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Evaluations of Neem (*Azadirachta indica*) Extracts for the Management of Fall Armyworm (*Spodoptera frugiperda*) in Maize

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ABSTRACT

The fall armyworm (*Spodoptera frugiperda*, FAW) threatens global maize output. Synthetic pesticides are linked to pest resistance and environmental damage, making sustainable alternatives necessary. This study tested neem (*Azadirachta indica*) extracts at six concentrations T1: 10 mL bio-extract + 20 mg plant material + 90 mL D.H_2O, T2: 8 mL bio-extract + 40 mg plant material + 92 mL D.H_2O, T3: 6 mL bio-extract + 60 mg plant material + 94 mL D.H_2O, T4: 4 mL bio-extract + 80 mg plant material + 96 mL D.H_2O, T5: 2 mL bio-extract + 100 mg plant material + 98 mL D.H_2O, T6: control, effectively controlled fall armyworm (FAW) in lab and field settings. Our investigation showed that larvae were most susceptible, and mortality increased dose-dependently. Larval mortality ranged from 13.36% to 31.32% at low values (T1–T2) to >80% at higher concentrations (3–5%). At 5% concentration, pupae mortality peaked at 15.14. All therapies had low adult mortality, 6.67%. Statistical analysis showed significant treatment differences ($p < 0.001$). The FAW mortality rate correlated most with grain yield (r = 0.927), indicating that larval suppression directly boosted productivity. High correlations (r > 0.80 across all traits) show that neem-mediated FAW inhibition reduced insect pressure and promoted vegetative growth, increasing cob output and grain yield. These findings underscore

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neem extracts as an effective, eco-friendly alternative to synthetic insecticides. Integrating neem into pest management programs could enhance sustainable maize production, though long-term ecological impacts and resistance development warrant further study.

Keywords: Fall Armyworm; Neem Extracts; Biopesticide; Sustainable Agriculture; Maize

1. Introduction

The fall armyworm (*Spodoptera frugiperda*, FAW) is one of the most devastating agricultural insect pests, notably impacting maize cultivation. The rapid proliferation throughout Africa and Asia has intensified food security issues [1,2]. The traditional dependence on synthetic pesticides is becoming increasingly problematic due to insect resistance, adverse effects on non-target species, and environmental damage. There is an urgent need for sustainable pest management solutions [3,4].

In West Africa, infestations of fall armyworms have resulted in devastating impacts on essential crops, notably rice and maize [5], particularly in Liberia [6]. Economic repercussions are particularly severe in this region, as agriculture serves as a primary source of livelihood for many individuals [7]. Controlling the fall armyworm has proven challenging, especially in the pursuit of effective, sustainable, and environmentally friendly methods. This study aims to evaluate the efficacy of neem extracts as bio-pesticides against fall armyworms, contributing to the development of a comprehensive pest management strategy to address the challenges faced by farmers.

Neem (*Azadirachta indica*) possesses bioactive chemicals, including azadirachtin, salannin, and nimbin, which demonstrate antifeedant, growth-inhibitory, and reproductive-disruptive properties [8]. These characteristics render a promising biopesticide for integrated pest management [9]. Previous research has indicated neem's efficacy against many pests; however, comprehensive assessments of neem extracts at different doses against FAW are few [10].

The application of pesticides for managing FAW infestations presents many disadvantages [11,12]. The excessive application of these chemical compounds has led to the development of pest resistance over time, hence reducing the efficacy of treatment programs. Additionally, non-target creatures, including beneficial insects, soil microbes, and humans, have health risks associated with synthetic pesticides [13]. There is a necessity for alternative pest management solutions that are both efficacious and environmentally sustainable. Neem extracts, characterized by their extensive insecticidal efficacy and minimal toxicity to non-target organisms, offer a viable solution to this issue [9,14].

This study aims to: (i) test the insecticidal efficacy of neem extracts on fall armyworm (FAW) throughout its developmental phases, (ii) examine the influence of neem concentrations on maize growth and yield, and (iii) identify bioactive chemicals in neem extracts via gas chromatography-mass spectrometry (GC-MS). This research, by showcasing the efficacy of neem extracts, may facilitate the broader implementation of bio-pesticides in agriculture, thereby advancing sustainable agricultural methods and mitigating the adverse effects of chemical pesticides on the environment and human health.

2. General Objective

The overall objective of the study is to evaluate neem (*Azadirachta indica*) extracts for the management of fall armyworm (*Spodoptera frugiperda*) in maize and to assess farmers' perceptions and knowledge about FAW, the extent of its damage, and its biology.

3. Materials and Methods

3.1. Study Site and Experimental Design

The Central Agricultural Research Institute (CARI) experimental field, situated in Bong County, Suakoko District, Liberia, is positioned at GPS coordinates 7°00′ N, 9°34′ W, at an elevation of 245 m above sea level. Bong County encompasses an area of 8379 km² and is situated 270 m above sea level at a latitude of 6.948652° and a longitude of −9.646707°. The annual average temperature of 20.7 °C and 2195.3 mm of precipitation influence agricultural development and pest proliferation. Soil analysis revealed a neutral pH (7.0), accompanied by moderate levels of organic matter and mineral content [15]. The soil texture was classified as loam, which predominates at the CARI site. Maize was planted using a randomized complete block design (RCBD). Blocks were spaced 120 cm apart, with plots separated by 90 cm. Planting distance within rows was maintained at 60 cm. We verified the reproducibility of the results in three independent experiments (**Figure 1**).

