Research Article

LABORATORY AND FIELD EVALUATION OF INSECTICIDES AGAINST FALL ARMYWORM (*Spodoptera frugiperda* J. E. SMITH) LARVAE ON MAIZE

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ABSTRACT

Fall armyworm (*Spodoptera frugiperda* J. E. Smith) is a destructive pest that threatens maize production globally, including in Nepal. A laboratory leaf dip bioassay was conducted at Agriculture and Forestry University, Chitwan, to evaluate the efficacy of insecticides: chlorantraniliprole 18.5% SC, emamectin benzoate 5% SC, spinetoram 11.7% SC, spinosad 45% SC, azadirachtin 1500 ppm, malathion 50% EC, and chlorantraniliprole + lambda-cyhalothrin 0.15% ZC. Second-instar larvae were tested using a Completely Randomized Design with four replications. At the end of the experiment, 100 percent mortality was recorded for all treatments except malathion and azadirachtin. A field trial was conducted in 2022 on spring maize (Rampur Composite) in Chitwan, employing a Randomized Complete Block Design with eight treatments, including malathion, wood ash, soap solution, sawdust, azadirachtin, sugar solution, chlorantraniliprole + lambda-cyhalothrin, and water spray as a control, which were replicated three times. Applications were made twice (at 24 and 45 days after sowing), and data were collected before and after each spray. Based on the percentage of plant infestation with live larvae and foliar damage caused by larvae, chlorantraniliprole + lambda-cyhalothrin was most effective, followed by azadirachtin. Local materials such as soap solution, wood ash, sawdust, and sugar solution also significantly reduced FAW damage. The study suggests that integrating chemical and local treatments offers a sustainable strategy for managing fall armyworm in maize.

Key words : Fall armyworm, maize, local materials, chlorantraniliprole+ lambda-cyhalothrin, azadirachtin

INTRODUCTION

In Nepal, maize (*Zea mays* L.) ranks second in terms of area and production, contributing 9,85,565 ha with a total production of 31,06,397 mt and a productivity of 3.15 mt/ha (MoALD, 2023). Maize production is impacted by insect pests and diseases, with significant losses attributed to fall armyworm (Ranum et al., 2014). Fall armyworm (*Spodoptera frugiperda*, J. E. Smith) is a polyphagous and highly destructive agricultural pest, particularly favoring maize and sweetcorn (Montezano et al., 2018; Sparks, 1979). According to Hardke et al. (2015), it is a sporadic pest characterized by migratory behavior and a high fecundity rate. In Nepal, this pest was first observed in Gaidakot, Nawalpur district, on May 9, 2019 (Bajracharya et al., 2019). Currently, this pest has spread to over 72 districts of Nepal, causing losses of 20-35% (PQPMC, 2019). Fall armyworm belongs to the Order Lepidoptera and has unique morphological features in larval and adult stages; the larva displays a white inverted 'Y' on the head, distinct black spots on the body, and four "dots" forming a rectangular shape on the eighth abdominal segment of the larval abdomen (Kalleshwaraswamy et al., 2018). The larval stage of this species feeds on growing maize leaves, creating elongated papery windows, and moves to the whorl, leaving moist sawdust-like frass near the funnel and upper leaves (CABI, 2017).

Pesticidal management is a common practice for fall armyworm management in Nepal and other developing countries in South Asia (Bhusal & Bhattarai, 2019). Spinosad, chlorantraniliprole, azadirachtin, and emamectin benzoate are the most frequently used insecticides for fall armyworm (Gahatraj et al., 2020). In laboratory studies, the mortality of fall armyworm was reported to be higher with new-generation insecticides like chlorantraniliprole, flubendiamide, and spinetoram, compared to the conventional options, lambda-cyhalothrin and novaluron (Hardke et al., 2014). Neem-based pesticides, spinetoram, emamectin benzoate, chlorantraniliprole, and spinosad are the commonly recommended pesticides to control the fall armyworm in Nepal (GC et al., 2019). Many insecticides recommended against fall armyworm in other countries are either not registered in Nepal or not readily available in the local market. Current management practices for the pest are not sustainable due to the increasing intensity of pesticide use to manage the fall armyworm. It is necessary to minimize the use of insecticides, especially those that are highly hazardous and broad-spectrum. Considering the present status, this study aims to assess the effectiveness of locally available materials and chemical insecticides for controlling *S. frugiperda*. This would play a prominent role in Integrated Pest Management (IPM), providing wider options for farmers in choosing insecticides.

