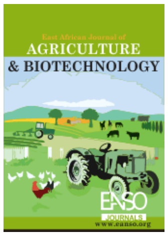

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Original Article

Field Efficacy of Microbial and Botanical Insecticides Against the Fall Armyworm on Maize in Serere District, Uganda

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ABSTRACT

The recent introduction of the fall armyworm (*Spodoptera frugiperda*) has significantly impacted maize production among smallholder farmers. Due to the harmful effects of the chemical insecticides (*Metarhizium anisopliae*, Mazao Achieve ® ICIPE 78, and Mazao Tickoff ® ICIPE 7), and Neem was tested in the field as a cheaper and safer alternatives. Experiments with treatments arranged in Randomised Complete Block Design (RCBD) with 4 replicates were conducted in the first (March-June) and second season (September-December) 2024 at Pingire Sub-county, Serere District, Uganda. *S.frugiperda* incidence, level of damage, larval populations, grain yield, and economic viability were measured. The results showed that the treated plots had reduced incidence, damage, and larval populations with significantly higher yield gain compared to untreated plots in both seasons. The incidence for the Striker, Achieve, and Tickoff was 22.50, 38.33, 52.50, and 30.83, 79.17, and 87.50 in the first and second seasons, respectively. The average number of larvae per plant for Striker, Achieve, and Tickoff was 0.43, 1.25, 1.81, and 0.60, 1.80, 2.45 in the first and second seasons, respectively. Grain yield was generally higher on treated plots as compared to untreated plots, with the exception of the Neem leaf extract. The percentage yield gain for Striker, Tickoff, and Achieve was 64.45, 28.60, and 24.86% respectively during the first season, and 53.27, 17.49, and 18.28% respectively during the second season. The three treatments, Striker, Achieve, and Tickoff, had a corresponding BCR>1 in both seasons. Achieve and Tickoff showed a higher degree of efficacy and economic viability for managing the *S.frugiperda* and could be explored by smallholder maize farmers; however, their use and application should follow an integrated management approach. Further research is needed to assess their effectiveness in various environments, with other treatments, local isolates, and concentrations.

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INTRODUCTION

Maize (Zea mays) is a cereal crop with an origin dating back 9000 years in the Central America and Mexico (Erenstein *et al*., 2022). Its wide variation in colour (i.e. yellow, white and blue colours) and attributes (i.e. dent/flint corn, sweet corn, baby corn, popcorn, waxy corn, oil maize, amylose maize and protein maize) allows its utilisation in various forms and purposes i.e. either for human consumption or livestock feed (Erenstein *et al*., 2022). Due to its high energy content, maize is an important and leading cultivated cereal in the world, preceded by rice and wheat *(*Kammo *et al*., 2019). In Sub-Saharan Africa, it is the leading important Cereal as compared to wheat and rice, where approximately 25 million hectares are cultivated and more than 80% of the population derives its livelihood, income, and food from its production (Awata *et al*., 2019). Globally, more maize is used as feed (56%) as compared to other purposes (20%) and food (13%), and the global per capita human consumption of maize is 18.5kg per year. However, in Africa, more maize is consumed as food (56%), with the highest food consumption in East Africa (66%). Additionally, the Per capita human consumption is high in Africa, especially Southern Africa, where average per capita human consumption of more than 100kg/capita/year occurs in Lesotho, Malawi, Zambia, and South Africa, and is increasing rapidly across Africa. In Uganda, it is produced by about 70-90% of the small-scale farmers (Epule *et al*., 2021). It is widely grown in various agroecologies of the country as it requires an annual well-distributed rainfall amount of 500mm to 800mm for its optimal growth (Epule *et al*., 2021).

The reduction in the maize yield has been greatly attributed to arthropod pests, for example, the maize stalk borer (*Busseola fusca*), spotted stalk borer (*Chilo partellus*), and various termites (Macrotermes and microtermes) (Assefa & Ayalew, 2019). The stem borer, for example, has been reported to be causing yield losses of 20-40% in the field and 30 to 90 % during storage (Kammo *et al.*, 2019). The situation has been worsened by the recent introduction of the fall armyworm (*Spodoptera frugiperda*) (J.Smith) (Lepidoptera: Noctuidae), an invasive species causing relatively higher yield losses in maize (Assefa & Ayalew, 2019) and native to North America's tropical and subtropical climates (FAO, 2018). After being discovered for the first time in Africa in 2016, it spread rapidly from West Africa throughout the continent, causing severe damage to the crops (Kammo *et al*., 2019). The pest threatens the livelihoods of poor small-scale farmers as USD 13 billion per annum worth of crops is reported to be at risk of being ravaged by it in the whole of Sub-Saharan Africa (Niassy *et al*., 2021). In June 2016, it was detected in Uganda in the Kayunga, Kasese, and Bukedea districts, where it spread to all districts

