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Biorationals and Synthetic Insecticides for Controlling Fall Armyworm and Their Influence on the Abundance and Diversity of Parasitoids

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Abstract: *Spodoptera frugiperda* (fall armyworm, FAW) is a significant economic pest of maize in Uganda. Many Ugandan maize farmers employ synthetic insecticides as their main form of control despite the negative impacts of these chemicals. We tested the effectiveness of *Beauveria bassiana*; General Biopesticide Cocktail (mixture of *B. bassiana*, *M. anisopliae*, *Isaria fumosoroseus*, *Lecanicillium lecani* and *Purporeocillium lilacanus* three strains of *Metarhizium anisopliae*, Nimbecidine® (azadirachtin 0.03%EC), and Roket® (cypermethrin 4% and profenofos 40%); and Amdocs® (emamectin benzoate 2% and abamectin 1%) on fall armyworm and parasitoids, respectively, in 2020 and 2021. The treatments with the greatest decrease in leaf damage and infestation were Amdocs® and Roket®, followed by Nimbecidine®. The biopesticides were not always more effective than the untreated control, though; their efficacy was often lower than that of the synthetic and botanical pesticides. We recovered one egg parasitoid, *Telenomus remus*, and seven egg and egg-larval parasitoids (*Coccygidium luteum*, *Coccygidium* sp., *Cotesia icipe*, *Chelonus* sp., *Micranisa* sp., *Charops* cf. *diversipes*, and an unidentified Tachinidae). Among these, *C.* cf *diversipes*, *Chelonus* sp., *C. luteum*, *C. icipe* and the Tachinidae were the most abundant. Parasitism was low, averaging 10% for egg masses and 5.3% for larvae. Application of synthetic pesticides and Nimbecidine® often resulted in higher yield when compared with the untreated control. In general, a low population of parasitoids was observed. Although the parasitoid population reduced in plots treated with Amdocs® and Roket®, the percentage of parasitism of FAW was not affected. In some instances, higher yields were realized in untreated control when compared with the treated plots. Pest management practices more compatible with biological control need to be considered for the management of fall armyworm.

Keywords: biopesticides; cypermethrin; emamectin benzoate; Nimbecidine®; parasitoids; profenofos; synthetic insecticides; yield

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1. Introduction

Maize (*Zea mays* L.) is the world's primary food, feed, income and industrial crop [1]. In Uganda, maize, cassava, banana and sweet potato are the four key staple crops [2]. Maize exports earned Uganda USD 86.39 million in 2022 [3]. Despite the importance of maize, its production is affected by many biotic and abiotic (climatic and edaphic) constraints.

Among the insect pests, the maize stalk borer, *Busseola fusca* (Fuller 1901); the spotted stalk borer, *Chilo partellus* (Swinhoe in 1885); and various termite species are recognized as key pests in Uganda [4,5]. Recently, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), commonly named fall armyworm (FAW), has also established as an economic pest of maize. *Spodoptera frugiperda*, native to the Americas, was first reported in Africa in early 2016 [6], from where it spread very quickly, and by 2017, it was found in most of sub-Saharan Africa [7]. The pest was first detected in Uganda in 2016 [8] and spread to all maize-producing regions by 2018 [8]. In Uganda, it was predicted that *S. frugiperda* could cause up to USD 193 million (11%) in losses in the maize sector [9]. In addition, *S. frugiperda* damage to cobs predisposes maize cobs to contamination with aflatoxins and fumonisins [10].

Farmers use several practices to control *S. frugiperda*, with the use of synthetic insecticides being widespread [11]. Using insecticides increases production costs, endangers human health, and negatively impacts the environment and beneficial insects [12]. Furthermore, the extensive use of synthetic insecticides to manage *S. frugiperda* has led to the development of resistance in the New World [13–15] and potentially in the introduced populations [16–18]. The evolution of resistance is a significant biosecurity issue to contend with and necessitates the search for sustainable and effective approaches. Pesticide use in farmers' fields also influences the population of natural enemies by altering the fitness of insect pests and natural enemies. For instance, chlorfenapyr, chlorpyrifos, and spinosad reduced the longevity of *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae) females exposed to treated host eggs [19], and cypermethrin reduced the number of ladybird beetles [20]. There is a need to develop an integrated strategy that incorporates biorationals (low-impact pesticides), including botanicals (plant-derived pesticides) and biopesticides derived from micro-organisms, which are deemed essential components to address the problems associated with managing *S. frugiperda* using these synthetic chemical insecticides.

In Africa, studies have demonstrated that *Metarhizium anisopliae*, *Beauveria bassiana* [21,22] and neem oil [23] have the potential to control *S. frugiperda* infestation in maize. Additionally, several parasitoid species have been reported to attack *S. frugiperda* in its native range [24] and its invasive range in Africa [25–30]. However, the effectiveness of biorationals (natural products derived from plants, animals, microbes and minerals or their derivatives) and their effects on the abundance of parasitoids has received limited attention in Africa. Studies on the influence of synthetic pesticides and biorational insecticides on the effectiveness of managing FAW and the abundance of parasitoids and parasitism have not been conducted in Uganda. In Ghana, parasitism was reduced in some fields treated with emamectin benzoate [31]. Similarly, *M. anisopliae* ICIPE 7, *M. anisopliae* ICIPE 41 and *M. anisopliae* ICIPE 78 reduced the emergence of *C. icipe* and parasitism of *S. frugiperda* in Kenya [32,33]. This is an indication that although biopesticides are considered more ecofriendly, they may have detrimental effects on natural enemies. This study, therefore, aimed to (1) determine the abundance and damage of *S. frugiperda* under different classes of insecticides and (2) establish the species composition and abundance of parasitoids associated with *S. frugiperda* under different classes of insecticides in the field.