MATERIALS AND METHODS

Laboratory Experiment

Colony management of fall armyworm

A leaf-dip bioassay experiment using some common insecticides against the fall armyworm was conducted at the Entomology laboratory of Agriculture and Forestry University (AFU) in June 2022. The experiment was designed as a Completely Randomized Design (CRD) with eight treatments, each replicated four times. It was set up in the laboratory using Petri dishes measuring 8.50 cm in diameter and 1.20 cm in height. The fall armyworm eggs, as described by Deshmukh et al. (2020), were collected along with maize leaves (crop variety: Rampur Composite) using scissors and placed in normal aerated polythene bags, which were taken to the entomology laboratory. The egg masses were then kept in a white transparent plastic box (19.00 cm x 12.50 cm x 7.50 cm) and placed inside the bug dorm (24.50 x 24.50 x 24.50 cm). A bug dorm is an insect rearing cage, ideal for rearing and breeding many types of insects (Anonymous, 2024). After the eggs hatched, the larvae were reared on chopped fresh maize leaves until they transitioned into second instars. Second-stage larvae were starved for 24 hours. The day after starvation, five active second-instar fall armyworm larvae were transferred to each Petri dish. Partially moistened filter paper was placed at the base of each Petri dish. Treated maize leaves were replaced every second day, and excreta were cleaned daily.

Leaf dip bioassay

Each treatment was dissolved in water to achieve the recommended concentration, as listed in Table 1. Maize leaves were collected from potted plants (25-day-old seedlings and 15.00 cm in height) and cut into pieces of equal dimensions (10.00 cm x 3.00 cm) using sterilized scissors. Freshly prepared leaf pieces were dipped in various insecticide solutions for one minute and allowed to dry for 5 minutes before being transferred to new Petri dishes. Leaves treated with sterile water served as controls. The number of dead and live larvae was counted and recorded in each Petri dish. Larval mortality was assessed at 12, 24, and 48 hours post-treatment. A larva was considered dead if no movement was observed when pricked with an inoculating needle.

Table 1. Treatments used in the leaf-dip laboratory bioassay experiment in Rampur, Chitwan, Nepal

Treatments	Trade Name	Dose (ml/ L of water)	Label
Chlorantraniliprole 18.5%SC	Cover	0.4 ml / L	Green
Emamectin Benzoate 5% SG	Kingstar	0.4 gm / L	Yellow
Spinetoram 11.7% SC	Largo	0.4 ml / L	Green
Spinosad 45% SC	Tracer	0.3 ml / L	Blue
Azadirachtin 1500 ppm	Neemras	5 ml/ L	Green
Malathion 50% EC	Malathion	1.5 ml/ L	Blue
Chlorantraniliprole + Lambda cyhalothrin 0.15% ZC	Ampligo	0.4 ml / L	Yellow
Control (water spray)	-	-	-

Field Experiment

The experiment was conducted in 2022 on spring maize (from March to June) (variety: Rampur Composite) in Rampur, Chitwan, Nepal, located at 27.6504070 N latitude and 84.3501430 E longitude, at an elevation of 228 meters above sea level (masl). Meteorological data during the study period are shown in Fig. 1. It utilized a Randomized Complete Block Design (RCBD) with eight treatments (including an untreated control), each replicated three times. The treatments are shown in Table 2. Each treatment plot measured 4 m × 3 m, consisting of four rows, each containing 20 maize plants. Row-to-row and seed-to-seed spacings were maintained at 75 cm × 20 cm, respectively. All agronomic practices followed the recommendations of the National Maize Research Program (NMRP), Rampur, Chitwan, Nepal. Insecticide concentrates were prepared using various formulations, viz. EC, SC. For this, the required quantity of insecticide (Table 2) was measured and poured into the knapsack sprayer, to which water was added and well mixed. The recommended dose (1 teaspoon/whorl) of certain safe materials (like wood ash and sawdust) was applied to the maize whorl. All treatments were administered twice during the study period. The first application occurred when a sufficient infestation was observed, coinciding with the crop being 24 days old (V4 stage). The second application was made 45 days after the maize sowing. During spraying, insecticides were specifically directed at the whorl region using a knapsack sprayer, while other non-chemical materials were placed at the center of the whorl. Observations were recorded before the treatments were applied (pre-treatment counts), and post-treatment observations were noted at 5, 10, and 15 days after each application. Sample plants were selected from the middle rows of maize plants in the net plot area. Observations focused on the total number of plant stands and the count of infected plants. Foliar damage on the upper four leaves and the whorl was observed. The percentage of plant infestation was calculated based on the number of infested plants relative to the total count of plants.