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by 2017. It has a wide host range of more than 80 plant species, such as millet, rice, corn, sorghum, vegetables, and cotton, if proper management is not instituted (FAO, 2017). The larvae are nocturnal and have a tropical origin; their migration, development, and persistence are greatly influenced by temperature. The rate of larval development tends to have a linear relationship with an increase in temperature (18ºC -30ºC), with the ideal temperature range for the egg, larval, and egg-to-adult development is at 26ºC and 30ºC (Prasanna *et al*., 2021). The fall armyworm undergoes complete metamorphosis. The lifecycle is completed in 30 days under favourable conditions (28ºC) with multiple generations expected in one season, especially in Sub-Saharan Africa (Niassy *et al*., 2021).

A wide range of management practices have been employed to reduce the pest burden and destruction of the maize crop in Uganda, including; chemical, cultural, biological, physical, and other approaches. All over Africa, synthetic insecticides are widely used. Their wide use has been attributed to access to subsidized or free pesticides by smallholder farmers from their governments (Tambo *et al*., 2023) and their effectiveness (Kansiime *et al*., 2019). Synthetic insecticides such as Emamectin Benzoate can cause larval mortality of 100% (Kumar *et al*., 2021). However, their wide use has come with serious challenges and consequences notably; most of the active ingredients used belong to moderately hazardous, WHO class II and slightly hazardous, WHO class III which is detrimental to the smallholder farmers whom a majority do not follow safety precautions for chemical use such as wearing of the protective gear (Kalyebi *et al*., 2023). Farmers also face challenges related to; correct timing of spray applications, use of proper application technique, correct dosage and formulation, and high cost of the insecticides (FAO, 2018), early identification of the pest, and awareness of their harmful effects (Matova, 2020). FAW is also reported to have already exhibited resistance to the carbamates, organophosphates, and pyrethroids in its area of origin (Abrahams, 2017). Furthermore, their rampant use has resulted from a lack of safer alternatives by the farmers and the government (Akutse *et al*., 2019). This therefore calls for intensive research on safer and sustainable management alternatives such as biological agents (i.e. predators, parasitoids, and entomopathogens or microbial pathogens) and botanical plant extracts, for example, Neem. Of the numerous microbial pathogens, Entomopathogenic fungi (EPF) isolates have been regarded to be potentially effective for managing the fall armyworm on maize (Russo *et al*., 2021). However, data and information on the efficacy and cost-effectiveness of the EPF isolates in the field are scant. Some of the isolates commercialized for the control of other pests such as spider mites and ticks, notably *Metarhizium anisopliae* ® Achieve (ICIPE 78) and *Metarhizium anisopliae* ® Tickoff (ICIPE 7), respectively, have proved to be effective in killing the eggs and neonate in the laboratory (Akutse *et al*., 2019). This study therefore aimed at assessing the field efficacy of microbial and botanical insecticides, *Metarhizium anisopliae*, MAZAO ACHIEVE ® ICIPE 78, and MAZAO TICKOFF ® ICIPE 7, and Neem, respectively, in reducing the incidence and damage caused by the fall armyworm and the costs of management of the pest. The study specifically aimed at assessing; (1) The effect of *M. anisopliae* ICIPE 78 & ICIPE 7 and Neem on fall armyworm larval populations on maize crop in the field. (2) The effect of *M. anisopliae* ICIPE 78 & ICIPE 7 and Neem on the incidence and level of damage caused by the fall armyworm on maize in the field. (3) The effect of *M. anisopliae* ICIPE 78 & ICIPE 7 and Neem on the yield of maize infested by the fall armyworm. And (4) the economic viability of *M. anisopliae* ICIPE 78 & ICIPE 7 and Neem for fall armyworm management.

MATERIALS AND METHODS

Study Area

The experiment was conducted at Pingire Sub County, located in Omiriai Village, Okidi Parish,

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Pingire Sub County, Pingire County, Serere District. The coordinates of Pingire Sub County are 1º, 25', 56''N and 30º, 22', 38'' E, and at a Latitude of 1.43227 and Longitude of 33.37742.