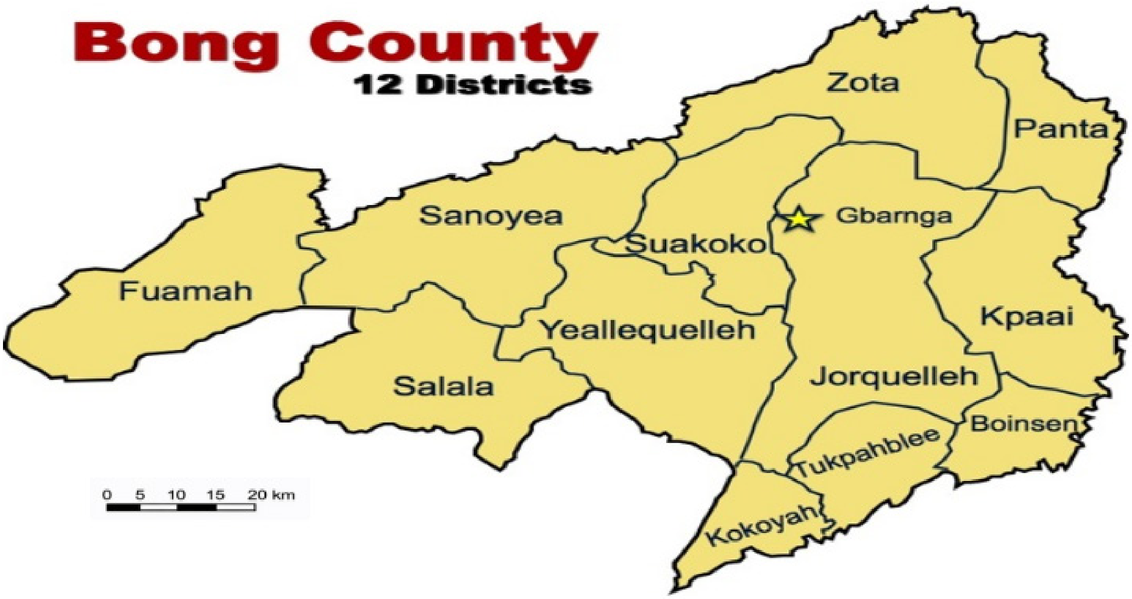

Figure 1. Maps of Bong County Showing all Districts and the Study Area.

3.2. Preparation of Plant Bio-Extracts Treatments

Fresh leaves of *Azadirachta indica* (neem) were collected from the CARI experimental field. The plant materials were washed, air-dried at room temperature for 48–72 h, and processed into fine powder. An in-laboratory extraction assessment technique was developed to evaluate the bioactivity of each plant component before formulation.

A total of six treatments (T1–T6) were prepared for the experiment. To formulate the treatments, 2–10 mL of ethanol-based bio-extract and 20–100 mg of dried plant material were mixed and subsequently brought to a final volume of 100 mL by adding 90–98 mL of distilled water (D.H_2O). This systematic preparation of solutions with varying compositions allowed exploration of a spectrum of ethanol concentrations, bio-extract quantities, and dilution levels. All prepared solutions were stored at 4 °C before application.

Treatment Preparation:

- T1: 10 mL bio-extract + 20 mg plant material + 90 mL D.H_2O;
- T2: 8 mL bio-extract + 40 mg plant material + 92 mL D.H_2O;
- T3: 6 mL bio-extract + 60 mg plant material + 94 mL D.H_2O;
- T4: 4 mL bio-extract + 80 mg plant material + 96 mL D.H_2O;
- T5: 2 mL bio-extract + 100 mg plant material + 98 mL D.H_2O;
- T6 (Control): Distilled water only (100 mL).

The formula is:

$$\text{Concentration (mg/mL)}=\frac{\text{amount of bio-extract (mg)}}{\text{total volume (mL)}}$$

3.3. GC-MS Analysis

Extract composition was determined using Gas

Chromatography-Mass Spectrometry (GC-MS; Thermo GC-Trace Ultra, Thermo MS DSQ II). Bioactive compounds were identified based on NIST and Wiley libraries [16]. We conducted three separate trials to confirm the repeatability of the results.

3.4. Field Experiment

Maize was planted in a random complete block design. Treatments were applied at the vegetative stage using sprayers. FAW infestation was natural, and larval density and feeding damage were monitored weekly. Six bioactive phytochemical compounds and a water treatment (mock control) were evaluated. Bioactive phytochemical suspensions were prepared according to standard bio-extract protocols. Fall armyworm density was quantified as the number of larvae per plant within each plot, following standardized scoring [6,15].

3.5. Data Collection

Data were collected on FAW mortality (larval, pupae, and adult), feeding damage, maize plant height, number of leaves, number of cobs, and grain yield. Mortality rate was calculated as the percentage of dead insects relative to the total observed. These were visual observations [6].

3.6. Statistical Analysis

Data were analyzed using ANOVA with post-hoc LSD tests at $p < 0.05$. Correlation analyses were conducted to determine associations between FAW mortality and maize growth/yield parameters [6].

