

RESEARCH ARTICLE OPEN ACCESS

Efficacy of Crude Extracts and Essential Oils of Selected Plants for the Management of Fall Armyworm (*Spodoptera frugiperda*) in Kenya

Catherine K. Mumo¹  | Phyllis W. Muturi¹  | Bernard M. Gichimu¹  | Simon T. Mukono² 

¹Department of Water and Agricultural Resource Management, University of Embu, P. O. Box 6–60100, Embu, Kenya | ²Department of Physical Sciences, University of Embu, P. O. Box 6–60100, Embu, Kenya

Correspondence: Catherine K. Mumo (catherinekuthea@gmail.com)

Received: 23 October 2025 | **Revised:** 12 April 2026 | **Accepted:** 9 May 2026

Academic Editor: Nidhi Chaudhary

Keywords: botanicals | damage severity | Embu County | pest incidence

ABSTRACT

Fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith), poses a serious threat to maize production in Kenya. This study aimed to assess the efficacy of crude extracts and essential oils of garlic (*Allium sativum*), red hot pepper (*Capsicum frutescens*), Sodom apple (*Solanum incanum*), and Mexican sunflower (*Tithonia diversifolia*) in controlling FAW. Sterile distilled water and Occasion Star 200SC synthetic pesticide constituted the negative and positive controls, respectively. The efficacy of the crude extracts was tested under field conditions for two cropping seasons. The pest dynamics in the field experiment were determined using the area under damage/pest curve (AUDPC). The highest pest incidence (AUDPC of 180–202) was observed in the negative control treatment, while the lowest (AUDPC of 46–49) was observed in the positive control (synthetic pesticide) treatment. Similarly, the highest damage severity (AUDPC of 100–131) was in the distilled water treatment, while the synthetic pesticide treatment recorded the lowest damage severity (AUDPC of 42). The crude extracts also significantly reduced FAW infestation and severity at variable levels compared to the control, except the Mexican sunflower which was relatively less effective. The efficacy of essential oils was tested in a laboratory bioassay against FAW third-instar larvae where garlic and red hot pepper oils caused 100% larval mortality within 48 h, but Sodom apple and Mexican sunflower were relatively less effective. This study confirmed the efficacy of the tested botanicals for FAW management at variable levels, highlighting their potential as sustainable alternative pesticides.

1 | Introduction

Maize (*Zea mays* L.) is a staple food crop in Kenya and among the primary food security crops in sub-Saharan Africa [1]. Green maize can be consumed either freshly boiled, roasted, or cooked mainly with beans, which enhances its nutritional and economic value [2]. Farmers prefer producing green maize to dry maize since the former is economically viable [3]. The value chain of the fresh maize enterprise is shorter compared to the dry maize enterprise, thus incurring lower labor costs [3]. Unfortunately,

green maize production in sub-Saharan Africa is constrained by numerous challenges including insect pests, diseases, climate change, and degraded soils [4]. In Kenya, the average yields per year have been fluctuating in the last decade despite the substantial increase in the acreage under maize production [5]. Fall armyworm (FAW) infestation is reported to contribute to more than a third of the yield loss of maize in Kenya, translating to approximately one million tons. The pest attacks both vegetative and reproductive stages of maize [6], and the infestation signs include elongated papery windows or ragged-edged holes on

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Copyright © 2026 Catherine K. Mumo et al. *International Journal of Agronomy* published by John Wiley & Sons Ltd.

leaves, larval frass in the whorls, and damage to tassels [7]. The damage to the whorls and ear feeding causes yield reduction and compromises the kernel quality.

Several locally available resources have been used in the management of FAW, and they include botanical extracts, soil, wood ash, sand, lime, soaps, and oils [8]. Natural plant products have been used as biopesticides for pest management and are perceived to be environmentally sound options owing to their biodegradability [9]. Crude plant extracts are plant products formed from extraction and separation processes where chemical components are rarely interfered with. Extraction of the plant crude extracts can be achieved using solvents, such as distilled water, methanol, or ethanol [10]. Botanical extracts from several plants have been reported to be effective against FAW. For instance, the neem extract powder can cause over 70% mortality to FAW larvae [11]. Plants also produce essential oils which are the secondary metabolites as part of a defense mechanism against pests and predators, attraction of pollinators, and seed dispersal [12]. These oils are produced in various parts, such as seeds, fruits, flowers, leaves, stems, or roots, depending on the plant species [13]. Botanical pesticides have minimal pesticide residue and are harmless to humans, crops, and the environment. Botanical pesticides have not only been used against field pests but also against storage pests [14].

Essential oils comprise complex secondary metabolite mixtures produced by plants as part of defense mechanisms against insects. Essential oils can be extracted and applied as biopesticides owing to their potential insecticidal, repellent, or antifeedant properties on pests [15]. Extracts from onion (*Allium cepa*) and garlic (*Allium sativum*) have biologically active compounds, such as saponins, alkaloids, flavonoids, and tannins, all associated with insecticidal activity [16]. For instance, essential oil from garlic has insecticidal activity against pests including *Blattella germanica*, *Reticulitermes speratus*, and *Sitophilus oryzae* [16]. Essential oils from leaves of *Tithonia diversifolia* also comprise terpenoids, terpenes, and lactones which have demonstrated insecticidal activity [17]. Red hot pepper has insecticidal properties attributed to capsaicinoids that are found predominantly in the fruit [18]. Capsaicinoids consist of chemicals, such as capsaicin, homocapsaicin, dihydrocapsaicin, and nordihydrocapsaicin [19]. Capsaicin accounts for up to 70% of the total capsaicinoids in hot pepper that causes irritation to insect pests and gives off a burning sensation [18]. The capsaicin chemical has a pungent smell with antifungal and antibacterial properties that protect plants [19].

Misuse of inorganic insecticides has resulted in pest resistance in some species [20]. The over reliance on synthetic insecticides can cause environmental contaminations. This necessitates the use of natural pesticides in pest management to reduce the impact on the ecosystem [21]. While synthetic insecticides provide fast curative action, the health hazards they pose and the patterns of resistance highlight the need for alternative strategies in pest control [9]. Some farmers have reported that local plant concoctions protect maize from FAW and are less toxic and safe to humans and the ecosystem and more sustainable in maintaining the yields and quality of green maize. Usually, botanical plants are widespread and can be sourced locally in many farming areas in Africa. They are cheap, eco-friendly, and effective options for smallholder farmers to control FAW. Therefore, this study aimed

to evaluate the efficacy and effectiveness of crude extracts and essential oils from selected botanical plants as sustainable alternatives for the management of FAW.

2 | Materials and Methods

2.1 | Crude Extract Experiment

2.1.1 | Description of the Study Area

The field experiment was conducted at the University of Embu Demonstration Farm in Embu West subcounty, Embu County (Figure 1). The site is found in the upper midland 2 (UM 2) agro-ecological zone at 0° 35' 25" S and 37° 25' 31" E at an altitude of 1494 m above sea level. The average annual rainfall of the area is 1230 mm with a bimodal pattern whereby the long rains occur between March and June, and the short rains are received between October and December. The mean annual temperature is 19.6°C with a mean maximum of 25°C and a mean minimum of 14.1°C. The area has an average annual potential evaporation of 1422 mm and evapotranspiration of 950 mm [22]. The soil is predominantly humic Nitisols which are deep, well-aerated with friable clay textures and with moderate to high intrinsic fertility [23].

2.1.2 | Experimental Design and Layout

The field experiment was laid out in randomized complete block design with six treatments replicated three times as shown in Figure 2. The experimental treatments consisted of Sodom apple (*Solanum incanum*) fruit extracts, Mexican sunflower (*T. diversifolia*) leaf extracts, red hot pepper (*Capsicum frutescens*) fruit extracts, garlic (*A. sativum*) clove extracts, distilled water (negative control), and Occasion Star 200SC synthetic pesticide (active ingredients: emamectin benzoate and indoxacarb) as the positive control. Maize (*Zea mays*), particularly the DH43 variety, was used as the test crop. Each experimental plot measured 5.25 m by 5.25 m with an alley of 1 m between the plots. Six rows of maize were planted in each plot at a spacing of 75 cm between rows and 30 cm between plants. The treatment application was done four times at 14-day intervals starting with three-week-old maize plants. The experiment was conducted for two seasons: October to December 2021 (short rains) and March to May 2022 (long rains) under natural infestation of FAW.