Study Design

The field study was conducted using a randomized complete block design with 6 treatments and 4 replicates. MAZAO ACHIEVE ® ICIPE 78 & MAZAO TICK OFF ® ICIPE 7 (from real IPMUganda), Neem leaf extract (*Azidarachta indica)* and Nimbecidine 0.03% (*Azidarachta indica*); and Striker (Lambda-cyhalothrin 106g/l+Thiomethoxam 141g/l), were used. The maize without insecticidal treatment was used as a control. Each block had 6 plots for 6 treatments. A distance of 1m was used to separate plots in a block, and a distance of 2m to separate blocks. Each plot in a block covered an area of 25m^2 (5m by 5m), and each block covered an area of 175m^2 (35m by 5m). The total area for the experiment was 700 m^2. This gave a total of 111 plants per treatment in a block and 666 plants per block. The total number of plants in the experiment was 2664 plants divided among the 5 insecticidal treatments and 1 control (FAO, 2018).

Field Agronomic Practices

The maize variety used was Longe 10H, which takes 120 days from planting to maturity. Land clearing was done by clearing the bushes, removing tree shrubs, and tree stumps. The first ploughing was done at 3 weeks before planting, and second ploughing at planting time. The maize seeds and fertilizers (DAP and Urea) were sourced from the Agro-inputs shops in Soroti. A germination test was conducted one week before planting, where seed lots of 85% and above germination percentage were planted. The seeds were planted at the onset of rains for both the first (March) and second season (September). Planting and basal fertilizer application were done at a spacing of 75cm by 30cm by digging the hole, placing one bottle top of DAP fertilizer, covering with a thin layer of soil, placing 2 seeds, and covering the hole with soil. 4 days after germination, gap filling was done. 2 weeding operations were conducted, the first at 3 weeks after planting and the second at 3 weeks after the first weeding. Thinning was done at first weeding to only 1 plant per hole. Urea was applied as a top dressing at 4 weeks after planting by digging a hole around the plants and placing one bottle of fertilizer. The treatments for managing the fall armyworm were applied following safety precautions for chemical use (i.e., use of protective gear, Gumboots, face, nose, mouth, and head masks, overalls, and gloves). The crop was harvested at physiological maturity, i.e., at a moisture content of 18-24%, a dark coating developed at the kernel's tip, and browning of the maize stalks and sheath.

Preparation of Insecticides

The treatments were prepared and applied following manufacturers' recommendations, i.e., Striker 247SC at a rate of 20mls per 20 litres, Neem leaf Extract and Nimbecidine 0.03% at a rate of 120mls per 20 litres (Bukoola chemicals product catalogue), ICIPE 78 & ICIPE 7 at a rate of 80mls per 20L (1L/ha) (www.realipm.com). A separate 20-litre knapsack sprayer was used for applying each of the chemicals (Sisay, 2018). Spraying of the insecticides was done either early morning (9:00 am) or late in the evening (4:00 pm), depending on the prevailing weather conditions on the spraying day. Any spray application that was followed by a significant rainfall within 6 hours after the rain was repeated a day after the rain (Sisay, 2018). Spray operations were completed for each treatment before moving to another treatment.

Preparation of Neem Leaf Extract

Neem leaf extract was prepared as described by (Gadi, 2017; Siazemo & Simfukwe, 2020), by gathering 1.25kg of the leaves, pounding them with a mortar and pestle, and then soaking them with 5 litres of water for the entire night. After obtaining the crude extract, it was sieved with a muslin cloth and diluted to 12.5 litres with water to prepare a

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10% solution (W/V). Soapy water was then added to serve as a sticker. The sticker was prepared by adding one teaspoonful of Omo to 1 litre of water. The soapy water was mixed with neem leaf extract at a ratio of 1 litre of soapy water to 10 litres of Neem leaf extract.

Data Collection

Pre-treatment Data Collection

The plots were assessed 24 hours before the application of the insecticidal treatments to confirm fall armyworm incidence. 10 plants were randomly sampled and tagged from each plot using the 'W' pattern, i.e., from the centre of the plot, picking each plant that was located after the count of 3 but avoiding 2 border rows and columns (Kuddus, 2019). The assessment was done by scouting the experimental field and visually observing the plants for the presence of the fall armyworm by taking note of the presence of larvae and fresh damage symptoms on the leaves (Kammo *et al*., 2019; Prasanna *et al*., 2021). The entire number of plants sampled and infested was documented to determine the incidence as described by (Kammo *et al*., 2019) as follows;

- ***Spodoptera frugiperda* incidence on plants**

= (Number of plants attacked/Total number of plants sampled) X 100 (1).