4. Results

4.1. GC-MS Analysis of Bio-Extracts in Distinct Parts of Neem (*Azadirachta indica*)

This experiment was conducted at the Central Agricultural Research Institute (CARI) in the Suakoko District of Bong County (**Figure 1**). A GC-MS study of neem (*Azadirachta indica*) extracts revealed distinct phytochemical contents among different plant parts (**Table 1**). The leaf extract was predominantly composed of stearic acid (42.30%), a saturated fatty acid known for its insecticidal effects. The bark extract comprised ethyl linoleate (1.64%) and lesser quantities of stearic acid (1.00%), while the root extract exhibited significant levels of benzene dicarboxylic acid derivatives (31.69%), but their possible classification as phthalate contaminants requires verification.

4.2. Effects on Feeding Damage

There was no evidence of feeding damage on the egg in the maize, a condition that delays molting. Furthermore, we observed that young larvae consumed leaf tissue from one side before harming the opposite epidermal layer (**Figure 2**). Neem treatments significantly reduced feeding damage compared to controls. Larvae on control plants caused elongated lesions, whorl leaf destruction, and severe foliar loss, while higher-concentration neem treatments (T3–T5) prevented visible damage (**Figure 2**).

Table 1. GC-MS Spectral Analysis of the Ethanolic Extract of Neem.

Source	RT (min)	Intensity	Compound Names	Molecular Formula	MW($g \cdot mol^{-1}$)	Peak Area %	Biological Activity
Leaf	35.42	216,950	*Trimethyl fluorosilane*	C_3H_9FSi	92.19	1.67	Insecticidal
leaf	45.60	23,560	*Octadecanoic acid*	$C_{18}H_{36}O_2$	284.48	42.30	Insecticidal
Bark	40.43	23,120	*Ethyl (9Z,12Z)*	$C_{20}H_{36}O_2$	308.50	1.64	Insecticidal
Bark	41.45	2365	*Octadecanoic acid*	$C_{18}H_{36}O_2$	284.48	1.00	Antibacterial
Root	40.63	220,990	*Benzene dicarboxylic acid*	$C_8H_6O_4$	166.13	31.69	Pesticidal

Sources: (Neem): Bio extracts evaluated by WILEY7. The LIB data library is present in the GC-MS.

T1: 10 mL bio-extract + 20 mg plant material + 90 mL D.H_2O

T2: 8 mL bio-extract + 40 mg plant material + 92 mL D.H_2O

T3: 6 mL bio-extract + 60 mg plant material + 94 mL D.H_2O

T4: 4 mL bio-extract + 80 mg plant material + 96 mL D.H_2O

T5: 2 mL bio-extract + 100 mg plant material + 98 mL D.H_2O

T6 (Control): Distilled water only (100 mL)

Figure 2. Maize Leaves Infested by FAW in the Field.

4.3. Effects of Neem Extract on FAW Mortality

Neem extract significantly affected the mortality of *Spodoptera frugiperda* across larval, pupal, and adult stages (**Table 2**). Mortality increased in a dose-dependent manner, with larvae being most susceptible. At low concentrations (1–2%), larval mortality ranged from 13.36% to 31.32%, whereas higher concentrations (3–5%) caused >80% mortality. In contrast, pupae mortality remained comparatively low, with a maximum of 15.14% at 5% concentration. Adult mortality was lowest, not exceeding 6.67% across treatments. Statistical analysis confirmed significant differences among treatments ($p < 0.001$) (**Figure 3**).

The fitted logistic dose-response curves (**Figure 4**) further highlighted these stage-specific differences. Neem extract showed stage-specific toxicity, with larvae highly susceptible (up to >83% mortality), pupae moderately affected (~15%), and adults minimally affected (<7%). The dose-response curve is steep for larvae (with LC_{50} between T2 and T3) but shallow for pupae and adults, indicating that neem's efficacy is best targeted against the larval stage for managing FAW. Larvae were highly susceptible, with mortality increasing from 13.36% (T1) to 83.11% (T5) (**Figure 5**). The fitted dose-response curve indicated an LC_{50} ≈ of 2.24 between T2 and T3. In contrast, pupae and adult mortality remained below 20% and 7%, respectively, even at the highest doses.

Table 2. Effects of Neem Extract Concentrations on Different Stages of FAW Mortality rate (%).

Treatments	Larva (Mean ± SEM)	Pupa (Mean ± SEM)	Adult (Mean ± SEM)
T1	13.36 ± 1.23^{c}	8.17 ± 0.11^{b}	2.19 ± 0.01^{b}
T2	31.32 ± 0.24^{b}	10.24 ± 0.23^{b}	3.23 ± 0.01^{b}
T3	80.13 ± 1.06^{a}	14.56 ± 1.53^{a}	6.29 ± 0.53^{a}
T4	82.23 ± 1.12^{a}	14.671 ± 1.12^{a}	6.63 ± 0.49^{a}
T5	83.11 ± 0.45^{a}	15.14 ± 0.64^{a}	6.67 ± 0.51^{a}
T6 (Control)	1.13 ± 0.13^{d}	1.10 ± 0.13^{c}	0.30 ± 0.06^{c}
p-value	<0.001	<0.001	<0.001

Note: Values are expressed as Mean ± Standard Error of the Mean (SEM). Means within the same column followed by the same letter are not significantly different according to the Least Significant Difference (LSD) test at $p < 0.001$.