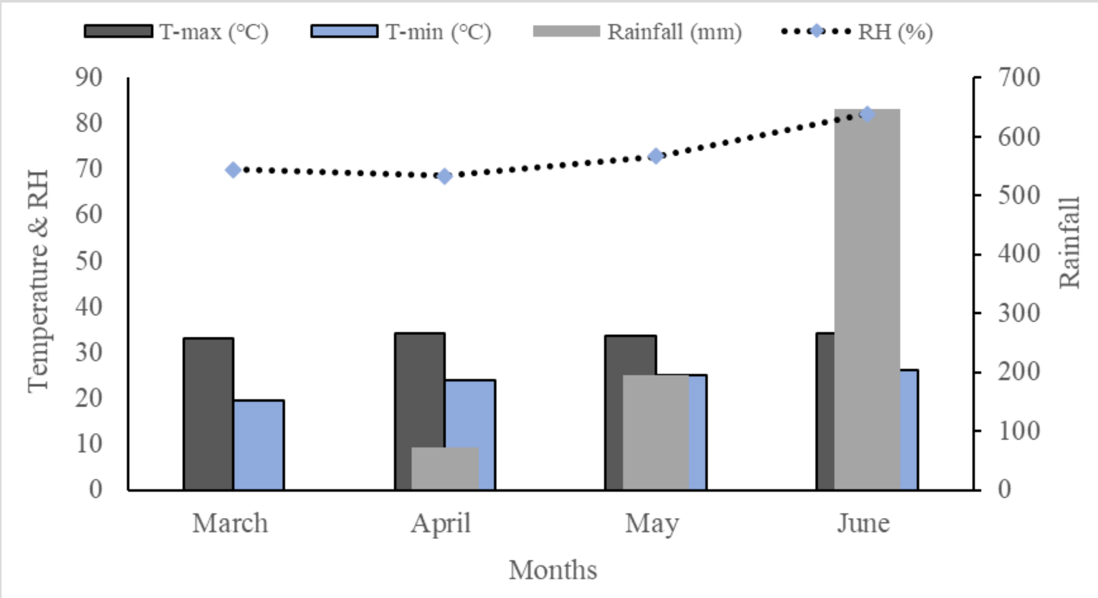

Fig. 1. Meteorological data during the experimental period in Rampur, Chitwan, 2022

Table 2. Details of treatments and their doses for field experiment in Rampur, Chitwan, Nepal

Treatments	Dose	Label	Reference
Malathion 50% EC	1.5 ml/ L	Blue	(Asare-Nuamah, 2020; Prasanna et al., 2018)
Wood ash	One teaspoon/whorl	None	(FAO, 2018; Prasanna et al., 2018)
Soap 10% solution	125 g/ L	None	(Asare-Nuamah, 2020)
Saw dust	One teaspoon/ whorl	None	(Harrison et al., 2019)
Azadirachtin (1500ppm)	5 ml/ L	Green	(Babendreier et al., 2020)
Sugar 20% solution	250 g/ L	None	(Bortolotto et al., 2014)
Chlorantraniliprole + lambda-cyhalothrin (Ampligo 150 SC)	0.4 ml/ L	Yellow	(Prasanna et al., 2018; Sisay et al., 2019)
Control	Water only	-	

Statistical analysis

In the laboratory bioassay, the data were tabulated in an Excel sheet, transformed using the square root data transformation, and analyzed using RStudio (version 4.1.3). Multiple comparisons among the treatments were conducted using the Least Significant Difference (LSD) test at both the 5% and 1% significance levels. The percentage of population reduction over control (% PROC) was then calculated using the modified Abbott's formula as suggested by Fleming and Retnakaran (1985) as follows:

$$\% \text{PROC} = [1-\{(Ta \times Cb)/(Tb \times Ca)\}] \times 100\%$$

Where,
Ta = Population of insects after treatment application.
Tb = Population of insects before treatment application.
Ca = Population of insect in control after treatment application,
Cb = Population of insects in control before treatment application.

For the field experiment, the collected data were tabulated and maintained in an Excel sheet. Data regarding the percentage of plant infestation underwent square-root transformation to fulfill the normality assumption. Analysis of variance (ANOVA) was used for data analysis using R-studio (version 4.1.3), and multiple comparisons among the treatments were performed using the Least Significant Difference (LSD) test at both the 5% and 1% significance levels (Gomez & Gomez, 1984). The number of infested plants was counted and converted into percent plant infestation using the following formula-

$$\text{Plant Infestation \%} = \frac{\text{Number of infested plants}}{\text{Number of total plants stand}} \times 100\%$$

RESULTS AND DISCUSSION

Laboratory Evaluation

Mortality of fall armyworm larvae after 12 hours of bioassay

There was a significant difference among the tested insecticides regarding the mortality of fall armyworm (Table 3). A reduction of about 90% in fall armyworm larvae compared to the control was found with spinetoram, followed by the treatment of chlorantraniliprole + lambda-cyhalothrin (86%), while the minimum reduction in fall armyworm larvae was recorded with chlorantraniliprole (10%) after 12 hours of application. According to Patidar et al. (2022), among the tested insecticides, spinetoram 11.7% SC was observed to be the most effective at reducing the larval population, followed by emamectin benzoate 5% SG and chlorantraniliprole + lambda-cyhalothrin 0.15% ZC, respectively. Spinetoram (11.7% SC) has been identified as the most effective pesticide, achieving the highest mortality of fall armyworm larvae in a very short time, as explained by Cook et al. (2004); Belay et al. (2012). Spinetoram is a fermentation product of *Saccharopolyspora spinosa* and an analog of the insecticide spinosad. It affects nicotinic acetylcholine-gamma-aminobutyric acid (GABA) receptors on postsynaptic membranes in insect nervous systems, causing abnormal neural transmission (Gao et al., 2021).

