloids, the method described by Muñoz et al (2021) for coumarins, the Shido Test for Flavonoids, the ferric Chloride Test for Phenols, the Froth test for Saponins, the Liebermann-Burchard Test for steroids, Braymer's Test for Tannins, and the Salkowski Test for Terpenoids. These tests confirmed the presence of phytochemicals relevant to insecticidal activity.

Percentage Mortality

The larval mortality was monitored at 6, 12, 24, 36, 48 and 72 hours after the treatment introduction. There were 10 larvae per treatment, and each treatment was replicated three times. A total of 150 larvae were used for all the treatments. Cumulative larval mortality was calculated by dividing the total number of dead larvae at each observation point by the total number treated larvae, then multiplying by 100. A larva was considered dead if it failed itself when placed on its dorsal side (Sisay et al. 2019). Larval survival was recorded for three (3) consecutive days. When there was natural mortality among the controls, the mortalities were corrected by using Abbott's formula (Finch, 2014).

$$Corrected\ Mortality\ (\%) = \frac{Mortality\ in_{\ Treatment} - Mort.in\ Control}{100 - Mort.in\ Control}\ x\ 100$$

Median lethal concentration (LC_{50})

Toxicity test to estimate the median lethal concentration (LC_{50}) were conducted using sterile containers lined with Whatman No. 1 filter paper. *S. frugiperda* larvae were individually introduced into each container. Values were calculated based on three independent trials, each consisting of ten larvae per treatment. A control group was included in each trial, treated only with distilled water. The LC_{50} of *Lantana camara, Chromolaena odorata*, and *Hyptis suaveolens* were determined by exposing larvae to a range of concentration as follows:

Table 1. Concentrations of insecticides and weed derived botanicals.

Percentage concentration	Concentration (g/ml)			mg/L
	Chromolaena odorata	*Hyptis suaveolens*	*Lantana Camara*	Cypermethrin
0	0	0	0	0
10%	2ml	2ml	2ml	28.3μL
25%	4ml	4ml	4ml	56.26μL
100%	20ml	20ml	20ml	281.3μL
50%	10ml	10ml	10ml	140.65μL
75%	15ml	15ml	15ml	210.94μL

Median lethal time (LT_{50}) estimation

The medial lethal time (LT_{50}) experiment was conducted using 35mm Petri dish lined with Whatman No. 1 filter paper. Larvae were observed at 5- hours intervals over a span of 72 hours to monitor mortality. Treatment was tested in three independent replicates, with 10 larvae used per treatments. Sterile distilled water was applied in the control.

Statistical Analysis

Data on mortality, pupation, and adult emergence were analyzed using one-way Analysis of Variance (ANOVA) through STAR software (IRRI, 2014) at a 5% level of significance. Treatment means were compared using the Least Significant Difference (LSD) test at 0.05 significance level. Mortality data were corrected using Abbott's formula (Abbott, 1925) and analyzed under a Completely Randomized Design (CRD). Median Lethal concentration (LC_{50}) and time (LT_{50}) values were computed through Probit analysis using PoloPlus version 2.0 software (LeOra Software LLC). Statistical significance between LC_{50} and LT_{50} estimates was evaluated by comparing 95% fiducial limits, with non- overlapping intervals indicating significant differences.

Ethics Disposal

All surviving insect pests, including those in the control and treatment groups, will be terminated to prevent environmental contamination or unintended release. Larvae will be placed in sealed containers and subjected to freezing at -20°C for 24 hours to ensure complete immobilization. Following this, the insect remains will be disposed of through incineration in accordance with institutional and local guidelines for biological waste management. This approach ensures proper handling and disposal of test organisms while maintaining research integrity.