2.1.3 | Preparation of Crude Extracts

One (1) kg of fresh Mexican sunflower (*T. diversifolia*) leaves was collected from the University of Embu field. A similar quantity of red-ripe hot pepper (*C. frutescens*) fruits and garlic (*A. sativum*) cloves was obtained from Embu open-air market. The extraction of crude extracts from test plants was done using the procedures adopted by Mugao et al. [24]. The test samples were washed with running tap water, then rinsed using distilled water, before being air-dried for 2 h at room temperature, after which they were dried using a sterilized blotting paper. Five hundred grams each of the three fresh products was cut separately into small pieces using a sterile scalpel, followed by oven-drying at 40°C for 2 weeks. The dry pieces were then ground into powder using a kitchen grinder. Their powder was separately packed in air-tight brown glass bottles and stored at room temperature for subsequent use. A 200 gm powder of each of the test samples was separately soaked

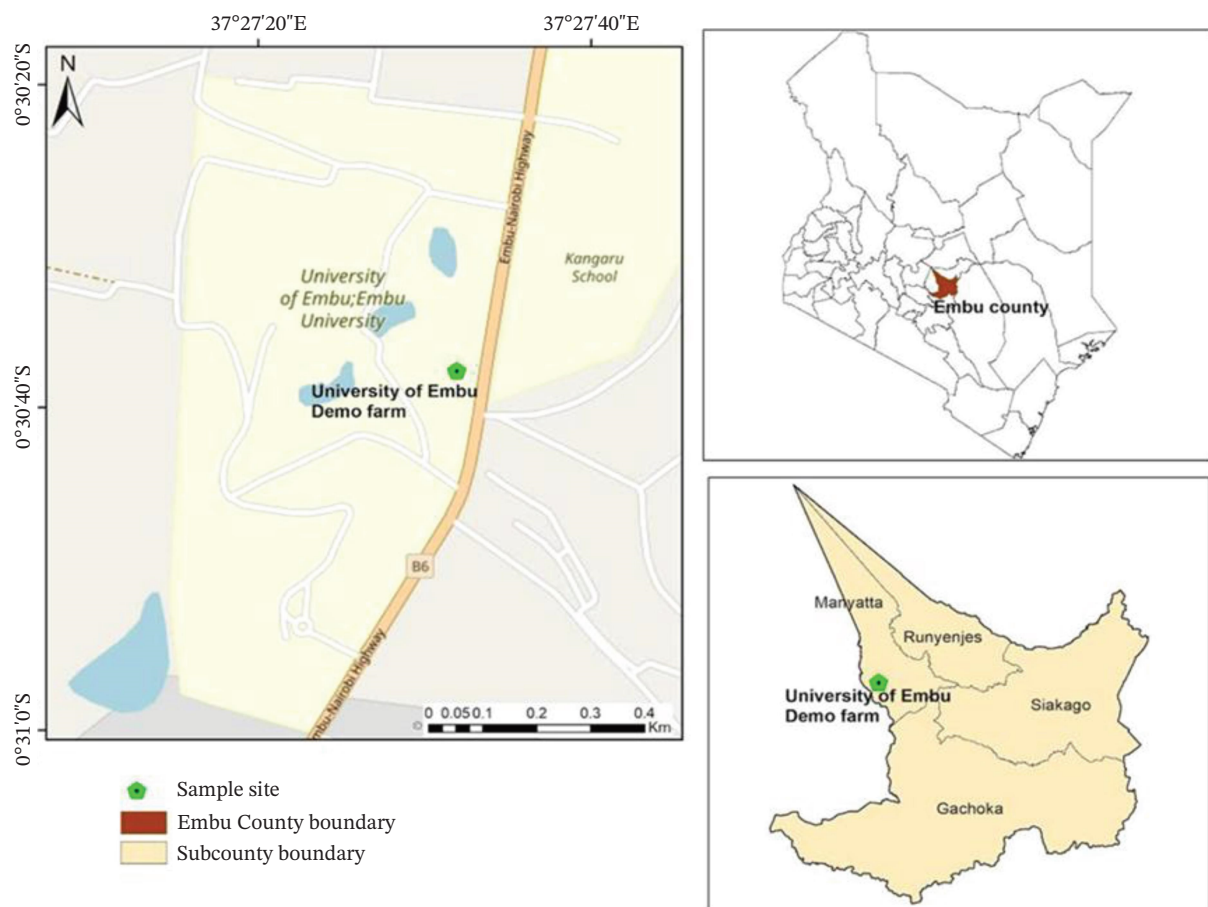


FIGURE 1 | The map of the University of Embu Demonstration Farm study site.

in 500 mL of sterile distilled water for 72 h after which the content was filtered using Whatman's paper (No. 2), and the filtrate was preserved in a refrigerator at 4°C as a stock solution. For Sodom apple (*S. incanum*), ripe fruits were collected from the University of Embu fields, washed thoroughly with running tap water to eradicate dirt and debris, and then rinsed using distilled water. They were then weighed and peeled to remove the pericarp. The extraction procedure described by Umar and Piero [25] was followed, whereby 1 kg of the peeled fruits was sliced into small pieces and soaked in 1 L of distilled water for 72 h. The

mixture was then filtered using Whatman's paper (No. 2), and the filtrate was transferred into 50-mL centrifugal tubes and preserved as stock solution at 4°C.

2.1.4 | Data Collection

At crop emergence, plant stand count was determined following the Biologische Bundesanstalt, Bundessortenamt and Chemical Industry (BBCH) standard system [26]. The three middle rows per plot were sampled for data collection from a total of nine (9)

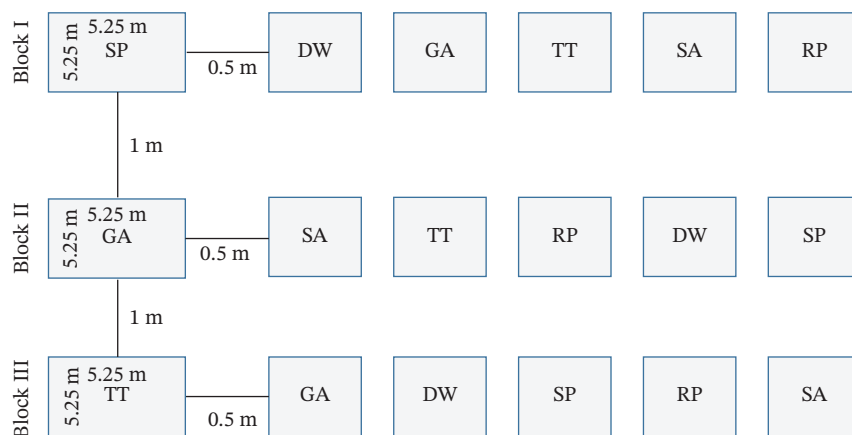


FIGURE 2 | Biopesticide experimental layout. SA: Sodom apple; TT: Mexican sunflower; GA: garlic; RP: red hot pepper; SP: synthetic pesticide; DW: distilled water.

central plants from each plot. Data were collected on the FAW incidence and severity, growth of the maize plant, as well as the yield and quality aspects of green maize. The pest incidence was calculated as the number of infested plants to the number of plants sampled per plot from the 4th to 14th week after maize germination at an interval of two weeks [27]. The pest severity was determined as visual observation of the foliar damage attributed to the pest using a scale of 1–5 as described by Hailu et al. [28], where 1 was clean with no visual infestation symptoms, 2 = very little damage, 3 = high level of damage where plants showed the presence of FAW larva feeding and most of the young leaves show infestation symptom, 4 = severe damage where almost 75% of the leaves are severely affected and excrement was visible on the infested areas and the maize whorls, and 5 = very severe damage where plant damage due to FAW was beyond control.

The growth data that were collected include plant height, stem girth, number of leaves per plant, and internode length. The yield and quality data included plant ear aspect, cob weight, maize stover weight, cob diameter, number of kernel rows per cob, and crop harvest index. Plant height was measured from the base to the tip of the plant using a meter rule [29]. Stem diameter was measured at the 4th internode using Vernier calipers [30]. The number of functional leaves per plant was determined by physically counting the green leaves from the sampled plants [31]. The plant ear aspect was assessed on a scale of 1–5, where 1 = clean, uniform, large, and well-filled ears, and 5 = ears with undesirable features [32]. Cob diameter was measured at the middle of the maize cob using Vernier calipers [33]. The crop harvest index was calculated as a ratio of cob weight to total maize stover weight [34].

2.1.5 | Data Analysis

The average pest incidence and damage severity were estimated by plotting progress curves showing trends of pest incidence and damage score over time (weeks) across different treatments and seasons. From the plotted curves, the cumulative area under damage/pest curve (AUDPC) for each graph was calculated in Microsoft Excel using the calculus theorem formula [35] as follows:

$$\text{AUDPC} = \sum_{i=1}^{n-1} \left(\frac{y_i + y_{i+1}}{2} \right) (t_{i+1} - t_i), \quad (1)$$

where AUDPC = area under damage/pest curve, n = total number of observations, y_i = percent pest incidence/damage score on the crop at the i th observation, and t = time (in weeks) at the i th observation beginning 4 weeks–14 weeks after maize germination.