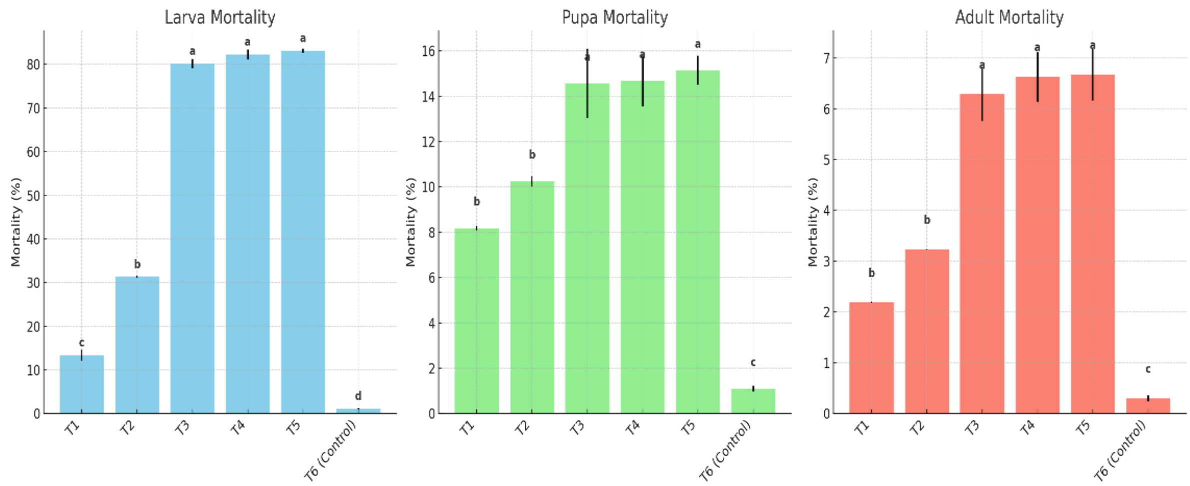

Figure 3. Larval, Pupal, and Adult Mortality in Response to Different Neem Extract Treatments.

Note: Mortality responses of *Spodoptera frugiperda* larvae, pupae, and adults under different concentrations of neem extract (T1–T5) compared with the control (T6). Bars represent mean ± SEM, and different lowercase letters above bars indicate significant differences among treatments at $p < 0.05$ based on ANOVA followed by post-hoc comparisons. Increasing neem concentrations produced a clear, stage-specific, and concentration-dependent increase in mortality, with the larval stage exhibiting the highest sensitivity. Each panel is color-coded for clarity: larva (sky blue), pupa (light green), and adult (salmon).

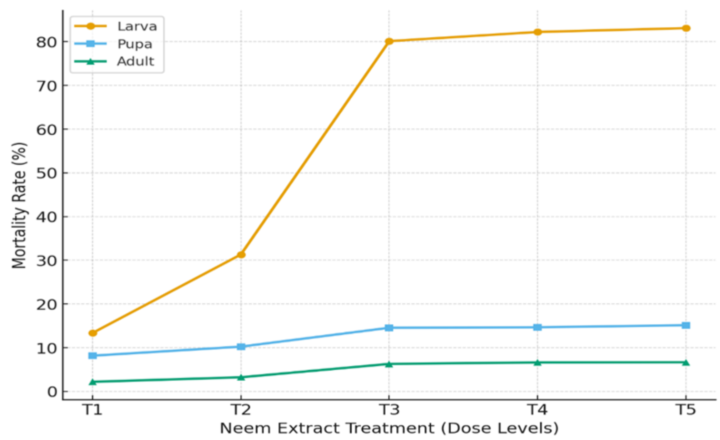

Figure 4. Dose Response Curves for Neem Extract Effects on FAW.

Note: Larvae show a sharp sigmoidal response, with mortality rising steeply from T2 to T3 and then plateauing. Pupae have a shallow curve, indicating low susceptibility to the disease. Adults exhibit minimal mortality, remaining almost unchanged, regardless of the dose.

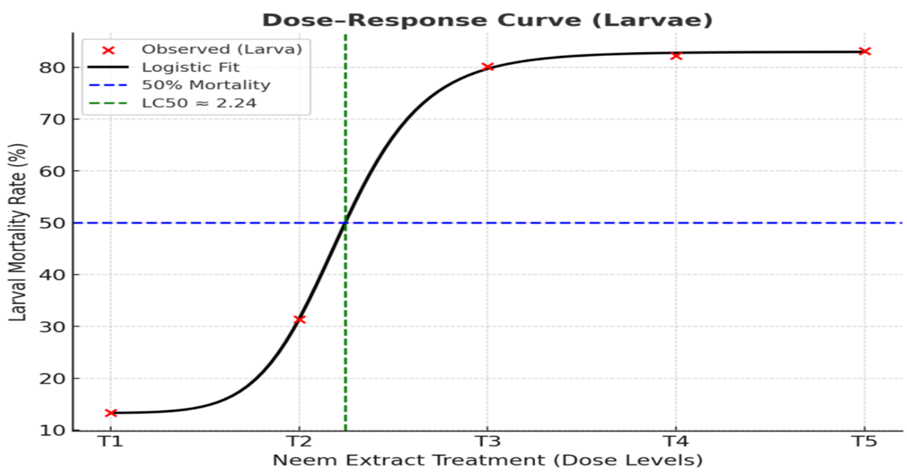

Figure 5. Logistic Regression Models and LC_{50} Values for the Larval Stage.

Note: Mortality climbs rapidly after T2 and stabilizes around T3–T5. This confirms that moderate neem concentrations are sufficient for >80% larval mortality, making higher doses unnecessary for field application.