RESULTS

A. *Phytochemical Screening of Selected Weed-Derived Botanical Insecticides*

Table 2. Phytochemical Screening of Weed-Derived Botanicals and Their Corresponding Bioactive Compounds

Treatments	Bioactive compounds			
	Anthocyanin	Coumarins	Flavonoids	Phenols
L. camara	(+)	(+)	(+)	(+)
H. suaveolens	(+)	(+)	(+)	(+)
C. odorata	(+)	(+)	(+)	(+)
Treatments	Bioactive compounds			
	Saponins	Steroids	Tannins	Terpenoids
L. camara	(+)	(+)	(+)	(+)
H. suaveolens	(-)	(+)	(+)	(+)
C. odorata	(+)	(+)	(+)	(+)

Phytochemical screening of *Lantana camara*, *Chromolaena odorata*, and *Hyptis suaveolens* confirmed the presence of bioactive compounds across all three botanicals, which are widely associated with insecticidal activity. However, saponins were not detected in *H. suaveolens*, potentially explaining its lower insecticidal efficacy.

B. *Larval Mortality of Spodoptera frugiperda at 48 Hours Post-Treatment with Botanical and Synthetic Insecticides.*

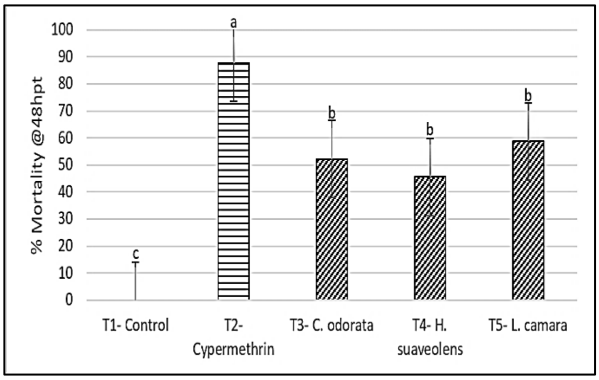

Fig.1. Mortality of *Spodoptera frugiperda* at 48 hours post-treatment (hpt) with weed-derived botanical and synthetic insecticides. Bars represent mean ± standard error (n=3); different letters represent significant differences at $p < 0.05$ using LSD.

In term of larval mortality at 48 hours post-treatment revealed that synthetic insecticide Cypermethrin (T_2) showed the highest mortality rate (87.77%), significantly outperforming both the control and botanical treatments.

Among the botanicals, *Lantana camara* (T_5) caused the highest mortality (58.57%), followed by *Chromolaena odorata* (T_3) and *Hyptis suaveolens* (T_4), which showed comparable but lower mortality rates (52.23% and 45.57%, respectively).

C. *Larval Mortality of Spodoptera frugiperda at 72 Hours Post-Treatment with Botanical and Synthetic Insecticides.*

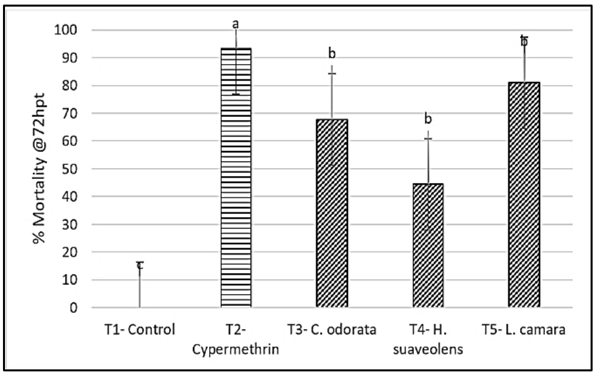

Fig. 2. Mortality of *Spodoptera frugiperda* at 72 hours post-treatment (hpt) with weed-derived botanical and synthetic insecticides.

Data are presented as the mean ± standard error based on three replicates (n = 3). Treatments marked with different letters indicate statistically significant differences at the 5% probability level, as determined by the Least Significant Difference (LSD) test.

The mortality rates of *Spodoptera frugiperda* larvae at 72 hours post-treatment using weed-derived botanicals and a synthetic insecticide. Among all treatments, Cypermethrin (T_2) demonstrated the highest larval mortality at 94%, significantly surpassing all other treatments ($p < 0.05$). Among the botanical extracts, *Lantana camara* (T_5) recorded the highest mortality at 87%, followed by *Chromolaena odorata* (T_3) with 68%, and *Hyptis suaveolens* (T_4) with 45%, the control group (T_1) consistently showed no mortality. Statistical analysis using ANOVA and the Least Significant Difference (LSD) test confirmed that all treatments were significantly different from the control ($p < 0.05$). Cypermethrin (T_2) also differed significantly from all botanical treatments, confirming its superior synthetic efficacy. Although not statistically equivalent to T_2, *L. camara* (T_5) exhibited mortality rates high enough to suggest comparable potential as a botanical insecticide.