The calculated AUDPC datasets were taken as average insect pest incidence and damage severity. The pest and crop datasets were checked for normality and homogeneity of variance using the Shapiro–Wilk and chi-square tests, respectively, before being subjected to analysis of variance (ANOVA) using XLSTAT software Version 2023. The separation of means was done using Tukey's honestly significant difference (HSD) at $\alpha = 0.05$. The relationship between pest infestation levels and plant growth and yield was established using Pearson's correlation analysis.

2.2 | Laboratory Bioassay

2.2.1 | FAW Culture

FAW neonates were sourced from FAW-infested maize fields at Kenya Agricultural and Livestock Research Organization (KALRO), Embu. Two hundred FAW neonates were placed in clear plastic containers and maintained in the laboratory while being fed with tender 2-to 3-week-old DH43 maize leaves for about 7 days until a sufficient population of 180 FAW larvae was obtained for the experiments. In the laboratory, the larvae were maintained at an ambient temperature of $25^\circ\text{C} \pm 1^\circ\text{C}$ and 75% relative humidity according to Ge et al. [36].

2.2.2 | Extraction of Essential Oils

Essential oils were extracted from Mexican sunflower leaves, Sodom apple fruits, garlic cloves, and red hot pepper fruits following the Soxhlet extraction method as described by Chouaibi et al. [37] and Zhang et al. [38]. A 10-g sample of each test plant was placed into cellulose extraction thimbles (internal diameter 30 mm $\times$ 80 mm; external diameter 32 $\times$ 80 mm Whatman) and then placed into a Soxhlet extractor with 250 mL hexane. The extraction procedure was carried out at 40°C for 6 h. The process was repeated until 15 mL of the extracts from each test plant was attained. After completion of the extraction process, the obtained extracts were rotated using a rotary evaporator to remove the solvent.

2.2.3 | Experimental Design and Layout

A completely randomized design (CRD) with 6 treatments replicated 3 times was adopted for this experiment. The treatments included purified essential oils of Sodom apple, Mexican sunflower, red hot pepper, and garlic. A synthetic pesticide (Occasion Star 200SC—active ingredients: emamectin benzoate and indoxacarb) served as a positive control, while distilled water was used as a negative control. Maize shoots were obtained from 3-week-old seedlings and were cut into 2–3 cm lengths using a sterile scalpel. The maize shoot pieces weighing 3 g each were placed in sterile clear plastic containers and sprayed with 3 mL of the purified essential oils per treatments. A 0.3 mL of the synthetic pesticide was diluted in 1 L of water, after which 3 mL of the resulting solution was measured and sprayed to the maize shoots. Five minutes after the treatment application, 10 third-instar larvae of FAW were transferred into each clear plastic container (see Figure 3).

2.2.4 | Data Collection and Analysis

FAW larva mortality was assessed and recorded at 24, 48, and 72 h after exposure to purified essential oil treatments. A larva was considered dead if it could not move itself or any of its body parts when placed on its dorsal surface and did not respond to touch. The mortality rate was used as a measure of the efficacy of the treatment against the FAW. The data were checked for normality using the Shapiro–Wilk test. The data were subjected to ANOVA using the R Statistical software Version 4.2.3 (R Core Team 2023), and separation of means was performed using Tukey's HSD at a $\alpha = 0.05$.

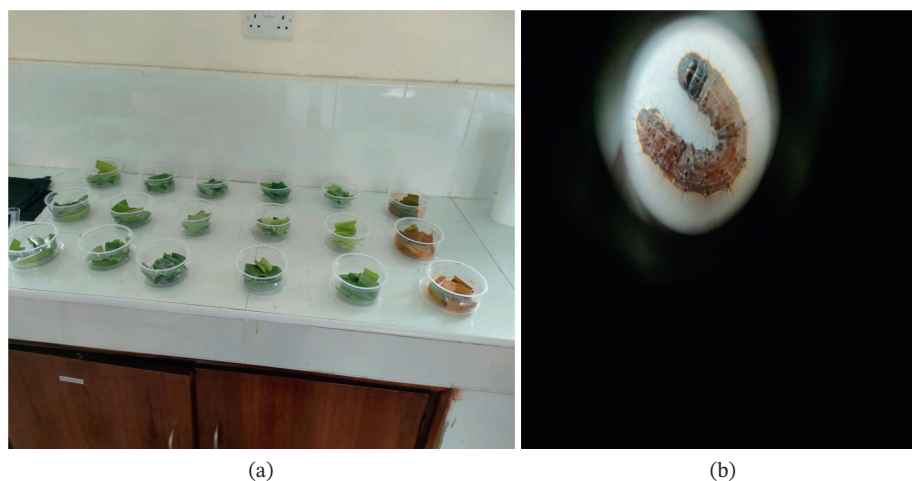


FIGURE 3 | Plate (a) treated maize shoots at the University of Embu Zoology Lab. Plate (b) third-instar FAW larva.

3 | Results

3.1 | Crude Extract (Field) Experiment

3.1.1 | Weather Data

Daily temperature and precipitation were recorded at the experimental site during the study period. The temperature ranged from 15°C to 29°C in the first season and 14°C to 29°C in the second season (Figure 4). Daily average temperatures were slightly higher in the first season (short rains) compared to the second season (long rains). Rainfall in the first season increased from 3.4 mm/day in November 2021 to 5.2 mm/day in December 2021 followed by a precipitous decrease in January 2022 (1.4 mm/day) signifying the end of the short rains. In the second season, the rains commenced in April 2022 with 5.2 mm/day followed by a decrease in May to 1.7 mm/day and a further decrease in June to 0.8 mm/day.

3.1.2 | FAW Incidence and Foliar Damage Severity

FAW incidence varied significantly ($p < 0.05$) among all treatments in both seasons. The lowest incidence was recorded in plots where synthetic pesticide (positive control) was applied, while the highest incidence was recorded in the plots where distilled water (negative control) was applied (Figure 5). The pest incidence was significantly lower in plots where the crude extracts of Sodom apple, garlic, and red hot pepper were applied compared to Mexican sunflower extracts in season one. In season two, all botanical extracts outperformed the negative control treatment. Similarly, analysis of the foliar damage severity showed that all treatments were significantly different ($p < 0.05$). The highest damage severity was observed in plots where distilled water was applied, while the lowest damage severity was recorded where the synthetic pesticide was applied (Figure 6). However, Sodom apple and garlic crude extracts exhibited significantly lower damage severity compared to Mexican sunflower extracts.

3.1.3 | Growth and Yield Variables of Maize

Maize growth and yield/quality varied significantly ($p < 0.05$) across treatments in terms of cob girth, cob length, and plant ear aspect in season one, with garlic crude extracts being the most

effective. There was no significant ($p > 0.05$) treatment effect on all tested growth variables as well as the number of cobs and the crop harvest index (Table 1). In season two, no significant ($p > 0.05$) treatment effect was observed on all the plant's growth and yield/quality components except on the plant ear aspect (Table 2). Combined season analysis showed no significant ($p > 0.05$) treatment effects for most of the growth and yield/quality variables except plant height, cob length, and plant ear aspect (Table 3). The highest plant height, cob length, and plant ear aspect were recorded in plots treated with synthetic pesticide. There were no significant seasonal variations in all growth and yield/quality components except for the stem girth ($p = 0.030$). There were no significant treatments and season interactions in all the growth, yield, and quality components.

3.1.4 | Effects of FAW Infestation on the Growth and Yield of Maize

There was significant positive correlation between FAW incidence and foliar damage severity in both seasons (Table 4). A nonsignificant correlation was observed between the pest dynamics and all the plant's growth, yield, and quality components.

3.2 | Laboratory Bioassay to Test the Efficacy of Essential Oils on FAW

Significant ($p < 0.05$) variations were observed among all the treatments in causing the mortality to FAW larvae at 24, 48, and 72 h after treatment application (Table 5). There was no significant variation between the three bioassays that were conducted. A combined analysis of all the three bioassays (Figure 7) showed that the synthetic pesticide caused 100% mortality within 24 h after application. However, both garlic and red hot pepper treatments recorded 83.33% mortality with the Mexican sunflower treatment recording the lowest mortality at 13.33%. After 48 h, garlic and red hot pepper treatments caused 100% mortality, followed by Sodom apple at 75.56% and distilled water at 59.38%, respectively, while Mexican sunflower was less effective, causing 38.89% mortality. Lastly, Mexican sunflower, Sodom apple, and distilled water caused 86.67%, 80%, and 65.56% mortality, respectively, with all other treatments recording 100% mortality at 72 h after application as shown in Figure 7.