Post-treatment Data Collection

3 spray applications were made at 2-week intervals targeting the seedling, vegetative, and tasseling stages (Kuddus, 2019). Fall armyworm infestation was assessed at the seedling, vegetative and tasseling stages by visually assessing the leaves, whorl, tassel, and the cobs for the fall armyworm larvae, feeding damage symptoms, and the frass (Kuddus, 2019). Post-treatment data was collected 6 days after the sprays to allow the *M.anisopliae* isolates to establish and infect the larvae, taking a record of the incidence of the fall armyworm, its damage level, and the number of caterpillars on the sampled plants (Kumari *et al*., 2020). The following parameters were assessed;

- *S.frugiperda* incidence on the plants as described above.
- **Number of larvae**
- **Davis leaf damage score**. This involved scoring the leaf damage through visual observation and using a scale of 1-9 to rate the damage on the leaves as described by (Chisonga *et al*., 2023). A score of 1-4 shall indicate minimal (low or mild) damage, 5-7 indicate marginal (medium or moderate) leaf damage, and 8-9 indicate extensive (High or severe) leaf damage (S. J. E. Smith *et al*., 2022).
- **Yield.** This was obtained by harvesting, drying, and taking measurements of the dry grains from the 10 tagged plants per plot, obtaining the average weight of each treatment, and extrapolating to yield per ha (kg/ha). The percentage yield gain was then calculated as illustrated in the formula below (Banerjee & Pal, 2020);
- **Percentage grain yield gain**=((Yield in treated plots-yield in untreated plots)/yield in untreated plots))X100 (2).
- **BCR**=Benefit of the treatment/crop protection cost (3). This was obtained by calculating the Total Crop Protection Cost (i.e., costs for buying each insecticide, application equipment, labour for pesticide application, and extra harvesting) and the benefit of the treatment (i.e., the difference between revenue from respective treatment plots and control plot (untreated plot)) (& Getu, 2018). BCR>1 meant that the insecticide treatment was economically viable, BCR<1 meant that the treatment was not economically viable, and BCR=1 meant that there was a break-even for the treatment used (Gayi *et al*., 2017).

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Data Analysis

Analysis of variance (ANOVA) was performed on the experimental data to see whether the treatments differ significantly in their ability to control the FAW. The treatment means were separated using the LSD at a 5% significance level if there were significant differences. Version 4.3.3 of the R statistical package was used for the analysis (Gayi *et al*., 2017)

RESULTS

Effect of Treatments on the Fall Armyworm Larval Populations

There was a significant effect of the treatments ($F_{5, 38}$= 17.99, P<0.001) and the seasons ($F_{1, 38}$=10.58, P<0.01) on the fall armyworm larval populations. The larval populations also differed significantly in the first season ($F_{5, 15}$=17.70, P<0.001) and the second season ($F_{5, 15}$=5.49, P<0.01). In the first season, the highest and lowest larval means were recorded from the control and striker, respectively, and the Tickoff (ICIPE 7) and striker, respectively, in the second season. In the first season, the means of Neem leaf and Achieve (ICIPE 78) were not significantly different, while the rest of the means, i.e., Control, Tickoff, Nimbecidine, and Striker, were significantly different in the second season, the larval means of the Control, Tickoff, and Neem leaf were not significantly different. Larval means of Achieve and Nimbecidine also showed non-significant differences. Generally, the mean larval populations were lower in the first season than in the second season (Table 1).

Table 1: FAW Mean Larval Populations (±SD) for the 3 Sprays for the First and Second Season 2024

Treatment	First Season	Second Season
	Mean ± SD	Mean ± SD
Control	2.45±0.44 a	2.43±0.72 a
Tickoff	1.81±0.28 ab	2.45±0.66 a
Neem leaf	1.48±0.38 bc	2.05±0.43 a
Achieve	1.25±0.15 bc	1.80±0.51 ab
Nimbecidine	1.07±0.50 cd	1.67±0.72 ab
Striker	0.43±0.14 d	0.60±0.14 b

**Treatments followed by the same letter are not significantly different.*

Effect of Treatments on Incidence and Level of Damage

Incidence of the Spodoptera frugiperda

There were significant differences in the *Spodoptera frupiderda* incidence between the treatments ($F_{5,38}$=23.08, P<0.001) and the seasons ($F_{1,38}$=48.35P<0.001). The incidence was significantly different among the treatments in both the first season ($F_{5,15}$=163.92, P<0.001) and the second season ($F_{5,15}$=20.14, P<0.001). The highest and lowest significantly different incidences were recorded in the Control and the Striker treatments, respectively, in the first season. During the second season, the highest incidence was recorded in the control, but was not significantly different from the Tickoff (ICIPE 7), Neem leaf, Achieve (ICIPE 78), and Nimbecidine. However, the lowest significantly different incidence was recorded in the striker treatment (Table 2). Generally, the incidence was higher in the second season than in the first season (Figure 1).