D. *Comparative Pupation Rates of Spodoptera frugiperda treated with Weed-Derived Botanicals and Synthetic Insecticides at 72 Hours Post-Treatment*

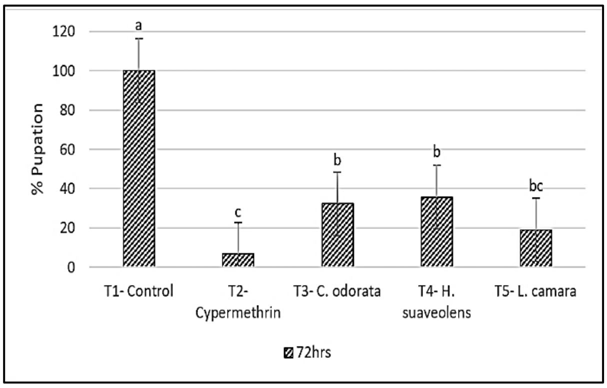

Fig. 3. Comparative pupation of *Spodoptera frugiperda* treated with weed-derived botanical and synthetic insecticides. .

Data are presented as the mean ± standard error based on three replicates (n = 3). Treatments marked with different letters indicate statistically significant differences at the 5% probability level, as determined by the Least Significant Difference (LSD) test.

The results demonstrated that all insecticide treatments significantly reduced the pupation rate of *Spodoptera frugiperda* compared to the untreated control (Figure 3), where nearly all larvae successfully pupated, indicating uninhibited development. Among treatments, Cypermethrin (T_2) was the most effective, reducing pupation to 6.67% consistent with its well-documented rapid neurotoxic action (Alam et al., 2019). Among the botanical insecticides, *Lantana camara* (T_5) exhibited the strongest inhibitory effect on pupation, reducing it to 18.9%, while *Chromolaena odorata* (T_3) and *Hyptis suaveolens* (T_4) showed moderate reductions, with pupation rates of 32.23–35.57%.

E. Comparative Effects of Weed-Derived Botanicals and Synthetic Insecticides on Adult Emergence of Spodoptera frugiperda.

Adult emergence of *Spodoptera frugiperda* was markedly influenced by both synthetic and botanical insecticide treatments (Figure 4). The untreated control (T_1) exhibited the highest adult emergence rate, with approximately 95.57% of larvae successfully maturing to adults. In contrast, Cypermethrin (T_2) significantly suppressed adult emergence to below 5.57%, reflecting its potent neurotoxic effects and disruption of larval development. Among the botanical treatments, *Lantana camara* (T_5) demonstrated the most pronounced inhibitory effect on adult emergence (16.67%), outperforming *Chromolaena odorata* (T_3) and *Hyptis suaveolens* (T_4), which showed moderate reductions with emergence rates of approximately 25.57% to 33.33%.

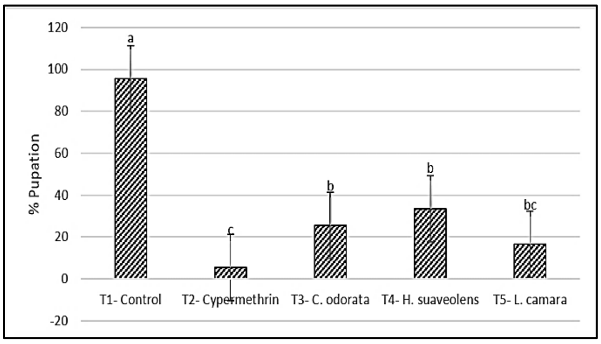

Fig. 4. Comparative adult emergence of *Spodoptera frugiperda* treated with weed-derived botanical and synthetic insecticides.

Data are presented as the mean ± standard error based on three replicates (n = 3). Treatments marked with different letters indicate statistically significant differences at the 5% probability level, as determined by the Least Significant Difference (LSD) test.