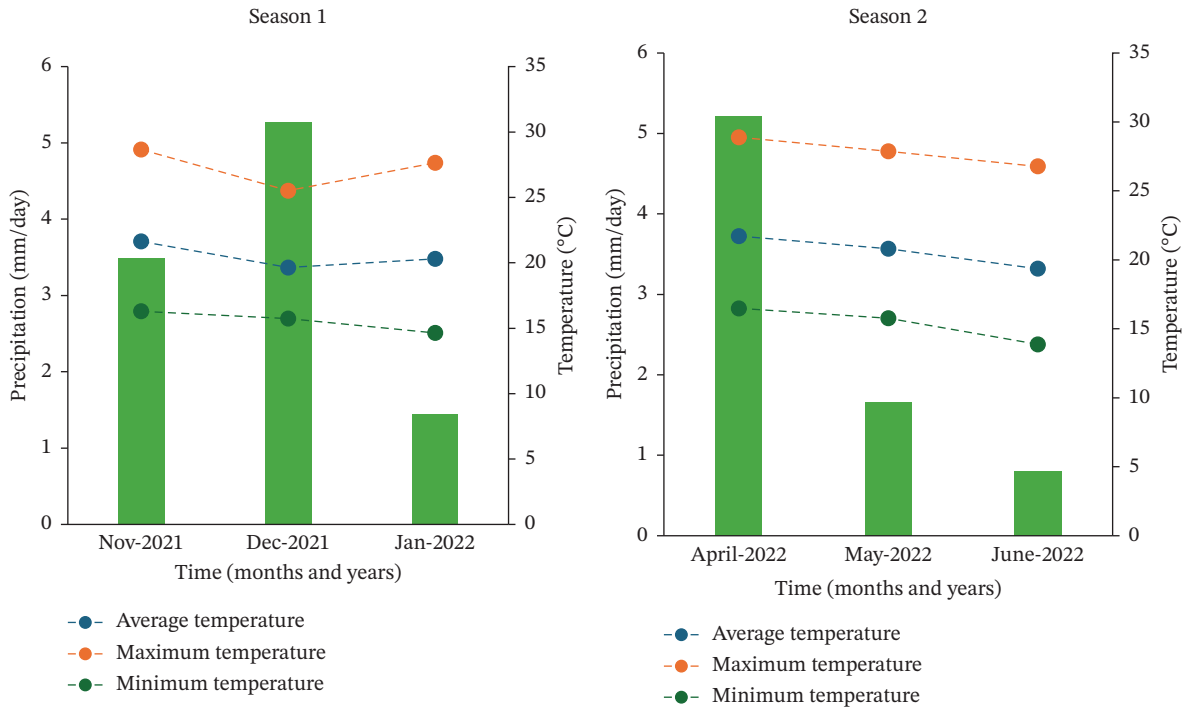


FIGURE 4 | Average rainfall (bar graph) and temperature (line graph) recorded at the experimental site through the short rain (1st season) and long rain (2nd season).

4 | Discussion

4.1 | Botanical Crude Extracts on Management of FAW

The study evaluated the efficacy of crude extracts from selected botanicals, namely Mexican sunflower, Sodom apple, garlic, and red hot pepper on the management of FAW in green maize. To understand the intensity of FAW infestation and damage severity over weeks, the AUDPC was computed. The AUDPC had previously been used to estimate injury/damage of diseases [39] and pests [40–42] over time. The AUDPC was also adopted by Kasoma et al. [43] to analyze the damage of FAW infestation

in screening resistant maize genotypes. The area under the curve discretizes the time when calculating the mean intensity of disease or pest between a pair of two adjacent time points followed by summing over specified time intervals [41]. The suitability of utilizing AUDPC to estimate the levels of pest incidence and severity was confirmed by the significant Pearson correlation that was observed between these two parameters indicating that higher FAW incidences resulted in higher foliar damage severity. A similar observation was made by Guera et al. [44].

The lower FAW infestation levels observed in plots where the synthetic pesticide (positive control) and the botanical crude

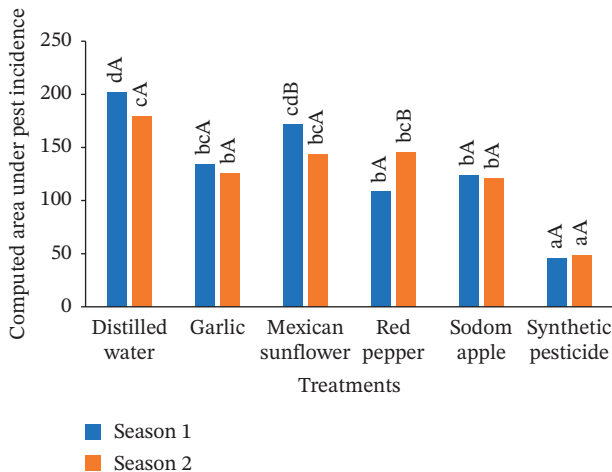


FIGURE 5 | Fall armyworm incidence on maize. Different small letters (a, b, bc, c, and d) indicate significant treatment effects, while different uppercase letters (A and B) indicate significant seasonal variations.

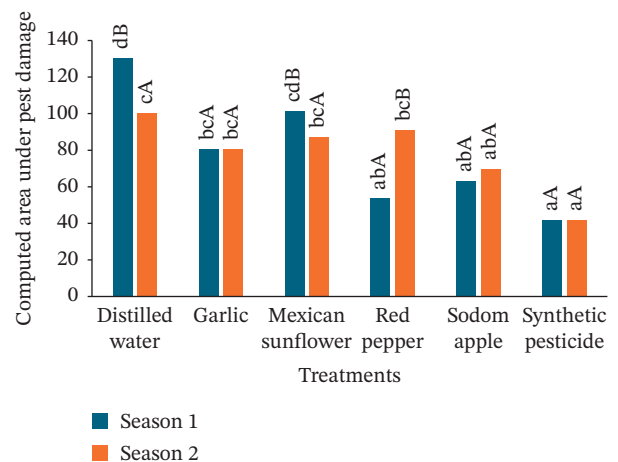


FIGURE 6 | Fall armyworm foliar damage severity on maize. Different small letters (a, ab, bc, c, and d) indicate significant treatment effects, while different uppercase letters (A and B) indicate significant seasonal variations.

TABLE 1 | Growth and yield components of maize in biopesticide treatments (season one).

Treatments	Growth components				Yield and quality components				
	Plant height (cm)	Internode length (cm)	Stem girth (cm)	Leaf number	Cob girth (cm)	Cob length (cm)	No. of cob rows	PEA	CHI
Distilled water	210.74	63.00	1.83	10.30	4.42abc	20.85a	13.11	3.00ab	2.89
Mexican sunflower	212.67	63.41	1.76	10.22	4.47ab	20.70a	13.56	2.33bc	2.96
Garlic	219.67	63.52	2.02	10.33	4.62a	21.89a	13.26	2.00c	2.74
Sodom apple	200.56	65.82	1.60	9.63	4.26bc	19.85ab	12.96	2.67bc	2.61
Synthetic pesticide	217.12	64.04	1.77	10.56	4.46ab	21.06a	13.19	1.00 d	2.87
Red pepper	184.04	55.53	1.63	9.85	4.17c	17.94b	12.59	3.667a	2.40
<i>p</i> value	0.066	0.645	0.168	0.325	0.002	0.002	0.412	< 0.0001	0.676
Standard error	7.650	4.271	0.107	0.296	0.054	0.043	0.305	0.202	0.262

Note: *p* values in bold are significant at *p* = 0.05; PEA = plant ear aspect—assessed based on the physical features of the maize plant ears; CHI = crop harvest index—ratio of cob weight to total maize stover weight.

extracts were applied are an indication of the potential efficacy of the botanical crude extracts as organic pesticides for sustainable management of FAW in green maize. These findings corroborate those of Tanyi et al. [27] who demonstrated the efficacy of the West African black pepper extract on FAW infestation in maize. Similar results were also reported by Mazed et al. [45] where selected botanical extracts demonstrated mortal toxicity to FAW larvae in maize under field conditions resulting in a substantial decrease in FAW severity in the treated plants. Sisay et al. [46] also reported significantly lower leaf injury by FAW larvae on plants treated with botanical crude extracts from *Schinus molle*, *Azadirachta indica*, and *Phytolacca dodecandra* as compared to untreated control plots. Also, Sunitha et al. [47] showed that botanicals, such as garlic bulb extract, Pongamia leaf extract, green chili pod extract, and custard apple leaf extract, were effective in reducing the larval population of FAW in sorghum. Likewise, Akeme et al. [48] reported that botanicals have similar efficacy to synthetic insecticides.