Mortality of fall armyworm larvae after 24 hours of bioassay

The treatment with spinetoram resulted in 100% mortality of fall armyworm larvae, followed by chlorantraniliprole + lambda-cyhalothrin (95%) within 24 hours of releasing fall armyworm larvae onto the Petri plate. The total reduction of the fall armyworm population over control was 75%, 70%, and 60% for malathion, emamectin benzoate, and spinosad, respectively. Similar results were observed by Sisay et al. (2019), who reported that spinosad and spinetoram caused more than 90% mortality in a laboratory experiment. Azadirachtin and chlorantraniliprole resulted in only 45% and 50% reduction of fall armyworm compared to the control (Table 3). Argentine et al. (2002) found that emamectin benzoate was highly effective against all lepidopteran pests. Emamectin benzoate was developed from the soil bacterium *Streptomyces avermitilis*, which induces a continuous flow of chlorine ions in GABA and at the H-Glutamate receptor site of insects (Liu et al., 2022). Similarly, spinosad was developed from the soil bacterium *Saccharopolyspora spinosa*, and its active component, spinosyn, acts on the nicotinic acetylcholine receptor of the insect (Thomson et al., 2000). Spinosad has been identified as the most effective pesticide, resulting in the highest mortality of fall armyworm larvae in a very short time, as explained by Cook et al. (2004).

Mortality of fall armyworm larvae after 48 hours of bioassay

There were no significant differences in the mortality of fall armyworm larvae across all treatments after 48 hours of treatment application. A similar experiment was conducted in the Chitwan district by Sharma et al. (2022), revealing that spinetoram, chlorantraniliprole + lambda-cyhalothrin, spinosad, emamectin benzoate, and chlorantraniliprole showed 100% mortality of fall armyworm larvae compared to the control within 48 hours of treatment application. Emamectin benzoate, spinosad, spinetoram, chlorantraniliprole, and chlorantraniliprole + lambda-cyhalothrin induced the highest mortality rates through the leaf-dip bioassay method for controlling second instar fall armyworm larvae (Idrees et al., 2022; Deshmukh et al., 2020). Tidke et al. (2021) also found that spinetoram 11.7% SC, exhibiting the lowest LC50 value of 0.01%, followed by chlorantraniliprole + lambda-cyhalothrin 0.15% ZC, with an LC50 of 0.02%, proved to be more toxic to the third instar larvae of *S. frugiperda* than all other tested insecticides. Similarly, in a laboratory diet bioassay, the third instars of a laboratory strain exhibited greater susceptibility to novel insecticides, including chlorfenapyr, methoxyfenozide, spinosad, emamectin benzoate, and tebufenozide (Adamczyk et al., 1999). Chlorantraniliprole acts on the nervous system of insects through the ryanodine receptor of insect muscles (Xu et al., 2022). In our experiment, chlorantraniliprole, emamectin benzoate, and spinosad caused lower mortality rates in the first twelve hours and achieved up to 100% mortality within 48 hours, similar to results obtained by Sisay et al. (2019), Hardke et al. (2011), and Thrash et al. (2013). The exposure time and concentration influence the mortality rates and toxicity levels of several insects, including the fall armyworm (Cook et al., 2004). The stage of fall armyworm larvae used in the bioassay experiment also impacts the mortality rate; early instars are generally more susceptible to insecticides than later stages. We used second-instar fall armyworm larvae for experimental purposes. According to Ghidiu and Andaloro (1993) and Adamczyk et al. (1999), the primary reasons for using early instar larvae (third instar) as test specimens include their sensitivity to biotic and abiotic stresses and higher susceptibility to insecticides compared to later instars. Additionally, third instar larvae were easy to rear, and no cannibalism was observed during the experimental preparations.