F. Lethal Concentration (LC_{50}) Estimation of Weed-Derived Botanicals and Synthetic Insecticides Against Spodoptera frugiperda.

The LC_{50} values presented in Table 3 demonstrate significant variation in the acute toxicity profiles, measured in terms of % (v/v), of both synthetic and botanical treatments against *Spodoptera frugiperda* under controlled laboratory conditions. Among the tested treatments, Cypermethrin (T_2) recorded the lowest LC_{50} value at 16.15% (v/v), showing its superior toxic potency, as it required the smallest concentration by volume to induce 50% larval mortality. This value, supported by non-overlapping 95% fiducial limits compared to botanical treatments, confirms the statistical significance of its higher efficacy. In contrast, the botanical treatments exhibited higher LC_{50} values, indicating relatively lower toxic activity. *Lantana camara* (T_5) achieved the lowest LC_{50} among the botanicals at 29.21% (v/v), followed by *Hyptis suaveolens* (T_4) at 33.08% (v/v) and *Chromolaena odorata* (T_3) at 37.25% (v/v). Although these values indicate varying degrees of efficacy, the overlapping fiducial limits suggest that differences among the botanical extracts are not statistically significant at the 95% confidence level, implying a comparable toxicological response.

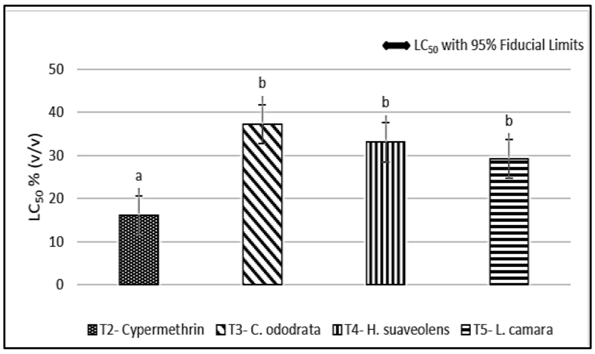

Fig 5. LC_{50} (%) of Synthetic and Botanical Treatments Against *Spodoptera frugiperda* Larvae

G. Lethal Time (LT_{50}) Analysis and Toxicodynamic Interpretation of Weed-Derived Botanicals and Synthetic Insecticides Against Spodoptera frugiperda.

The LT_{50} values summarized in Table 4 demonstrate clear variation in the temporal dynamics of insecticidal activity among the tested treatments against *Spodoptera frugiperda* larvae. Cypermethrin (T_2) exhibited the shortest LT_{50} at 24.18 hours, indicating the fastest toxic effect. This rapid action is consistent with the neurotoxic mode of action of pyrethroids, which disrupt sodium ion channel regulation, leading to quick immobilization and mortality in target pests.

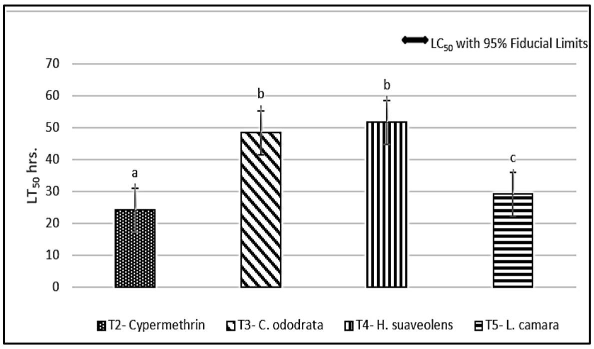

Fig 6. LT_{50} (Hours) of Synthetic and Botanical Insecticides Against *Spodoptera frugiperda* Larvae

In contrast, the botanical treatments exhibited slower toxic responses, as evidenced by their higher LT_{50} values. *Lantana camara* (T_5) recorded an LT_{50} of 39.46 hours, followed by *Chromolaena odorata* (T_3) at 48.44 hours, and *Hyptis suaveolens* (T_4) at 51.73 hours. The difference in LT_{50} values suggests that while all botanical extracts possess lethal properties, their insecticidal activity requires longer exposure times to achieve 50% mortality.