The observed efficacy of the tested botanicals in reducing FAW infestation and damage severity in maize indicates the presence of insecticidal properties in the tested botanicals. The insecticidal potential of red hot chili and garlic was also reported by Baidoo & Mochiah [49]. Their study assessed the effectiveness of these botanicals in controlling cabbage pests, such as diamondback moth (*Plutella xylostella*), cabbage aphid (*Brevicoryne brassicae*), cabbage looper (*Trichoplusia ni*), and cabbage webworm (*Hellula undalis*). The pesticidal efficacy of chili pepper extracts was also reported against African pod bug (*Clavigralla tomentosicollis*) and Fabricius (*Maruca vitrata*) in cowpea [50]. Gebreziher [51] also demonstrated the efficacy of garlic extract and neem extracts in controlling immature FAW. The garlic extracts were also reported by [47] to be effective against both the FAW egg masses and larval populations, thus underscoring its potential to serve as an alternative to chemical insecticide in FAW management. Further, repellent activity of the aqueous crude fruit sap extracted from Sodom apple (*S. incanum*) against green peach aphids was also demonstrated by Umar et al. [25].

TABLE 2 | Growth and yield components of maize in biopesticide treatments (season two).

Treatments	Growth components				Yield and quality components				
	Plant height (cm)	Internode length (cm)	Stem girth (cm)	Leaf number	Cob girth (cm)	Cob length (cm)	No. of cob rows	PEA	CHI
Distilled water	211.70ab	64.24	1.59	10.41	4.55	20.32	13.04	2.67b	2.39
Mexican sunflower	206.44ab	63.61	1.54	10.22	4.36	20.22	12.67	2.67b	2.79
Garlic	207.33ab	66.94	1.54	9.82	4.35	20.04	12.59	2.33b	2.32
Sodom apple	219.26ab	68.35	1.65	10.41	4.63	20.44	13.04	2.00bc	2.40
Synthetic pesticide	237.30a	69.30	1.59	10.30	5.92	20.05	12.96	1.00c	2.57
Red pepper	176.74b	56.19	1.57	10.11	4.42	18.16	12.52	4.00a	2.49
<i>p</i> value	0.087	0.215	0.943	0.800	0.517	0.322	0.221	< 0.0001	0.693
Standard error	12.094	3.617	0.087	0.332	0.637	1.653	0.181	0.251	0.214

Note: *p* values in bold are significant at *p* = 0.05; PEA = plant ear aspect—assessed based on the physical features of the maize plant ears; CHI = crop harvest index—ratio of cob weight to total maize stover weight.

TABLE 3 | Growth and yield components of maize in biopesticide treatments (combined seasons).

Treatments		Growth components				Yield and quality components				
		Plant height (cm)	Internode length (cm)	Stem girth (cm)	Leaf number	Cob girth (cm)	Cob length (cm)	No. of cob rows	PEA	CHI
Distilled water		211.22ab	63.62	1.711	10.35	4.49	20.58ab	13.07	2.83b	2.64
Mexican sunflower		209.56ab	63.51	1.652	10.22	4.42	20.46ab	13.11	2.50b	2.87
Garlic		213.50a	65.23	1.78	10.07	4.48	20.97ab	12.93	2.17b	2.53
Sodom apple		209.91ab	67.08	1.62	10.02	4.45	20.14ab	13.00	2.33b	2.51
Synthetic pesticide		227.21a	66.67	1.68	10.43	5.19	22.55a	13.07	1.00c	2.72
Red pepper		180.39b	55.91	1.60	9.98	4.29	18.05a	12.56	3.83a	2.44
<i>p</i> value		0.006	0.167	0.839	0.623	0.390	0.021	0.414	< 0.0001	0.541
Standard error		7.392	3.106	0.099	0.218	0.306	0.801	0.203	0.167	0.174
Seasonal variations	Season 1	207.47	62.57	1.77a	10.15	4.40	20.38	13.11	2.44	2.74
	Season 2	209.80	64.77	1.58b	10.21	4.70	20.54	12.80	2.44	2.49
<i>p</i> value		0.703	0.394	0.030	0.732	0.240	0.815	0.075	1.000	0.089
Standard error		4.268	1.793	0.057	0.126	0.177	0.462	0.117	0.096	0.101
Treatment × season (<i>p</i> values)		0.488	0.992	0.519	0.765	0.418	0.400	0.589	0.156	1.00

Note: *p* values in bold are significant at *p* = 0.05; PEA = plant ear aspect—assessed based on the physical features of the maize plant ears; CHI = crop harvest index—ratio of cob weight to total maize stover weight.

This study showed no significant treatment effects on most of the growth and yield components despite the relatively higher pest infestation and severity recorded in the negative control treatment. This was an indication of the resilience of the DH43 maize variety to FAW infestation, enabling it to continue growing and produce near normal yields regardless of the leaf damage. This observation was further confirmed by lack of significant correlation between the pest dynamics and the plant parameters. This finding is in line with Abang et al. [52] who showed that maize plants can compensate for FAW foliar damage, particularly under favorable conditions, and may produce normal yields even with high levels of infestation. Similar observation was made by Mumo et al. [1] in a modified climate-smart push-pull experiment where they found that the growth and yield of maize remained unchecked even under high FAW infestation in the monocrop plots. They attributed this observation to the favorable environmental factors including optimum rainfall and good soil fertility that enhanced the maize tolerance to pest infestations.

Similarly, Siazemo & Simfukwe [53] obtained similar maize yields in plots treated with extracts of garlic, neem, and china-berry and those treated with cypermethrin, a common synthetic pesticide. On the contrary, [54] recorded higher yield losses caused by FAW in maize plots treated with biopesticides including powdered plants as compared to synthetic pesticides.

4.2 | Efficacy of Essential Oils From the Test Plants on FAW Larval Mortality

Laboratory bioassay evaluated the efficacy of essential oils from the selected test plants on FAW larval mortality. The findings showed that essential oils from all the tested botanicals caused significantly higher mortality on FAW third-instar larvae as compared to the negative control (distilled water). These results confirmed the toxicity of essential oils of the selected botanicals against FAW larvae, thus indicating their potential for industrial exploitation in the production of organic pesticides. The potential

TABLE 4 | Pearson’s correlation between fall armyworm infestation levels and the maize growth and yield variables.

Crop variables	Season 1		Season 2	
	Pest incidence	Damage severity	Pest incidence	Damage severity
Plant height	0.093	0.037	−0.405	−0.435
Internode length	0.056	0.039	−0.274	−0.312
Stem girth	0.121	0.103	0.062	−0.007
Leaf number	−0.112	−0.105	0.024	−0.079
Cob girth	0.176	0.136	−0.408	−0.395
Cob length	0.134	0.122	−0.441	−0.432
Rows per cob	0.250	0.224	−0.014	−0.063
Crop harvest index	0.136	0.189	−0.053	−0.065
Damage severity	0.978	—	0.980	—

Note: Correlation values in bold show significant correlation at *p* = 0.05.

TABLE 5 | Fall armyworm mortality rate under different treatments (bioassays 1, 2, and 3).

Monitoring time	Treatment	Bioassay 1	Bioassay 2	Bioassay 3	Bioassay separation	
					<i>p</i> value	Std error
24 h	Distilled water	46.67 dA	53.33 dA	46.67 dA	0.332	3.333
	Mexican sunflower	10.00 eB	10.00 eB	20.00 eA	0.729	1.916
	Sodom apple	63.33 cA	63.33 cA	63.33 cA	1.000	3.333
	Red pepper	80.00 bB	90.00 bA	80.00 bB	1.000	3.826
	Garlic	80.00 bB	90.00 bA	80.00 bB	0.296	3.826
	Synthetic pesticide	100.00 aA	100.00 aA	100.00 aA	1.000	2.461
Treatment separation	<i>p</i> value	< 0.001	< 0.001	< 0.001		
	Std error	1.925	1.925	1.925		
48 h	Distilled water	56.67 bA	60.00 cA	60.00 bA	0.927	6.939
	Mexican sunflower	33.33 cB	43.33 dA	40.00 cA	0.178	2.722
	Sodom apple	73.33 bA	76.67 bA	76.67 bA	0.850	4.714
	Red pepper	100.00 aA	100.00 aA	100.00 aA	1.000	2.461
	Garlic	100.00 aA	100.00 aA	100.00 aA	1.000	2.461
	Synthetic pesticide	100.00 aA	100.00 aA	100.00 aA	1.000	2.461
Treatment separation	<i>p</i> value	< 0.001	< 0.001	< 0.001		
	Std error	4.714	3.043	2.723		
72 h	Distilled water	63.33 cA	66.67 dA	66.67 dA	0.729	3.333
	Mexican sunflower	80.00 bB	90.00 bA	90.00 bA	0.729	9.203
	Sodom apple	73.33 bB	83.33 cA	83.33 cA	0.125	4.714
	Red pepper	100.00 aA	100.00 aA	100.00 aA	1.000	2.461
	Garlic	100.00 aA	100.00 aA	100.00 aA	1.000	2.461
	Synthetic pesticide	100.00 aA	100.00 aA	100.00 aA	1.000	2.461
Treatment separation	<i>p</i> value	< 0.001	< 0.001	< 0.001		
	Std error	1.925	1.925	1.925		

Note: Values in bold are significant at $\alpha = 0.05$. Different small letters (a, b, c, and d) indicate a comparison of treatments, while different uppercase letters (A and B) indicate a comparison of bioassays.