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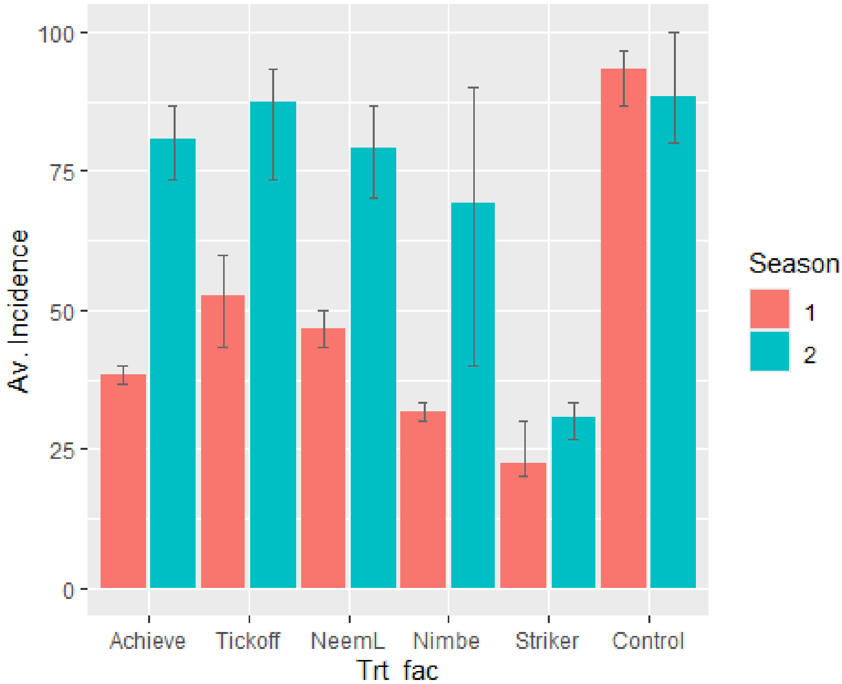
Figure 1: Mean Incidence (±SD) of *S.frugiperda* on Treated Maize during the First and Second Season of 2024 in Serere District



**NeemL is Neem leaf extract and Nimbe is Nimbecidine*

Damage Rating Scale on the Leaves

The leaf damage rating differed significantly among the treatments during the first season ($F_{5,15}$=85.77, P<0.001) and the second season ($F_{5,15}$=8.06, P<0.001). The damage rating was highest in the control and lowest in the Striker, but significantly different in the first and second seasons, respectively. There was mild or minimal damage by the fall armyworm on the maize plants across all the treatments, with the exception of the control, which tended towards medium damage (Table 2).

Table 2: Means of Average FAW Incidence & DRS for First and Second Seasons 2024 (±SD)

Treatment	Incidence	DRS
	Mean ± SD	**Mean ± SD**
First Season		
Control	93.33±04.71 a	4.70±0.27 a
Tickoff	52.50±07.39 b	3.31±0.31 b
Neem leaf	46.67±02.72 b	2.23±0.27 c
Achieve	38.33±01.92 c	2.23±0.47 c
Nimbecidine	31.67±01.92 c	1.70±0.22 c
Striker	22.50±05.00 d	0.83±0.05 d
Second Season		
Control	88.33±08.39 a	3.97±1.09 a
Tickoff	87.50±09.57 a	3.40±0.34 a
Achieve	79.17±05.69 a	2.58±1.05 a
Neem leaf	80.83±08.77 a	2.49±0.84 ab
Nimbecidine	69.17±21.14 a	2.33±0.86 ab
Striker	30.83±03.19 b	0.64±0.14 b

**Treatments with the same letter are not significantly different. Incidence=Average percent of plants infested after the three treatment applications, DRS=Damage rating scale on the leaves*

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Grain Yield of Maize Treated with Microbial and Botanical Insecticides