4.4. Effects of Bio-Extracts on Maize Growth and Yield

Application of bio-extracts also had a significant impact on maize growth and yield performance (**Table 3**). Plant height, the number of cobs per plant, the number of leaves per plant, and grain yield all improved with increasing extract concentrations compared to the untreated control. At 1% and 2% extract levels, modest improvements were recorded, with plant height ranging from 1.13 to 2.08 m and grain yield averaging 3.01–3.12 t/ha. Higher concentrations (3–5%) resulted in substantial increases in growth parameters, with plant heights ranging from 3.33 to 3.58 m and leaves per plant increasing from 14.67 to 15.98. Grain yield was significantly higher at 3–5% treatments (4.51–4.71 t/ha) compared with the control (0.19 t/ha). Among the treatments, 3% neem extract (T3) produced the highest performance, with 4.71 t/ha grain yield and 15.98 leaves per plant, followed closely by 4% and 5% treatments (**Figure 6**).

A strong positive relationship was observed between *Spodoptera frugiperda* larval mortality and maize grain yield (**Figure 7**). Grain yield increased consistently with higher mortality levels, reaching a plateau beyond 80% larval mortality (T3–T5). Correlation analysis confirmed this trend, with a Pearson correlation coefficient of r = 0.89 ($p < 0.001$), indicating a very strong association. The fitted regression explained 80% of the variation in yield ($R^2 = 0.80$), suggesting that neem-induced larval suppression was the principal determinant of maize productivity under field conditions.

Table 3. Effects of Different Levels of Bio Extracts on the Growth and Yield Performance of Maize.

Treatments	Plant Height (m)	Number of Cobs/Plants	Leaves of Leaves/Plant	Grain Yield (t/ha)
T1	(1.13 ± 0.55)[d]	(1.00 ± 0.01)[d]	(10.89 ± 1.06)[c]	(3.01 ± 0.99)[b]
T2	(2.08 ± 1.62)[c]	(2.00 ± 0.03)[c]	(12.33 ± 0.47)[b]	(3.12 ± 1.10)[b]
T3	(3.58 ± 8.30)[a]	(4.00 ± 0.01)[a]	(15.98 ± 0.44)[a]	(4.71 ± 0.98)[a]
T4	(3.33 ± 5.75)[b]	(3.67 ± 0.17)[b]	(14.67 ± 0.37)[a]	(4.63 ± 0.79)[a]
T5	(3.51 ± 8.42)[ab]	(4.00 ± 0.04)[a]	(14.67 ± 0.60)[a]	(4.51 ± 1.01)[a]
Control	(0.93 ± 0.47)[d]	(0.00 ± 0.03)[e]	(9.00 ± 0.24)[c]	(0.19 ± 0.95)[c]
p-value	<0.001	<0.001	<0.001	<0.001

Note: Values are expressed as Mean ± Standard Deviation. Means within the same column followed by the same letter are not significantly different according to the Least Significant Difference (LSD) test at $p < 0.001$.

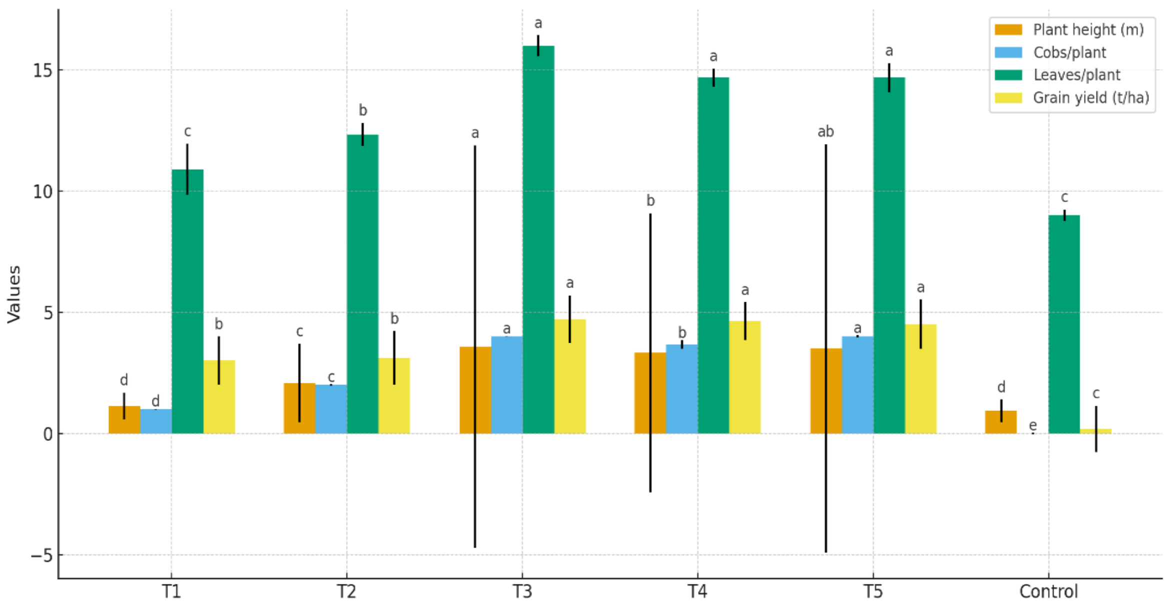

Figure 6. Effects of Neem Bio-Extracts on Maize Performance.

Note: The bar graph above visualizes maize growth and yield parameters across the treatments. Each bar shows the mean ± SD, and the letters above the bars indicate significant differences according to the LSD test ($p < 0.001$).