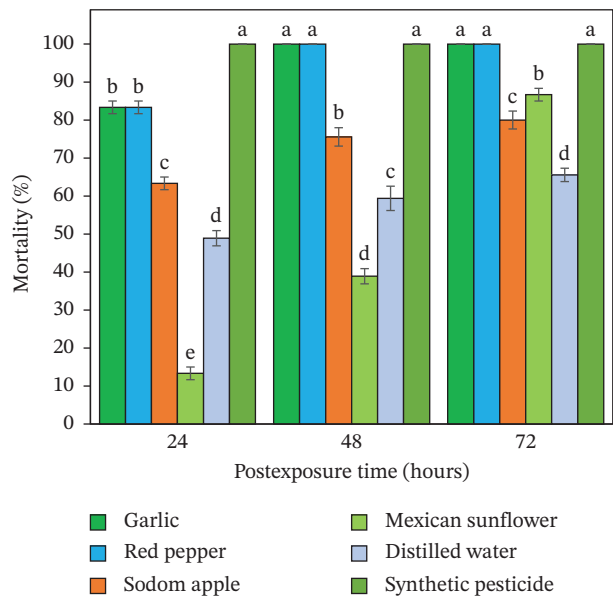


FIGURE 7 | Fall armyworm mortality rate after exposure to different treatments. Different small letters (a, b, c, d, and e) above the error bars indicate significant differences among the treatments at $p = 0.05$ according to Tukey's HSD test.

of different botanicals in controlling FAW has also been demonstrated in other similar laboratory experiments [46, 55–58]. The synthetic pesticide (Occasion Star 200SC—active

ingredients: emamectin benzoate and indoxacarb) attained 100% larval mortality within 24 h; thus, it had a higher knockdown effect as compared to the botanicals. Similar observation was made by Sisay et al. [46] that synthetic pesticides are more lethal to FAW larvae in laboratory and screenhouse trials. Contrary to our expectations, the negative control (distilled water) treatment also recorded substantial larval mortality of 48.87%, 58.38%, and 65.56% at 24, 48, and 72 h after application. This shows that some of the mortality that was observed was possibly stress-related mortality that occurs when the organism's physiology is overwhelmed by the change in its environment. This observation contradicts the findings of Akter et al. [59] who recorded no larval mortality in the control treatment at 24, 48, and 72 h after water spraying. Moreover, previous studies indicate that the survival of FAW larvae is highly influenced by the diet quality and controlled rearing conditions, with high mortality being observed under suboptimal feeding and environmental stress [60].

In this study, garlic and red pepper essential oils attained 100% larval mortality within the first 48 h; thus, they also showed a significantly higher knockdown effect close to that of the synthetic pesticide. These results agreed with those of Keerthi et al. [15] who demonstrated that essential oils of red hot pepper and garlic oil caused significant larval mortality within 72 h after application. However, the essential oils from Sodom apple and the Mexican sunflower showed significantly lower larval mortality compared to garlic and chili pepper. The Mexican

sunflower oils were apparently less toxic to the FAW larvae causing lower mortality than the control (distilled water) in the first 48 h, considering that some of this mortality may be attributed to external factors. These results concur with those of Kardinan and Maris [55], Mourad et al. [57], and Sisay et al. [46] who also showed significant variations in mortality rates caused by different botanicals on the third-instar FAW larvae.

The mode of action of different botanicals may occur from different phytochemicals that may have repellent, antifeedant, or pesticidal properties that deter, inhibit feeding behavior, or inhibit the growth of the pest. Qualitative phytochemical examination by Umar and Piero [25] demonstrated that the crude extract from the *S. incanum* fruit sap consists of alkaloids, flavonoids, cardiac glycosides, terpenoids, saponins, and tannins which contribute to its insecticidal activity. The major active compound of hot pepper seeds is capsaicin. The red hot pepper seed oils also contain polyunsaturated fatty acids and about 70% linoleic acids [37]. Additionally, Dobón-Suárez et al. [61] reported the presence of other crucial bioactive compounds, such as phytosterols, polyphenols, tocopherols, and aromatic compounds in red pepper seed oils. The major active compounds in the essential oil of garlic include diallyl disulfide, diallyl sulfide, diallyl trisulfide, methyl disulfide, and dimethyl disulfide [62]. Keerthi et al. [15] majorly associated the allyl disulfide component of garlic oil to its larvicidal activity against FAW larvae.

Biopesticides play a key role in promoting sustainable agriculture by reducing the damage associated with synthetic pesticides [63]. Despite their benefits, future research could focus on exploring the mechanism of action of the botanical extracts, testing different plant formulations or concentrations, or examining the integration with other pest management strategies. Further studies could aim to perform gas chromatography–mass spectrometry (GC-MS) analysis on the botanical plant oils to screen for the active compounds and validate the insecticidal properties. Additionally, research approaches toward sustainability and commercialization of botanical pesticides require attention.

5 | Conclusion and Recommendation

The field experiments conducted in this study confirmed the efficacy of the crude extracts of garlic, red hot pepper, and Sodom apple in the management of FAW under natural conditions, though at variable levels. Further, the laboratory experiments demonstrated that essential oils of these three botanicals are potentially toxic to FAW larvae. Based on these findings, this study recommends the incorporation of the crude extracts of garlic, red hot pepper, and Sodom apple in integrated pest management (IPM) strategies in small-scale production of maize and other cereals within the FAW host spectrum. In addition, the study recommends industrial exploitation of these botanicals for the production of organic pesticides to enable their sustainable utilization even at large-scale production. This initiative would be impactful in reducing overreliance on synthetic pesticides, thus enhancing human and ecosystem safety in the production of maize and related crops.

Acknowledgments

The authors are grateful to Mr. Samuel Thuita, Mr. Peter Anunda, Mr. Douglas Mageto, Mr. Jeremy Mugendi, Mr. Kevin Wanjala, Mr. Anthony

Nyaga, and Ms. Brenda Apiyo from the University of Embu for their technical support.

Funding

The work was carried out with the aid of a grant from UNESCO and the International Development Research Centre, Ottawa, Canada.

Disclosure

The views expressed herein do not necessarily represent those of UNESCO, IDRC, or its Board of Governors.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be available from the corresponding author upon request.

References

1. C. K. Mumo, P. W. Muturi, and B. M. Gichimu, “A Modified Climate-Smart Push-Pull Technology for the Management of Fall Armyworm (*Spodoptera frugiperda*) in the Semiarid Lands of Kenya,” *International Journal of Agronomy* 2024, no. 1 (January 2024): 8038142, <https://doi.org/10.1155/2024/8038142>.
2. W. d. S. Candido, C. M. Silva, M. L. Costa, et al., “Selection Indexes in the Simultaneous Increment of Yield Components in Topcross Hybrids of Green Maize,” *Pesquisa Agropecuária Brasileira* 55 (2020): e01206, <https://doi.org/10.1590/s1678-3921.pab2020.v55.01206>.
3. C. A. Wongnaa, I. A. Apike, M. A. Aryee, M. A. S. Hagan, and D. Awunyo-Vitor, “Fresh or Dry Maize or Both: Which is Most Economical and Preferred by Farmers?” *Journal of Agriculture and Food Research* 16 (June 2024): 101158, <https://doi.org/10.1016/j.jafr.2024.101158>.
4. N. Alexandridis, B. Feit, J. Kihara, et al., “Climate Change and Ecological Intensification of Agriculture in Sub-Saharan Africa—A Systems Approach to Predict Maize Yield Under Push-Pull Technology,” *Agriculture Ecosystems and Environment* 352 (August 2023): 108511, <https://doi.org/10.1016/j.agee.2023.108511>.
5. Fao, *East Africa Regional Market Intelligence Report* (2017).
6. T. Kumela, J. Simiyu, B. Sisay, et al., “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, no. 1 (January 2019): 1–9, <https://doi.org/10.1080/09670874.2017.1423129>.
7. T. R. Bilbo, F. P. F. Reay-Jones, and J. K. Greene, “Evaluation of Insecticide Thresholds in Late-Planted Bt and Non-Bt Corn for Management of Fall Armyworm (*Lepidoptera: Noctuidae*),” *Journal of Economic Entomology* 113, no. 2 (2020): 814–823, <https://doi.org/10.1093/jee/toz364>.
8. A. J. Hruska, *Fall Armyworm (Spodoptera frugiperda) Management by Smallholders* (CABI Rev, 2019), 1–11, <https://doi.org/10.1079/PAVSNNR201914043>.
9. A. L. Souto, M. Sylvestre, E. D. Tölke, J. F. Tavares, J. M. Barbosa-Filho, and G. Cebrián-Torrejón, “Plant-Derived Pesticides as an Alternative to Pest Management and Sustainable Agricultural Production: Prospects, Applications and Challenges,” *Molecules* 26, no. 16 (August 2021): 4835, <https://doi.org/10.3390/molecules26164835>.
10. A. R. Abubakar and M. Haque, “Preparation of Medicinal Plants: Basic Extraction and Fractionation Procedures for Experimental Purposes,” *Journal of Pharmacy and BioAllied Sciences* 12, no. 1 (January 2020): 1–10, https://doi.org/10.4103/jpbs.JPBS_175_19.
11. N. Altaf, M. Arshad, M. Z. Majeed, et al., “Comparative Effectiveness of Chlorantraniliprole and Neem Leaf Extract Against Fall Armyworm,

- Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae),” *Sarhad Journal of Agriculture* 38, no. 3 (2022): <https://doi.org/10.17582/journal.sja/2022/38.3.833.840>.
12. A. Lyubenova, L. Georgieva, and V. Antonova, “Utilization of Plant Secondary Metabolites for Plant Protection,” *Biotechnology and Biotechnological Equipment* 37, no. 1 (March 2023): 2297533, <https://doi.org/10.1080/13102818.2023.2297533>.
 13. P. Bolouri, R. Salami, S. Kouhi, et al., “Applications of Essential Oils and Plant Extracts in Different Industries,” *Molecules* 27, no. 24 (December 2022): 8999, <https://doi.org/10.3390/molecules27248999>.
 14. R. Vijayan, C. S. Vidhya, Ramkumar, et al., “Use of Botanicals Plant for Stored Grain Pest Management: A Critical Review,” *International Journal of Plant and Soil Science* 35, no. 21 (November 2023): 801–809, <https://doi.org/10.9734/ijpss/2023/v35i214047>.
 15. M. C. Keerthi, S. S. Suroshe, S. Doddachowdappa, et al., “Bio-Intensive Tactics for the Management of Invasive Fall Armyworm for Organic Maize Production,” *Plants* 12, no. 3 (February 2023): 685, <https://doi.org/10.3390/plants12030685>.
 16. M. Munyore and N. B. Rioba, *Evaluation of Garlic (Allium sativum) and Onion (Allium cepa) Extracts for the Management of Fall Armyworm (Spodoptera frugiperda) on Baby Corn (Zea mays L.) Under Greenhouse Conditions* (2020).
 17. F. A. Opondo, I. O. K’Owino, S. C. Chepkwony, and V. J. Kosgei, “In Vitro Antibacterial Activity of Essential Oils From *Tithonia diversifolia* Leaves and Flowers Against *Ralstonia solanacearum*,” *Advanced Image Video Process* 10, no. 2 (April 2022): <https://doi.org/10.14738/aivp.102.12172>.
 18. W. V. Gumbeze, R. D. Katsaruware-Chapoto, K. Christopher, W. N. Mangadze, C. J. Hatungimana, and M. Mandingaisa, “The Effectiveness of Hot Pepper (*Capsicum frutescens* L.) Extracts in Managing Major Pests of Cabbage (*Brassica oleracea* L.) Under Rain Fed Conditions,” *American International Journal of Sciences and Engineering Research* 6, no. 5 (2023).
 19. S. Kumar, M. Sarpras, F. Mushtaq, S. Singh, A. Thattantavide, and A. Kumar, “Capsaicin-Producing Plants: Species Diversity, Distribution and Botanical Details,” in *Capsaicinoids* (Singapore: Springer Nature Singapore, 2024), 1–24, https://doi.org/10.1007/978-981-99-7779-6_1.
 20. J. Van den Berg and H. du Plessis, “Chemical Control and Insecticide Resistance in *Spodoptera frugiperda* (Lepidoptera: Noctuidae),” *Journal of Economic Entomology* 115, no. 6 (December 2022): 1761–1771, <https://doi.org/10.1093/jee/toac108>.
 21. L. N. Nyongesa, K. Kiprotich, D. Omayio, et al., “Potential for Integrated Botanicals and Host Resistance in Maize for Management of Fall Armyworm in Kenya,” *African Crop Science Journal* 33, no. 3 (August 2025): 309–325, <https://doi.org/10.4314/acsj.v33i3.6>.
 22. R. Jaetzold, H. Schmidt, Z. B. Homet, and C. A. Shisanya, “Farm Management Handbook of Kenya: Natural Conditions and Farm Information,” *Nairobi East Provincial Ministry of Agriculture* 11 (2007).
 23. K. M. Wanjohi, *Tillage, Crop Residue and Inorganic Nitrogen Effects on Crop Yields, Soil Carbon and Nitrogen in Kirimari Ward in Embu County, Kenya* (Kenyatta University, 2019).
 24. L. G. Mugao, P. W. Muturi, B. M. Gichimu, and E. K. Njoroge, “In Vitro Control of *Phytophthora infestans* and *Alternaria solani* Using Crude Extracts and Essential Oils from Selected Plants,” *International Journal of Agronomy* 2020 (2020): 1–10, <https://doi.org/10.1155/2020/8845692>.
 25. A. Umar and N. M. Piero, “Bio Efficacy of Aqueous Crude Fruit Sap Extract of *Solanum incanum* Against Green Peach Aphids *Myzus persicae* Sulzer (Homoptera: Aphididae),” *Entomology, Ornithology and Herpetology* 5, no. 169 (2015): 983–2161, <https://doi.org/10.4172/2161-0983.1000169>.
 26. Q. Zhao, Y. Qu, and D. Liu, “Real-Time Monitoring of Maize Phenology Using Ground Camera Fusion Information,” *Smart Agricultural Technology* 10 (March 2025): 100850, <https://doi.org/10.1016/j.atech.2025.100850>.
 27. C. B. Tanyi, R. N. Nkongho, J. N. Okolle, A. S. Tening, and C. Ngosong, “Effect of Intercropping Beans With Maize and Botanical Extract on Fall Armyworm (*Spodoptera frugiperda*) Infestation,” *International Journal of Agronomy* 2020 (May 2020): 1–7, <https://doi.org/10.1155/2020/4618190>.
 28. G. Hailu, S. Niassy, K. R. Zeyaur, N. Ochatum, and S. Subramanian, “Maize–Legume Intercropping and Push–Pull for Management of Fall Armyworm, Stemborers, and Striga in Uganda,” *Agronomy Journal* 110, no. 6 (2018): 2513–2522, <https://doi.org/10.2134/agronj2018.02.0110>.
 29. C. J. Stubbs, B. Kunduru, N. Bokros, et al., “Moving Toward Short Stature Maize: The Effect of Plant Height on Maize Stalk Lodging Resistance,” *Field Crops Research* 300 (September 2023): 109008, <https://doi.org/10.1016/j.fcr.2023.109008>.
 30. J. Xue, S. Gao, Y. Fan, et al., “Traits of Plant Morphology, Stalk Mechanical Strength, and Biomass Accumulation in the Selection of lodging-Resistant Maize Cultivars,” *European Journal of Agronomy* 117 (2020): 126073, <https://doi.org/10.1016/j.eja.2020.126073>.
 31. M. D. Asfaw, “Effects of Animal Manures on Growth and Yield of Maize (*Zea mays* L.),” *J. Plant Sci. Phytopathol* 6, no. 1 (2022): 33–39.
 32. T. Kosgei, D. Makumbi, E. K. Mageto, et al., “Genetic Analysis of Ear, Husk, and Tassel Traits in Tropical Maize Under Diverse Environments,” *Frontiers in Plant Science* 16 (August 2025): 1618054, <https://doi.org/10.3389/fpls.2025.1618054>.
 33. B. S. Meena and A. Bhelave, “Physical Characteristics of Maize Plants for Development of Maize Cobs Picker,” *Biological Forum—An International Journal* (2023): 408.
 34. W. Liu, P. Hou, G. Liu, et al., “Contribution of Total Dry Matter and Harvest Index to Maize Grain yield—A Multisource Data Analysis,” *Food and Energy Security* 9, no. 4 (November 2020): e256, <https://doi.org/10.1002/fes3.256>.
 35. M. J. Jeger and S. L. H. Viljanen-Rollinson, “The Use of the Area Under the Disease-Progress Curve (AUDPC) to Assess Quantitative Disease Resistance in Crop Cultivars,” *Theoretical and Applied Genetics* 102, no. 1 (2001): 32–40, <https://doi.org/10.1007/s001220051615>.
 36. S. Ge, B. Chu, W. He, et al., “Wheat-Bran-Based Artificial Diet for Mass Culturing of the Fall Armyworm, *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae),” *Insects* 13, no. 12 (December 2022): 1177, <https://doi.org/10.3390/insects13121177>.
 37. M. Chouaibi, L. Rezig, S. Hamdi, and G. Ferrari, “Chemical Characteristics and Compositions of Red Pepper Seed Oils Extracted by Different Methods,” *Industrial Crops and Products* 128 (February 2019): 363–370, <https://doi.org/10.1016/j.indcrop.2018.11.030>.
 38. H. Zhang, Y. Yuan, X. Zhu, et al., “The Effect of Different Extraction Methods on Extraction Yield, Physicochemical Properties, and Volatile Compounds From Field Muskmelon Seed Oil,” *Foods* 11, no. 5 (February 2022): 721, <https://doi.org/10.3390/foods11050721>.
 39. Y. Mengist and Y. Moges, “Participatory Evaluation of Maize Varieties for the Management of Maize Gray Leaf Spot Disease (*Cercospora zeae Maydis*) at Gondar Zuria District, Northwest Ethiopia,” *Journal of Dryland Agriculture* 5, no. 1 (2019): 1–6, <https://doi.org/10.5897/JODA2018.0001>.
 40. N. P. Castilla, A. M. Stuart, O. Makara, et al., “Characterization of Cropping Practices, Pest Constraints, and Yield Variation in Irrigated Lowland Rice of Cambodia,” *Crop Protection* 135 (2020): 104906, <https://doi.org/10.1016/j.cropro.2019.104906>.
 41. G. C. Jahn, “Effect of Neem Oil, Monocrotophos, and Carbosulfan on Green Leafhoppers, *Nephotettix virescens* (Distant)(Homoptera: Cicadellidae) and Rice Yields in Thailand,” 31 (1992), 8, <https://hdl.handle.net/10125/11285>.