Management of fall armyworm using chemicals is more prevalent in the Nepalese context; however, employing these synthetic pesticides incurs high costs and raises potential environmental and human health concerns, along with pest-related issues (Tudi et al., 2021; Muratet et al., 2015; Choudhary et al., 2018). Azadirachtin caused more than an 80% reduction in fall armyworm populations compared to the control within 48 hours after the larvae were released onto a Petri plate. Neem seed powder has been shown to effectively kill fall armyworm larvae, consistently achieving over 70% mortality in laboratory studies (Maredia et al., 1992). Similarly, Tavares et al. (2010) reported that the application of 0.25% neem oil extract under laboratory conditions resulted in 80% larval mortality. To reduce the over-reliance on insecticides and minimize the harmful effects of toxic synthetic options, neem-based insecticides (i.e., azadirachtin) and relatively safe bio-rational insecticides such as spinosad and chlorantraniliprole may serve as alternative solutions for fall armyworm management.

Table 3. PROC% of second instar fall armyworm larvae at 12hrs, 24hrs, and 48hrs after treatment application in laboratory leaf dip bioassay in Chitwan, Nepal, 2022

Treatments		12 hrs		24 hrs		48 hrs	
	Initial larva number	Mean dead larvae (No.)	PROC %	Mean dead larvae (No.)	PROC %	Mean dead larvae (No.)	PROC %
Chlorantraniliprole 18.5%SC	5	0.5(0.9)□□	10%	2.5(1.7)□	50%	5.0(2.4)	100%
Emamectin Benzoate 5% SG	5	1.5(1.4)□	30%	3.5(2.0)□	70%	5.0(2.3)	100%
Spinetoram 11.7% SC	5	4.5(2.2)□	90%	5.0(2.4)□	100%	5.0(2.4)	100%
Spinosad 45% SC	5	1.8(1.5)□□	36%	3.0(1.9)□□	60%	5.0(2.4)	100%
Azadirachtin 1500 ppm	5	1.0(1.2)□□	20%	2.3(1.7)□	45%	4.3(2.2)	85%
Malathion 50% EC	5	2.8(1.8)□	56%	3.8(2.1)□□	75%	4.8(2.3)	95%
Chlorantraniliprole + Lambda cyhalo-thrin 0.15% ZC	5	4.3(2.2)□	86%	4.8(2.3)□□	95%	5.0(2.4)	100%
Control (water spray)	5	0.0(0.7)□	-	0.3(0.8)□	-	0.5(0.9)	-
SEm		0.1183		0.0817		0.0598	
CV%		13.10%		8.90%		5.60%	
LSD		0.3452		0.2386		0.1745	
Grand Mean		2.03125		3.125		4.3125	
P- value		**		*		ns	

CV: Coefficient of Variation; LSD: Least Significant Difference; SEm: Standard Error of Mean; **: Significance at 1% ($p<0.001$); *: Significance at 5% ($p<0.05$); ns: Non-significance; hrs: hours; Mean values in columns separated by the same letters are not statistically different by LSD at $P \leq 0.05$; figures in parentheses indicate transformed values.

Field Evaluation

Conventional and new generation insecticide molecules, along with selected local materials, were assessed in the field against *S. frugiperda*, providing a broader range of options for its management.

Effect of Insecticides and Local Materials on Maize Plant Infestation

All the insecticides were found to be significantly effective in reducing fall armyworm infestation after both the first and second sprays. Based on damage symptoms on the whorl and upper four leaves, chlorantraniliprole + lambda cyhalothrin 0.15% ZC were consistently found to be superior compared to other treatments, followed by azadirachtin 1500 ppm and a 10% soap solution. The application of chlorantraniliprole reduced the maximum infestation of *S. frugiperda* on maize whorls, followed by chlorantraniliprole + lambda-cyhalothrin, after three days of treatment application (Hardke et al., 2011). Similarly, neem-based pesticides have shown effectiveness against fall armyworm in laboratory and field conditions (Babendreier et al., 2020; GC et al., 2019). Soap solution has also been reported to be effective to a certain extent against fall armyworm larvae. Soap has also been effectively used to manage insect pests, particularly for soft-bodied insects such as aphids, some scales, psyllids, whiteflies, mealybugs, thrips, and spider mites (Buss & Brown, 2002). Even though the mode of action of insecticidal soaps is not clearly understood, it is known that target pests need to contact the soap solution. Apart from soap, wood ash, sawdust, and soil have been used for a long time by several smallholder farmers in America to control fall armyworm (Wyckhuys et al., 2007).

First Spray

The data on the effect of different insecticides and local materials on the larval population of *S. frugiperda* revealed that all treatments were significantly superior to the untreated control in reducing the damage percentage of *S. frugiperda* with the first spray at 5, 10, and 15 days after spraying (Table 4). The recorded data on plant infestation the day before the first spray showed no significant difference among treatments. Plants treated with chlorantraniliprole + lambda cyhalothrin (4.87%), followed by azadirachtin (5.82%), soap solution (5.93%), and malathion (5.96%), displayed considerably less infestation during the initial spraying (5 days after spray) and were found statistically comparable to each other.