Total Grain Yield and Total Yield Gain

The total grain yield differed significantly between the treatments ($F_{5,38}$=14.33, P<0.001) and the seasons ($F_{1,38}$=5.64, P<0.05). There were significant differences in the total grain yield between the treatments in both the first season ($F_{5,15}$=8.25, P<0.001) and the second season ($F_{5,15}$=4.89, P<0.01). During the first season, the highest and lowest total grain yields were recorded in the Striker and Neem leaf, respectively. The same results were also recorded in the second season for the highest and lowest grain yield (Table 3). During both seasons, total grain yield was higher in Tickoff (ICIPE 7), Achieve (ICIPE 78), and Nimbecidine than in the Control. Neem Leaf total grain yield was lower than the Control in both seasons. The yield gain for Tickoff, Achieve, and Nimbecidine was 28.60%, 24.86%, 02.28%, and 17.49%, 18.28%, 10.73% in the first and second seasons, respectively. During the first season, plots treated with Striker differed significantly in the total grain yield from the rest of the treatments. There were no significant differences in the total grain yield between the Tickoff and Achieve in both seasons, but these differed significantly from the rest of the treatments (Table 3).

Table 3: Means Yields of the Treatments for Seasons 1 and 2, 2024 (Kg/ha)

Treatment	Yield (kg//ha)	Yield gain (%)
	Mean ± SD	
Season 1		
Striker	5973.8±733.78 a	64.45
Tickoff	4671.6±648.48 ab	28.60
Achieve	4535.8±516.12 ab	24.86
Nimbecidine	3715.4±654.86 b	02.28
Control	3632.7±621.93 b	-
Neem leaf	3041.6±817.73 b	-16.27
Season 2		
Striker	5153.0±1445.56 a	53.27
Tickoff	3950.1±422.78 b	17.49
Achieve	3976.9±682.07 b	18.28
Nimbecidine	3722.7±561.17 bc	10.73
Control	3362.1±225.46 bc	-
Neem leaf	2511.7±484.38 c	-33.86

Treatments followed by the same letter are not significantly different.

*Yield gain ((Yield in treated plots- Yield in untreated plots)/Yield in untreated plots)*100.*

Economic Viability of Microbial and Botanical Insecticides

Total Crop Protection Cost per Hectare

The Total Crop protection costs were higher in Tickoff (ICIPE 7) and Achieve (ICIPE 78) in the first and second seasons, respectively, and lowest in Neem leaf in both seasons (Table 4).

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Table 4: Crop Protection Cost for the Treatments during the First and Second Season of 2024

Treatment	Items	Unit Cost (UGX)	Total Cost (UGX) First season	Total Cost (UGX) Second Season
Achieve	Biopesticide	75,000	225,000	225,000
	Labour for application	12,500	37,500	37,500
	Knapsack sprayer	65,000	65,000	65,000
	Extra harvesting		90,310	61,480
	Total cost		**417,810**	**388,980**
Tickoff	Biopesticide	75,000	225,000	225,000
	Labour for application	12,500	37,500	37,500
	Knapsack sprayer	65,000	65,000	65,000
	Extra harvesting		103,890	58,800
	Total cost		**431,390**	**386,300**
Striker	Pesticide	15,000	45,000	45,000
	Labour for application	12,500	37,500	37,500
	Knapsack sprayer	65,000	65,000	65,000
	Extra harvesting		234,110	179,080
	Total cost		**381,610**	**326,590**
Neem leaf	Collection &preparation	10,000	30,000	30,000
	Labour for application	12,500	37,500	37,500
	Knapsack sprayer	65,000	65,000	65,000
	Extra harvesting		-59,110	-85,040
	Total cost		**73,390**	**47,460**
Nimbecidine	Pesticide	60,000	180,000	180,000
	Labour for application	12,500	37,500	37,500
	Knapsack sprayer	65,000	65,000	65,000
	Extra harvesting		8,270	36,060
	Total cost		**290,770**	**318,560**

**Cost of a single spray computed based on per per-hectare rate of application*
**Harvested yield above the untreated plot estimated at UGX 100,000 per tonne*

Revenue, Benefit, and Benefit-Cost Ratio

The revenue was higher in Tickoff (ICIPE 7) than in Achieve (ICIPE 78), Nimbecidine, and Neem leaf in the first season, and Achieve than in Tickoff and Nimbecidine in the second season. The same trend was recorded for the benefit and Benefit-Cost ratio of the treatments in both seasons (Table 6). Generally, the Benefit and Cost-Benefit ratios (BCR) of the treatments were higher in the first season than the second season, except for the Nimbecidine, whose revenue, Benefit, and Benefit-Cost ratios were higher in the second season. Economic viability was recorded in only the plots treated with Striker, Tickoff, and Achieve (ICIPE 78), with Striker having the highest BCR in both seasons.