42. S. Savary, N. Mroberts, P. D. Esker, L. Willocquet, and P. S. Teng, "Production Situations as Drivers of Crop Health: Evidence and Implications," *Plant Pathology* 66, no. 6 (2017): 867–876, <https://doi.org/10.1111/ppa.12659>.
43. C. Kasoma, H. Shimelis, M. D. Laing, and B. Mekonnen, "Fall Armyworm Infestation and Development: Screening Tropical Maize Genotypes for Resistance in Zambia," *Insects* 13, no. 11 (2022): 1020, <https://doi.org/10.3390/insects13111020>.
44. O. G. M. Guera, F. Castrejón-Ayala, N. Robledo, et al., "Geostatistical Analysis of Fall Armyworm Damage and Edaphoclimatic Conditions of a Mosaic of Agroecosystems Predominated by push-pull Systems," *Chilean Journal of Agricultural Research* 83, no. 1 (2023): 14–30, <https://doi.org/10.4067/s0718-58392023000100014>.
45. M. K. Mazed, M. M. Rahman, E. Ara, M. S. Hossain, and M. R. Amin, "Field Efficacy of Selected Insecticides and Botanicals Against Fall Armyworm in Maize," *Journal of Entomology and Zoology Studies* 10, no. 6 (November 2022): 33–38, <https://doi.org/10.22271/j.ento.2022.v10.i6a.9103>.
46. B. Sisay, T. Tefera, M. Wakgari, G. Ayalew, and E. Mendesil, "The Efficacy of Selected Synthetic Insecticides and Botanicals Against Fall Armyworm, *Spodoptera frugiperda*, in Maize," *Insects* 10, no. 2 (2019): 45, <https://doi.org/10.3390/insects10020045>.
47. S. V. L. Sunitha, M. Swathi, T. Madhumathi, and P. A. Kumar, "Efficacy of Botanicals Against Fall Armyworm, *Spodoptera frugiperda* (JE Smith) in Sorghum," *Journal of Experimental Zoology India* 26, no. 1 (2023): 481–488, <https://doi.org/10.51470/jez.2023.26.1.481>.
48. C. N. Akeme, C. Ngosong, S. A. Sumbele, et al., "Different Controlling Methods of Fall Armyworm (*Spodoptera frugiperda*) in Maize Farms of Small-Scale Producers in Cameroon," *IOP Conference Series: Earth and Environmental Science* 911, no. 1 (November 2021): 012053, <https://doi.org/10.1088/1755-1315/911/1/012053>.
49. P. K. Baidoo and M. B. Mochiah, "Comparing the Effectiveness of Garlic (*Allium sativum* L.) and Hot Pepper (*Capsicum frutescens* L.) in the Management of the Major Pests of Cabbage *Brassica oleracea* (L.)," *Sustainable Agriculture Research* 5, no. 2 (April 2016): 83, <https://doi.org/10.5539/sar.v5n2p83>.
50. K. S. Pagire, "Eco-Friendly Management of Fall Armyworm, *Spodoptera frugiperda* (JE SMITH) in Maize," *Diss. Mahtema Pluekrishi Vidyapeeth* (2024): 1–203.
51. H. G. Gebreziher, "Review on Management Methods of Fall Armyworm (*Spodoptera frugiperda* JE Smith) in Sub-Saharan Africa," *International Journal of Entomology Research* 5, no. 2 (2020): 9–14.
52. A. F. Abang, S. Nanga Nanga, M. K. Agbodzavu, et al., "Maize Plants can Recover From Fall Armyworm Damage Under Optimum Crop Production Conditions in Humid Tropical Agro-Ecologies," *Journal of Economic Entomology* 117, no. 6 (December 2024): 2269–2280, <https://doi.org/10.1093/jee/toae235>.
53. M. K. Siazemo and P. Simfukwe, "An Evaluation of the Efficacy of Botanical Pesticides for Fall Armyworm Control in Maize Production," *OALib* 07, no. 09 (2020): 1–12, <https://doi.org/10.4236/oalib.1106746>.
54. A. I. Jalali, M. Ali, H. M. Hammad, and F. Z. A. Khan, "Effects of Biorational Approaches and Synthetic Pesticides on Fall Armyworm Management and Arthropod Diversity in Maize," *Pakistan Journal of Zoology* 56, no. 6 (2024): 1–9, <https://doi.org/10.17582/journal.pjz/20231114071402>.
55. A. Kardinan and P. Maris, "Effect of Botanical Insecticides Against Fall Armyworm *Spodoptera frugiperda* J. E. smith (*Lepidoptera: Noctuidae*)," *IOP Conference Series: Earth and Environmental Science* 653, no. 1 (February 2021): 012060, <https://doi.org/10.1088/1755-1315/653/1/012060>.
56. S. Mugwanya, in *Evaluation of the Potential of Chili Pepper and Neeem Leaf Aqueous Extracts to Control Fall Armyworm (Spodoptera frugiperda) on Maize Plants* (Busitema University, 2021), <https://hdl.handle.net/20.500.12283/1323>.
57. S. A. Mourad, I. A. El-Sappagh, A. E. H. Khalil, and S. M. El-Amir, in *Efficacy of Some Synthetic Insecticides and Botanical Oils Against Fall Armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae), on Maize in Egypt* (2022), <https://ejbsf.journals.ekb.eg/>.
58. N. B. Rioba and P. C. Stevenson, "Opportunities and Scope for Botanical Extracts and Products for the Management of Fall Armyworm (*Spodoptera frugiperda*) for Smallholders in Africa," *Plants* 9, no. 2 (February 2020): 207, <https://doi.org/10.3390/plants9020207>.
59. I. Akter, M. A. Hossain, M. A. Alim, and H. F. EL Taj, *Ovicidal and Larvicidal Efficacy of Four Botanical Oils Against *Spodoptera frugiperda* (FAW) Infesting Maize* (2023), 371.
60. S. Thirawut, W. Sutjaritthammajariyangkun, A. Rukkasikorn, P. Punyawattoe, U. Noonart, and Y. Kobori, "Pesticide Susceptibility Monitoring of Fall Armyworms (*Spodoptera frugiperda* (J.E. Smith)): A Simple Methodology for Information-Sharing Among Southeast Asian Countries," *CABI Agriculture and Bioscience* 4, no. 1 (June 2023): 19, <https://doi.org/10.1186/s43170-023-00160-8>.
61. A. Dobón-Suárez, P. J. Zapata, and M. E. García-Pastor, "A Comprehensive Review on Characterization of Pepper Seeds: Unveiling Potential Value and Sustainable Agrifood Applications," *Foods* 14, no. 11 (June 2025): 1969, <https://doi.org/10.3390/foods14111969>.
62. L. Huang, Z. Liu, J. Wang, et al., "Bioactivity and Health Effects of Garlic Essential Oil: A Review," *Food Science and Nutrition* 11, no. 6 (June 2023): 2450–2470, <https://doi.org/10.1002/fsn3.3253>.
63. E. O. Fenibo and T. Matambo, "Biopesticides for Sustainable Agriculture: Feasible Options for Adopting Cost-Effective Strategies," *Frontiers in Sustainable Food Systems* 9 (October 2025): 1657000, <https://doi.org/10.3389/fsufs.2025.1657000>.