The data recorded for *S. frugiperda* ten days after spraying revealed significant differences among the treatments. The treatment with chlorantraniliprole + lambda cyhalothrin outperformed the other treatments, showing a 4.79% plant infestation and providing the best protection against *S. frugiperda*, followed by the treatment of azadirachtin (4.00%), malathion (7.12%), and soap solution (7.20%), which were statistically similar to one another. The next most effective treatment observed was wood ash (8.16%), followed by sawdust (8.27%) and sugar solution (8.51%), respectively. However, the highest percentage of plant infestation was recorded in an untreated plot, with a 9.24% infestation.

Similarly, the data observed fifteen days after spraying exhibited significant differences among the treatments. The least plant infestation was observed with the treatment of chlorantraniliprole + lambda cyhalothrin (6.24%), which was statistically comparable to the treatment with soap solution (7.10%). The highest percentage of plant infestation was noted in the untreated plot (9.34%), which was statistically similar to the treatments with wood ash (8.84%), sugar solution (8.60%), sawdust (8.30%), malathion (7.99%), and azadirachtin (7.86%).

Table 4. Effect of different treatments on percentage plant infestation before and after the first spray at Rampur, Chitwan, 2022

Treatments	Plant Infestation (%)			
	Pre-spray	**5 DAS**	**10 DAS**	**15 DAS**
Malathion 50% EC	5.94 (35.51)	5.96 (35.89)^{cd}	7.12 (52.20)^{b}	7.99 (64.44)^{ab}
Wood ash	5.81 (33.73)	7.12 (51.15)^{bc}	8.16 (66.94)^{ab}	8.84 (78.31)^{a}
Soap solution (10%)	4.80 (23.55)	5.93 (36.64)^{cd}	7.20 (53.53)^{b}	7.10 (51.81)^{bc}
Sawdust	5.33 (29.09)	7.09 (50.48)^{bc}	8.27 (68.50)^{ab}	8.30 (68.95)^{ab}
Azadirachtin 1500 ppm	6.03 (37.21)	5.82 (34.89)^{cd}	6.94 (49.07)^{b}	7.86 (62.23)^{ab}
Sugar solution (20%)	6.09 (37.36)	7.43 (56.05)^{ab}	8.51 (72.50)^{ab}	8.60 (73.98)^{ab}
Chlorantraniliprole + Lambda cyhalothrin (0.15% ZC)	5.81 (33.88)	4.87 (23.70)^{d}	4.79 (23.37)^{c}	6.24 (39.23)^{c}
Control	6.15 (37.90)	8.69 (76.12)^{a}	9.24 (85.39)^{a}	9.34 (87.26)^{a}
SEm (±)	0.16	0.42	0.48	0.35
LSD	1.24	1.32	1.78	1.37
CV%	12.37	11.42	13.51	9.77
p-value	ns	*** (<0.001)	** (<0.001)	** (<0.001)
F-value	1.25	7.52	5.37	4.77
Grand mean	5.75	6.61	7.53	8.03

CV: Coefficient of Variation; LSD: Least Significant Difference; SEm: Standard Error of Mean; ***: Significance at < 0.1% (p<0.001); **: Significance at 1% (p<0.001); ns: Non-significance; DAS: Day After Sowing; Mean values in columns separated by the same letters are not statistically different by LSD at P≤ 0.05; figure in parenthesis indicate original values.

Second Spray

The leaf damage caused by fall armyworm larvae was further reduced after the second spraying. All treatments resulted in a significantly lower percentage of leaf damage compared to the control at 5, 10, and 15 days after spraying (Table 5). Five days after the second spray, chlorantraniliprole + lambda cyhalothrin recorded the lowest plant infestation (4.81%), which was significantly better than soap solution (6.96%), malathion (7.36%), azadirachtin (7.53%), wood ash (7.53%), sugar solution (8.04%), and sawdust (8.21%), all of which were statistically comparable to one another. In contrast, the untreated control plot exhibited a higher percentage of plant infestation at 9.21%.

Ten days after the second application, the highest percentage of plant infestation by fall armyworm was observed in the control plot (8.88%), followed by maize plots treated with malathion, sawdust, azadirachtin, sugar solution, wood ash, and soap solution, which had infestation percentages of 8.14%, 8.10%, 8.04%, 7.90%, 7.36%, and 7.15%, respectively. These treatments were statistically similar to one another. Chlorantraniliprole + lambda cyhalothrin was found to be the most effective against fall armyworm among the treatments, showing the lowest infestation percentage of 5.55%.