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Table 6: Revenue, Benefit, and Benefit-Cost Ratio per Hectare for the First and Second Season 2024

Treatment	Revenue[1] (UGX)	Benefit[2] (UGX)	TCPC[3] (UGX)	BCR[4]
First Season				
Control	2,542,890	-		
Striker	4,181,660	1,638,770	381,610	4.08
Tickoff	3,270,120	727,230	431,390	1.69
Achieve	3,175,060	632,170	417,810	1.51
Nimbecidine	2,600,780	57,890	290,770	0.20
Neem leaf	2,129,120	-413,770	73,390	-5.64
Second Season				
Control	2,353,470	-		
Striker	3,607,100	1,253,630	326,590	3.84
Achieve	2,783,830	430,360	388,890	1.11
Tickoff	2,765,070	411,600	386,300	1.07
Nimbecidine	2,605,890	252,420	318,560	0.79
Neem leaf	1,758,190	-598,590	47,460	-12.54

[1]*Mean yield X Price per kg (1 kg estimated at 700 UGX)*
[2] *Revenue of the treated plots- Revenue of the untreated plot.*
[3] *Total crop protection cost of the treatments as in the table above.*
[4] *Benefit/TCPC, TCPC=Total Crop Protection Cost.*
BCR>1 is economically viable.

DISCUSSIONS

Effect of Neem Leaf, Achieve (ICIPE 78) and Tickoff (ICIPE 7) Larval Populations, Incidence, and Level of Damage

Generally, the results showed significantly lower larval numbers, incidence, and the level of damage in the treatments as compared to the untreated plot during both seasons. The results suggest a high potential of the treatments in controlling the *S.frupiperda* on maize fields in terms of reduction in the larval populations, incidence, and the level of damage to the maize. The performance of Nimbecidine and Neem leaf extract may be due to the ability of *Azidarachtin* to suffocate the insects, hence leading to their death, and its multiple modes of action as it acts as a repellent, antifeedant, insect growth regulator, and attractant (Mukanga *et al*., 2022). The performance of the *M.anisopliae* products can be attributed to their sensitivity to environmental conditions (Temperature and Relative humidity) for effective infection of the larvae and the eggs, and causing epizootics (Onsongo *et al*., 2019). Their slow action in comparison to the synthetic insecticides (htpps://realipm.com) and their reported high mortality to the eggs and neonate larvae under the laboratory conditions (Akutse *et al*., 2019).

The results of this study correlate with the findings of the previous field studies for example *M.anisopliae* 10g/l was reported to be the second-best treatment to *B.bassiana* 10g/l with 81.92% larval number reduction in a field study involving *B.bassiana* 10g/l, *M.anisopliae* 10g/l, EPN, *B.bassiana* 8g/l and *M.anisopliae* 8g/l (Patil *et al*., 2023). Furthermore, Otim *et al*., (2023) reported the EPFs performance to be either higher or similar to the untreated plots in reducing the damage of the fall armyworm and increasing the yield of maize. The results of the study also relate to the previous studies conducted in the field of efficacy of the botanical extracts. For example, Siazemo & Simfukwe, (2020), reported the botanical Neem extracts to be effective in reducing the fall armyworm larval numbers and subsequent damage as compared to

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other botanical extracts. High larval mortality rates have also been reported when Neem seed extracts and extracts from other plants were applied (Sisay *et al*., 2019). Jeanne *et al*., (2022) also reported neem oil extract to be effective in lowering the incidence, reducing larval numbers, and cob damage as compared to other biopesticide products it was assessed with.

Effect of Achieve (ICIPE 78), Tickoff (ICIPE 7) & Neem-based Products on the Maize Grain Yield.