The 95% fiducial limits provide insight into the statistical difference among treatments. Cypermethrin's fiducial limits (21.87–26.39 h) did not overlap with those of the botanical treatments, indicating a statistically faster action. Among botanicals, *L. camara* had fiducial limits (36.63–42.42 h) that were clearly lower than those of *C. odorata* (44.16–53.82 h) and *H. suaveolens* (46.21–59.40 h), suggesting significantly faster toxicological action compared to the latter two. However, the overlapping confidence intervals between *C. odorata* and *H. suaveolens* suggest no significant difference between their LT_{50} values.

DISCUSSION

This study assessed the insecticidal potential of aqueous leaf extracts from *Lantana camara*, *Chromolaena odorata*, and *Hyptis suaveolens* in managing *Spodoptera frugiperda*, with Cypermethrin serving as the synthetic insecticide standard. The main findings revealed that *L. camara* demonstrated the highest bio-efficacy among the botanicals in reducing larval survival, pupation, and adult emergence, although Cypermethrin remained superior in overall effect. The phytochemical screening revealed that all three-plant extract contained bioactive compounds known for their insecticidal properties, such as flavonoids, tannins, and terpenoids (Alam et al. 2019). Among treatments, *L. camara* exhibited the most comprehensive and varied composition, which also included saponins.

The observed effects of *L. camara* and *C. odorata* indicate their potential usefulness as botanical tools in pest control (Ayalew et al. 2020).These plants could offer an affordable and locally available solution for farmers. More than just comparing effectiveness, the result point to practical applications in farming systems where access to commercial insecticides is limited or discouraged. The potential of commonly available weeds to serve as low-cost, sustainable pest control options could reduce dependence on synthetic insecticides. This is especially relevant in integrated pest management (IPM) systems where resistance, environmental contamination, and non-target effects are growing concerns. Promoting these plant-based solutions could enhance local bioresource utilization and support more resilient farming practices.

The significant of this study is its focus on locally available botanicals that are typically considered problematic weeds. Transforming these into pest management resources supports circular, low-input agricultural systems. Additionally, the integration of phytochemical profiling and bioassay evaluation offers a holistic perspective on the mode of action and efficacy. However, the study also has limitations. Laboratory conditions do not fully replicate field environments, where factors such as UV degradation, rain, and pest behavior may influence botanical efficacy. Also, crude aqueous extracts may vary in potency due to plant age, collection time, and environmental factors, which were not standardized in this trial. Further investigation under semi-field or field conditions, with refined formulations or concentrations, would strengthen practical applicability. In summary, while synthetic insecticides like Cypermethrin remain highly effective, *L. camara* and *C. odorata* show encouraging potential as botanical alternatives. Their use could contribute meaningfully to sustainable pest management efforts, particularly where chemical inputs are limited or undesirable.

CONCLUSIONS

Based on the results, the *Lantana camara* emerged as the most promising botanical insecticides among the tested species, demonstrating significant effects on all development stages of *S. frugiperda*. Although synthetic insecticides still outperform in rapid action, *L. camara* provides a more sustainable and locally accessible option. Its potential for integration into pest management systems, further field testing and product development.

RECOMMENDATIONS

It is recommended to further explore *Lantana camara* for field- level management, especially in areas facing pesticide resistance. Future research should focus on optimizing extract concentration, improving formulation methods and conducting greenhouse and field trials to validate laboratory findings. Additionally, economic viability should be assessed through cost- benefit analysis to determine scalability and farmers adoption potential. Studies should also quantify the active compounds responsible for insecticidal effects using advanced phytochemical techniques such HPLC, and GC-MS).

Verification of extract consistency and formulation standardization should be prioritized to ensure efficacy and safety. Furthermore, potential impacts on non-target organisms such as pollinators and beneficial predators must be evaluated to ensure ecological safety. The intervention's alignment with organic production standard should also be assessed to support certification and potential inclusion in organic- integrated pest management (IPM) system. Finally, training programs for farmers and agricultural technicians should be developed to promote proper extraction, handling, and application of botanical insecticides, enhancing their practical use and sustainability.

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DECLARATION

For language and Readability Enhancement, like grammar and style, authors utilized AI tools. https://chatgpt.com/c/7ba8a29b-6f6a-42d6-93fe-b2dea89f80b3.

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