The data recorded for *S. frugiperda* fifteen days after spraying illustrated significant differences among the treatments, with the mean plant infestation percentage ranging from 6.33% to 8.51%. The minimum plant infestation (6.33%) was observed in the chlorantraniliprole + lambda cyhalothrin-treated plot. The next most effective treatment was the soap solution (7.12%), followed by wood ash

(7.28%), which are statistically similar to each other. However, the highest percentage of plant infestation (8.51%) was recorded in the control plot, followed by malathion (8.49%), sugar solution (8.41%), sawdust (8.40%), and azadirachtin (8.26%), all found statistically on par with each other.

Table 5. Effect of different treatments on percentage plant infestation before and after the second spray at Rampur, Chitwan, 2022

Treatments	Plant Infestation (%)			
	Pre-spray	**5 DAS**	**10 DAS**	**15 DAS**
Malathion 50% EC	7.99 (64.44)^{ab}	7.36 (55.94)^{b}	8.14 (66.51)^{ab}	8.49 (72.16)^{a}
Wood ash	8.84 (78.31)^{a}	7.53 (57.17)^{ab}	7.36 (54.53)^{b}	7.28 (53.19)^{b}
Soap solution (10%)	7.10 (51.81)^{bc}	6.96 (49.31)^{b}	7.15 (51.63)^{b}	7.12 (50.82)^{b}
Sawdust	8.30 (68.95)^{ab}	8.21 (67.37)^{ab}	8.10 (65.58)^{ab}	8.40 (70.86)^{a}
Azadirachtin 1500ppm	7.86 (62.23)^{ab}	7.53 (57.36)^{ab}	8.04 (65.38)^{ab}	8.26 (68.40)^{a}
Sugar solution (20%)	8.60 (73.98)^{ab}	8.04 (64.71)^{ab}	7.90 (62.54)^{ab}	8.41 (70.83)^{a}
Chlorantraniliprole + Lambda cyhalothrin (0.15%ZC)	6.24 (39.23)^{c}	4.81 (23.60)^{c}	5.55 (31.43)^{c}	6.33 (40.21)^{c}
Control	9.34 (87.26)^{a}	9.21 (84.88)^{a}	8.88 (79.16)^{a}	8.51 (72.37)^{a}
SEm (±)	0.35	0.45	0.35	0.29
LSD	1.37	1.62	1.24	0.76
CV%	9.77	12.41	9.26	5.54
p-value	** (<0.001)	** (<0.001)	** (<0.001)	*** (<0.001)
F-value	4.77	5.64	5.93	10.88
Grand mean	8.03	7.46	7.64	7.85

CV: Coefficient of Variation; LSD: Least Significant Difference; SEm: Standard Error of Mean; ***: Significance at < 0.1% (p<0.001); **: Significance at 1% (p<0.001); DAS: Day After Sowing; Mean values in columns separated by the same letters are not statistically different by LSD at P≤ 0.05; figure in parenthesis indicate original values.

Among the tested insecticides and safe materials, chlorantraniliprole + lambda-cyhalothrin 0.15% ZC was observed to be the most effective in reducing plant infestation, followed by azadirachtin at 1500 ppm. Sisay et al. (2019) noted that the application of the synthetic insecticides Karate 5 EC, Coragen 200 SC, Radiant 120 SC, Dimethoate 40%, Tracer 480 SC, and Ampligo 150 SC was effective, significantly increasing fall armyworm larval mortality, reducing leaf damage, and enhancing biomass in maize compared to the untreated control. The insecticides methomyl + novaluron, chlorantraniliprole + lambda-cyhalothrin, and deltamethrin exhibited an ovicidal effect, reduced the emergence rate of *S. frugiperda* larvae, and may be recommended for managing *S. frugiperda* (Soares et al., 2021). Among the pesticidal plants, neem was likely the most widely used (James et al., 2010; Yarou et al., 2017). Babendreier et al. (2020) reported that neem-based pesticides showed an equal effect in controlling fall armyworm damage to emamectin benzoate, which is widely utilized as a safe chemical pesticide for pest control. Azadirachtin (a neem-based pesticide) acts as an antifeedant, repellent, and growth inhibitor to pests while being low in toxicity to non-target pests (Brahmachari, 2004). Therefore, it may be the best alternative option against synthetic insecticides for fall armyworm management.