The results showed a higher and statistically significant difference in the Total grain yield of the Entomopathogenic Fungi-treated plots as compared to the untreated plots. In the first season, neem-based products were not statistically different from the untreated plot in Total grain yield, with synthetic neem higher than the control and Neem leaf lower than the control. During the second season, Achieve and Tickoff were not significantly different but differed significantly from the neem-based products (Nimbecidine and Neem leaf), the control, and Striker. These results suggest the potential of Entomopathogenic fungal and neem-based products in controlling the *Spodoptera frugiperda* populations on maize in the field and reducing excessive crop injury as compared to the untreated plots. This could probably lead to improved photosynthetic activity, higher growth and development, faster maize recovery from pest damage, and an increase in yields better than the control. The poor performance of the Neem leaf could have been due to inadequate dosage to provide sufficient control against the larvae, especially the late instars. However, synthetic neem showed promising performance.

The findings in this study correlate with studies of (Spodoptera *et al*., 2022) who reported significantly higher yields when infested maize was treated with Mazao Achieve and corn oil formulations of ICIPE 41. In other related field studies, reduced cob damage and significantly higher yields than the untreated plots were recorded when *M.anisopliae* products were applied (Patel *et al*., 2022). Ramanujam *et al*., (2020) also reported a more than 50% increase in yield when maize was treated with *M.anisopliae* products.

Positive results have also been reported in studies conducted in relation to neem-based products. Kamunhukamwe *et al*., (2022) recorded an increased yield when neem biopesticide was applied. Another study by (Mukanga *et al*., 2022), revealed a reduction in cob damage and an increase in yield when crude aqueous leaf extracts were applied to maize plants. These studies contrast the results obtained from Neem leaf extract but concur with the results from Nimbecidine concerning the yield beyond the untreated plot. This could have been due to inadequate concentration of Neem leaf extract to kill the fall armyworm larvae, the effect of the environmental factors, i.e. temperature and rainfall, which could have affected its stability, hence reducing its efficacy. Ahissou *et al*., (2022) reported botanical products (*Azidarachta indica* and *Carapa procera*) to be less toxic to the fall armyworm larvae, and higher lethal doses beyond the recommended doses were only effective at killing the young instars and deterring the larvae from eating leaves. Azidarachtin in Neem breaks up quickly under sunlight and leaves a low residual effect in the field (Maria *et al*., 2016).

Economic Viability of Using ICIPE 78 (Achieve) and ICIPE 7 (Tickoff), and Neem-based Products for Managing the Fall Armyworm

The results showed that Entomopathogenic Fungal products of Achieve and Tickoff had a BCR>1 in both seasons. However, the neem-based products had a BCR<1, with neem leaf far below the untreated plot. BCR>1 indicates that the treatments are economically viable. The variations in economic viability could be attributed to the level of efficacy of the treatments in reducing fall armyworm damage and facilitating faster maize recovery so as to contribute to a greater yield gain. It can also be attributed to the difference in the costs of the treatments. These results can be correlated to the

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results of studies on other pests, as there are limited studies conducted on economic viability as regards to *Spodoptera frugiperda*. For example, (Babendreier *et al*., n.d.) reported BCR >1 and BCR<1 when neem-based products (0.33%) were used for fall armyworm control on maize at different locations. Achieve and Tickoff are economically viable and could sustainably increase the incomes and profits of the smallholder maize farmers when included in the integrated pest management programs for the fall armyworm.

CONCLUSION

The reduction in the larval numbers, the level of damage, and yield losses by the tested EPFs and synthetic neem suggest a significant contribution to the suppression of the *S.frugiperda* populations under field conditions. Higher yield gain and BCR>1 by the EPF products suggest a strong economic benefit to the smallholder farmers. These field findings suggest a strong ground and promising results for the development and commercialization of Achieve and Tickoff as biopesticides for the management of the fall armyworm. The positive results from the synthetic neem also suggest a good point for its upscaling among smallholder farmers. However, the results reported may be limited as they were conducted in one location and using only one dose and dilution for the case of the neem leaf extracts. Future studies should focus on conducting multilocational dose assays and using local isolates, as they are well adapted to the environment and could offer better performance and efficacy.

Recommendations

Based on the study findings, the researcher recommends that Achieve and Tickoff be included in the integration pest management programs for the fall armyworm as safer and cheaper alternatives to the chemical insecticides, but environmental conditions should be considered when applying them, especially high temperatures, which can affect their efficacy.

Areas for Further Research

The following areas are recommended for further research;

- Efficacy of microbial insecticides in combination with synthetic chemicals in the field and varied environmental conditions.
- Effect of microbial insecticides on the natural enemies of *S.frugiperda* in the field.
- Efficacy of different doses of microbial and neem-based products against the *S.frugiperda* in the field.
- Bioassays and field efficacy of the locally isolated EPF on the *S.frugiperda* on maize.

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