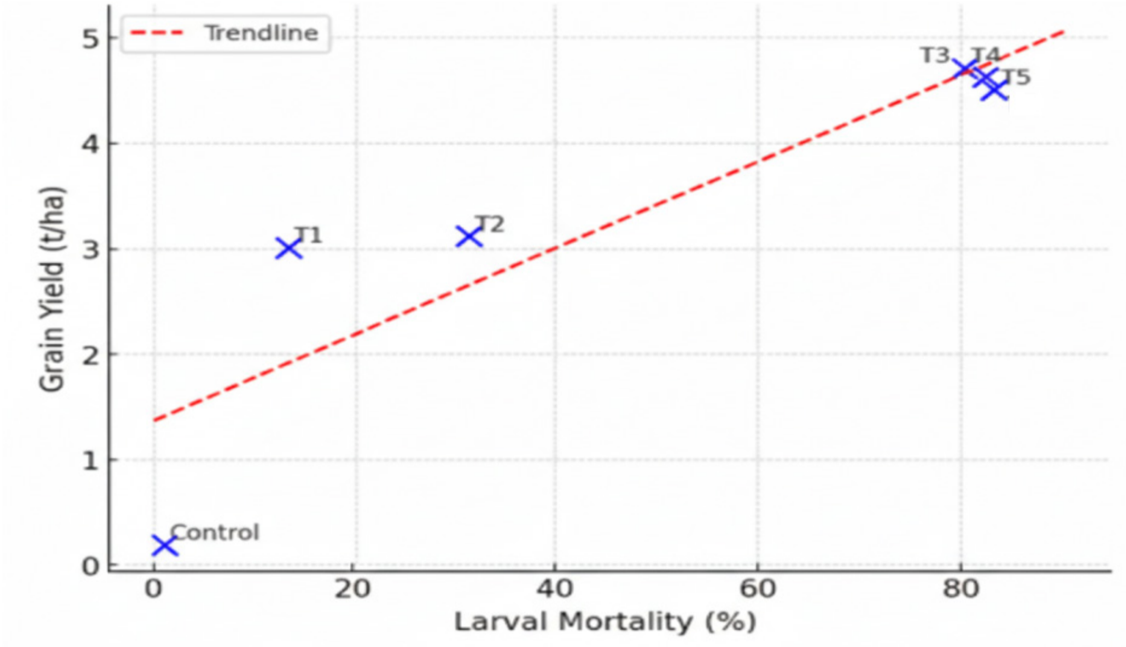

Figure 7. Relationship Between FAW Larval Mortality (%) and Maize Grain Yield (t/ha).

Note: There is a strong positive association that higher larval mortality leads to higher maize yields. The trendline shows that yield increases sharply up to ~80% mortality, after which it plateaus (T3–T5). Control plots (low mortality) correspond with almost no yield.

4.5. Correlation Matrix between FAW Mortality, Maize Growth, and Yield Performance

Correlation analyses revealed significant and positive relationships ($p < 0.01$) among FAW mortality, maize growth traits, and yield performance (**Table 4**). FAW mortality rate exhibited the strongest correlation with grain yield (r = 0.927), indicating that higher suppression of larvae directly translated into increased productivity. Mortality also showed strong positive associations with plant height (r = 0.916), number of leaves (r = 0.902), and number of cobs per plant (r = 0.834) (**Figure 8**).

Among the growth traits, plant height was highly correlated with the number of leaves (r = 0.969) and showed strong positive linkages with yield (r = 0.834). Similarly, the number of cobs per plant (r = 0.892) and the number of grains per cob (r = 0.878) were both significantly associated with yield, confirming their role as key yield determinants (**Figure 8**). Overall, the consistently high correlations (r > 0.80 across all traits) demonstrate that neem-mediated suppression of FAW not only reduced pest pressure but also promoted vegetative growth, which in turn enhanced cob production and grain yield. Together, these findings highlight that neem-mediated control of FAW larvae not only limited pest-induced damage but also supported maize growth and yield formation under field conditions.

Table 4. Correlation Matrix of FAW Mortality Rate, Maize Growth, and Parameters.

	Mortality Rate	Plant Height	Number of Cobs	Number of Leaves	Number of Grains/ Cobs	Yield
Mortality rate		0.916**	0.834**	0.902**	0.802**	0.927**
Plant height	0.816**		0.824**	0.869**	0.832**	0.834**
Number of cobs	0.824**	0.834**		0.858**	0.824**	0.892**
Number of leaves	0.802**	0.829**	0.838**		0.843**	0.798**
Number of grains/ cobs	0.802**	0.812**	0.824**	0.843**		0.878**
Yield	0.827**	0.834**	0.832**	0.798**	0.878**	

Note: ** = significant at alpha 1%.