In our study, a 10% soap solution demonstrated the lowest percentage of plant damage, following chlorantraniliprole + lambda-cyhalothrin and azadirachtin. It was reported to be effective against insect pests by reducing their population densities in eggplant and okra farms in Ghana (Mochiah et al., 2011). We were not aware of any published study testing soap solution against fall armyworm, but it has been noted to possess certain fungicidal and insecticidal effects. For instance, Forchibe et al. (2017) found that soap solution (*Alata samina*) at a higher w/v concentration (2- 2.5%) was effective to some extent in managing aphids on cabbage in Ghana. During our experimental period, some maize plants became wilted, desiccated, and dead after the application of soap solution in the whorl. A similar effect was also observed by Chipere (2019); he reported that some respondents indicated wilting and death of maize plants if too much fertilizer and detergents were applied. This phytotoxicity can be attributed to the partially corrosive nature of fertilizers and detergents. There is still a need for more detailed studies to better understand how this soap solution can potentially work, the concentrations needed, and the best types of soap/detergents to use. The present results align with the findings of Kumela et al. (2019) and Matova et al. (2020), who observed that placing sand, sawdust, or wood ash in the whorls of maize plants and drenching plants with tobacco extracts can be effective methods for managing fall armyworm. Several locally available substances were commonly used by smallholders to try to control the fall armyworm, including the application of salt, urine, oils, detergents, ash, and soaps (Rwomushana et al., 2018; Hruska, 2019). The use of sand, ash, detergent, tobacco extracts, manure, and fertilizer is also not a new method among smallholder farmers in Africa and has also been utilized in the Americas (FAO, 2018; Kumela et al., 2019; Rwomushana et al., 2018). However, in Africa, South Asia, and Central America, several 'local' methods not based on pesticides have been employed for managing *S. frugiperda*, such as applying ash, sawdust, or soil to the maize whorl, or spraying solutions based on soap, fish soup, or sugars (Harrison et al., 2019; Hruska et al., 2019). According to Kumela et al. (2019), in Kenya, about 39% of farmers reported using traditional control methods, such as adding soil to the plant whorl or drenching tobacco extracts to damage plants.

Based on our results, the use of locally available materials such as wood ash, sawdust, and sugar solution was superior to the untreated control in managing fall armyworms, though they did not differ significantly from one another. A recent study showed that fewer than 1% of farmers in Ghana and about 5% of farmers in Zambia use wood ash to control fall armyworms (Tambo et al., 2020). Soil and ash have long been employed by smallholder farmers in the Americas for fall armyworm control (Wyckhuys & O'Neil, 2007), and generally in Africa as well (Abate et al., 2000; Mochiah et al., 2011). Pouring sand and wood ash into the leaf whorl or spraying with rabbit urine has also been reported to effectively combat fall armyworm larvae (FAO, 2018; Ibrahim et al., 2012; Kemunto et al., 2022). Ash may block the spiracles of the target insect, leading to suffocation and death, while soil may prevent the pest from accessing the plant or affect the larvae through abrasion. These strategies are thought to deter larval feeding or desiccate the pest's larvae. Sand, sawdust, and ash were notably abrasive and irritated the soft-skinned larvae, forcing them out of the whorl or directly killing fall armyworm larvae (Harrison et al., 2019). A first and second round of sprays with the sugar solution further resulted in a significant reduction in the percentage of plant infestation. The mean percentage of plant infestation across this treatment ranged from 6.09% to 8.60% and was better than the untreated control. Bortolotto et al. (2014) stated that white sugar and molasses treatment increases parasitism on *S. frugiperda* in the field but does not significantly reduce the pest population. Sugar solutions applied to leaves attract natural enemies, such as solitary wasps, parasitoids, and ants, enhancing their foraging capabilities (Harrison et al., 2019; Georgiev, 2005). The present results align with the findings of Canas and O'Neil (1998), who observed that sugar-solution-treated maize had significantly higher densities of natural enemies, 18% lower fall armyworm infestation, and 35% lower leaf area damage compared to water-only treatments in Honduras.

CONCLUSIONS

In response to the need for sustainable control of fall armyworm, both laboratory and field trials were conducted using chlorantraniliprole, emamectin benzoate, spinosad, spinetoram, malathion, chlorantraniliprole + lambda-cyhalothrin, azadirachtin, and locally available materials such as sawdust, wood ash, sugar solution, and soap solution in Chitwan. The insecticides spinetoram, spinosad, chlorantraniliprole, chlorantraniliprole + lambda-cyhalothrin, and emamectin benzoate, regarded as the positive control in this set of trials, overall showed good results regarding larval mortality and damage reduction. Some bio-rational compounds, including spinosad, spinetoram, chlorantraniliprole, and the botanical pesticide azadirachtin, are recommended as key components of any integrated pest management scheme to combat fall armyworm. If chemical insecticides are to be selected, chlorantraniliprole + lambda-cyhalothrin may be the preferred choice. These tested local materials—wood ash, sawdust, sugar solution, and soap solution- serve as organic and environmentally friendly preventive options. Their efficacy increases when combined with other integrated pest management (IPM) strategies for the sustainable management of *S. frugiperda*. Furthermore, the interaction of these local materials with other factors, such as rainfall, should be further studied.

ACKNOWLEDGEMENTS

The authors express their gratitude to the Directorate of Research and Extension (DOREX) of Agriculture and Forestry University, Department of Entomology/AFU, and the National Maize Research Program (NMRP) for their financial and technical support during the study period.

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