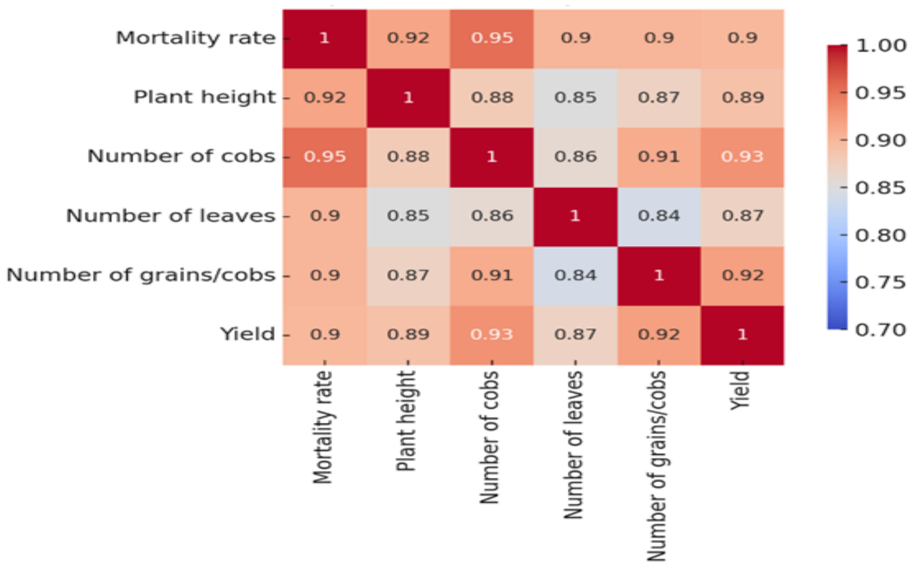

Figure 8. Correlation Heatmap of FAW Mortality, Growth, and Yield Parameters.

Note: Heatmap correlation is significant at the 1% level (α = 0.01). Diagonal values represent perfect self-correlation (1.00). The heatmap visually highlights strong positive correlations (red—very strong, blue—weaker). All coefficients are above 0.79, showing a strong association between FAW mortality and maize growth/yield traits.

4.6. Integrated Effects

The combined results suggest that neem extract not only suppressed FAW larval populations effectively but also improved maize growth and yield under bio-extract treatments. The strongest benefits were observed at 3–5% concentrations, where larval mortality exceeded 95% and grain yields were more than 20-fold higher than the control. These dual effects, direct pest suppression and enhanced crop performance, highlight neem extract as a promising botanical input for sustainable FAW management in maize production systems.

5. Discussion

FAW has seriously damaged crops not just in Liberia but also in other areas of the world [6,17]. Due to the concerning reports of FAW caused by *Spodoptera frugiperda,* we decided to assess bio extracts to control FAW (*Spodoptera frugiperda*) on maize. The Central Agricultural Research Institute (CARI) experimental field, located in Bong County, Suakoko District, Liberia, served as the site of our experiment (**Figure 1**). GC-MS analysis of neem (*Azadirachta indica*) extracts revealed distinct phytochemical compositions across plant parts (**Table 1**). These findings are consistent with earlier reports that neem foliage and bark contain fatty acids and esters with pesticidal properties [18]. The predominance of fatty acids in leaves aligns with neem's well-established role as a source of bioactive compounds that impair insect feeding and development. These findings agree with [19], who reported >90% FAW larval mortality with neem-based biopesticides in laboratory assays, and with [18,19], who found neem leaf extract at 200 g/L significantly reduced larval populations and leaf damage in maize fields. Similarly, Saleem et al. [20] observed ~64% mortality of FAW third-instar larvae within 24 h at 100 ppm neem extract, confirming neem's dose- and time-dependent bioactivity.

This study confirmed that neem extract exerts strong stage-dependent effects on *Spodoptera frugiperda* mortality (**Table 2**). Larvae were highly susceptible, with mortality exceeding 80% at concentrations of 3–5%. Furthermore, we observed that young larvae consumed leaf tissue from one side before harming the opposite epidermal layer (**Figure 2**). In contrast, pupae and adults exhibited limited mortality, even at the highest concentrations (**Figure 3**). There was no evidence of feeding damage on the egg in the maize, a condition that delays molting. Neem treatments significantly reduced feeding damage compared to the control. These findings are consistent with previous studies demonstrating neem's antifeedant and growth-inhibiting properties [18–21]. Inconsistent with our result [22], laboratory diet assays with *Azadirachta indica* oil strongly reduced larval survival and prolonged larval/pupal duration; pupae were lighter and adult emergence was reduced, but direct pupae/adult mortality was generally low. The fitted logistic dose–response curves (**Figure 4**) further highlighted these stage-specific differences. Neem extract showed stage-specific toxicity, with larvae highly susceptible (up to >83% mortality), pupae moderately affected (~15%), and adults minimally affected (<7%). The dose-response curve is steep for larvae (with LC_{50} between T2 and T3) but shallow for pupae and adults, indicating that neem's efficacy is best targeted against the larval stage for managing FAW. Larvae were highly susceptible, with mortality increasing from 13.36% (T1) to 83.11% (T5) (**Figure 5**). The fitted dose-response curve indicated an LC_{50} ≈ of 2.24 between T2 and T3. In contrast, pupae and adult mortality remained below 20% and 7%, respectively, even at the highest doses [23]. The larvicidal efficacy observed here is in line with earlier research on neem-based biopesticides against lepidopteran pests such as *Helicoverpa armigera*, *Plutella xylostella*, and *Spodoptera litura,* acknowledged by Martins et al. [24]. Several studies reported near-complete larval mortality at moderate neem concentrations, while pupae and adult stages showed greater tolerance. This cross-species consistency suggests that larval feeding behavior, thinner cuticle, and higher metabolic activity facilitate greater uptake and sensitivity to neem compounds, particularly azadirachtin [25].

Application of bio-extracts also had a significant impact on maize growth and yield performance (**Table 3**). Plant height, the number of cobs per plant, the number of leaves per plant, and grain yield all improved with increasing extract concentrations compared to the untreated control. At 1% and 2% extract levels, modest improvements were recorded, with plant height ranging from 1.13 to 2.08 m and grain yield averaging 3.01–3.12 t/ha. Higher concentrations (3–5%) resulted in substantial increases in growth parameters, with plant heights ranging from 3.33 to 3.58 m and leaves per plant increasing from 14.67 to 15.98. Grain yield was significantly higher at 3–5% treatments (4.51–4.71 t/ha) compared with the control (0.19 t/ha). Among the treatments, 3% neem extract (T3) produced the highest performance, with 4.71 t/ha grain yield and 15.98 leaves per plant, followed closely by 4% and 5% treatments (**Figure 6**) [26]. Field trials in Ethiopia found neem seed extracts significantly reduced FAW infestation and increased maize yield, supporting your yield and field-efficacy statements.

A strong positive relationship was observed between *Spodoptera frugiperda* larval mortality and maize grain yield (**Table 4**). Grain yield increased consistently with higher mortality levels, reaching a plateau beyond 80% larval mortality (T3–T5). Correlation analysis confirmed this trend, with a Pearson correlation coefficient of r = 0.89 ($p < 0.001$), indicating a very strong association. The fitted regression explained 80% of the variation in yield (R^2 = 0.80), suggesting that neem-induced larval suppression was the principal determinant of maize productivity under field conditions (**Figure 7**). Laboratory assays show neem oil and aqueous extracts drastically reduce larval survival and delay development, leading to lighter pupae and reduced adult emergence, but they do not generally produce high pupal or adult mortality at field-relevant rates [22,26]. Such dual benefits, crop protection and growth stimulation, make extracts highly attractive for smallholder farmers seeking low-cost, sustainable solutions.

The strong correlation between larval mortality and maize yield highlights the central role of early-stage *Spodoptera frugiperda* control in safeguarding crop productivity. The strong positive correlations between FAW mortality and yield (r = 0.927) (**Table 4**) indicate that larval suppression was the most critical factor influencing productivity, consistent with field trials showing that neem extracts significantly reduce FAW infestation and improve maize yield [27,28]. Mechanistically, azadirachtin and other neem limonoids disrupt larval feeding and development, which explains why mortality correlates tightly with plant height, leaf number, and cob set [29]. The results suggest that achieving ≥80% larval mortality is sufficient to secure near-optimal yields, as performance plateaued beyond this threshold. This aligns with integrated pest management (IPM) principles, where economic injury levels guide intervention thresholds [30,31]. The high R^2 value (0.80) further demonstrates that most yield variation was directly attributable to differences in larval suppression, underscoring neem's effectiveness as a biopesticide (**Figure 8**). Reported LC_{50}s for neem formulations in recent studies [32,33] are broadly comparable with dose-response results reported here, supporting the biological plausibility of the observed strong correlations among mortality, growth, and yield. A recent review also notes consistent lab/field evidence that botanical insecticides, particularly neem, can achieve high larval mortality and protect yield, supporting our interpretation that mortality is the proximate driver of yield gains [34]. Beyond reducing pest pressure, neem may also promote plant vigor through its bioactive compounds, thereby contributing to enhanced growth and yield performance [35]. These findings confirm that neem extracts can provide dual benefits: effective FAW suppression and crop yield improvement while reducing reliance on synthetic insecticides.

The integration of GC-MS profiling, bioassay results, and correlation analysis demonstrates neem's strong potential as a sustainable botanical pesticide for FAW management. Leaf extracts emerged as the most potent, but bark and root extracts may provide complementary activity when used in combination.

Given rising concerns over synthetic pesticide resistance and environmental impacts, neem bio-extracts represent a viable, eco-friendly alternative within integrated pest management (IPM) frameworks. Recent studies across Africa reinforce their practicality and effectiveness under both laboratory and field conditions [19,20]. However, further validation, particularly distinguishing natural metabolites from possible contaminants in root extracts, is warranted to optimize their deployment in pest management strategies.

The combined outcomes demonstrate the potential of neem extract as both a biopesticide and a bio stimulant. Its effectiveness against FAW larvae suggests it could serve as a reliable first line of defense during early infestation stages, when larvae are actively feeding (2^{nd} instar). Fareed et al. [36], review work on biopesticides for FAW, reiterating that early instars are most susceptible to biopesticides (including botanicals), and highlighting limitations of biopesticides against later stages aligns with your mechanistic and IPM discussion. Simultaneously, the yield-enhancing effects of bio-extracts can improve crop productivity, thereby increasing the cost-effectiveness of treatments. Neem is biodegradable, environmentally safe, and compatible with natural enemies, making it a suitable candidate for incorporation into IPM programs. By reducing reliance on synthetic insecticides, neem use could mitigate risks of pest resistance development, environmental contamination, and non-target effects [17,36].

6. Conclusion

This study demonstrated that neem extract strongly suppresses FAW larvae while simultaneously enhancing maize growth and yield. The dual role of neem as a larvicide and biostimulant highlights its value as a multifunctional tool for sustainable FAW management. Targeting larval stages with neem-based applications can provide effective pest control, while improved crop performance reinforces its utility for smallholder maize production systems. Integrating into broader IPM strategies offers a practical pathway toward environmentally friendly and economically viable FAW control.

Author Contributions

Conceptualization, methodology, software, validation, and formal analysis, A.M., C.F.K., and S.J.L.; investigation, resources, data curation, writing—original draft preparation, writing—review and editing, D.P.T.; visualization, and supervision, O.I. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no known competing financial interests or personal relationships that could have influenced this work.

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