2. Materials and Methods

2.1. Study Sites

The experiment was conducted at the National Crops Resources Research Institute (NaCRRI), Namulonge, and the Ngetta Zonal Agricultural Research and Development Institute (ZARDI), located in the Lira and Wakiso districts. These sites were chosen because they are in different agroecological zones. The NaCRRI has a bimodal rainfall and is 0.52111° N of the Equator and 32.62685° E, and it is at an altitude of 1200 m above sea level. It receives annual rainfall between 800 and 1100 mm, with slightly humid conditions (average 65%) and an average annual temperature of 22 °C. The soil is dark, reddish-brown, sandy loam, with a pH range of 5.5 to 6.2. Ngetta ZARDI is in Northern Uganda at

2.294531° N and 32.92067° E, at an altitude of about 1077 m asl. It has a bimodal rainfall pattern with a short period between the two seasons. The mean annual rainfall is about 1300 mm. The average temperature of the district is 30 °C.

2.2. Experimental Layout

The experiments were laid out in a Randomized Complete Block Design (RCBD) with six and nine treatments in two seasons of 2020 and 2021, respectively. Each year's first and second rainy seasons are distinguished by the letters A and B, respectively. The treatments were replicated four times. The synthetic insecticides and biopesticides used in this experiment are detailed in Table 1. The General Biopesticide Cocktail comprised *Beauveria bassiana*, *Isaria fumosoroseus*, *Lecanicillium lecani*, *Metarhizium anisopliae* and *Purporeocillium lilacanus*. An untreated control was also included for comparison. Amdocs® and Nimbecidine® were sourced from the open market, while *Beauveria bassiana*, *Metarhizium anisopliae* and the General Biopesticide Cocktail were sourced from Milkweed Biologicals, a producer and distributor of biological control agents in Uganda. *Metarhizium anisopliae* ICIPE 7- and *Metarhizium anisopliae* ICIPE 78-based biopesticides (registered as Detain® and Achieve®), which have been demonstrated to be effective in Kenya, Tanzania and Uganda, respectively, and recommended for managing FAW [21], were sourced from RealIPM (https://realipm.com/products/ accessed on 13 December 2023). Roket® was chosen because it is the most widely used insecticide for controlling *S. frugiperda* among farmers. Nimbecidine® and other biopesticides were considered more human and environment-friendly bioproducts. The doses used were either recommended by the producers (entomopathogens/biopesticides) or researchers (Nimbecidine®, Amdocs® and Roket®).

Table 1. List of insecticides/treatments used in the study.

Treatments	Manufacturer/Producer	Category	Active Ingredients	Application Rate (per 20 L)
Untreated control	-		-	-
Beauveria bassiana (Bb)	Milkweed Biologicals, Kampala, Uganda	Biopesticide	*Beauveria bassiana* spores	20 g
General Biopesticide Cocktail (GBC)	Milkweed Biologicals, Kampala, Uganda	Biopesticide	*Beauveria bassiana*, *Isaria fumosoroseus*, *Lecanicillium lecani*, *Metarhizium anisopliae* and *Purporeocillium lilacanus*	20 g
Metarhizium anisopliae (Ma)	Milkweed Biologicals, Kampala, Uganda	Biopesticide	*Metarhizium anisopliae* spores	20 g
Metarhizium anisopliae ICIPE 7 (Ma ICIPE 7)	Real IPM, Thika, Kenya	Biopesticide	*Metarhizium anisopliae* strain ICIPE 7	20 mL
Metarhizium anisopliae ICIPE 78 (Ma ICIPE 78)	Real IPM, Thika, Kenya	Biopesticide	*Metarhizium anisopliae* strain ICIPE 78	20 mL
Nimbecidine®	S. Stanes and Company limited, Coimbatore, Tamil Nadu, India	Botanical	Azadirachtin 0.03% EC	120 mL
Roket®		Synthetic insecticide	Profenofos 40% + Cypermethrin 4% EC	30 mL
Amdocs®		Synthetic insecticide	Emamectin benzoate 2% + Abamectin 1%	35 mL

The Longe 10H maize was sourced from Nalweyo Seed Company (NASECO, Kampala, Uganda) and planted in 2020A, 2021A and 2021B. In 2020B, we used the Longe 5 maize variety from pearl seeds because of seed unavailability.

The plant spacing was 75 cm × 25 cm, between and within rows, respectively. Each plot measured 6 m × 5 m. Two seeds of each variety were planted per hill and later thinned to one seedling per hill after emergence. The study was conducted under natural infestation, from planting up to harvest. Spraying with the different insecticides was performed three times at 10-day intervals from 10 days after the emergence (DAE) of seedlings using a 20 L Farmate NS-20 knapsack sprayer. Di ammonium phosphate (50 Kg/ha) was applied as a blanket treatment at planting. The plots were top-dressed with urea (50 Kg/ha) 3–4 weeks after planting. Hand weeding was performed three times using a hoe, and no irrigation was applied.

2.3. Data Collection

Data on leaf damage and FAW abundance were collected starting at 10 days after seedling emergence (DAE), then at 10-day intervals, up to 50 DAE. Each time, data were collected before spraying the fields. Data were collected from 20 plants randomly selected per plot. Data on damage severity were collected using a scale of 0–9, representing the different levels of damage, according to the Davis scale [34], where: 0 = No visual leaf injury, 1 = Only pin-hole damage on a few leaves, 2 = Pin-hole and small circular hole damage to leaves, 3 = Pinholes, small circular lesions and a few small elongated (rectangular shaped) lesions of up to 1.3 cm in length are present on whorl and furl leaves, 4 = Several small to mid-sized 1.3 to 2.5 cm in length elongated lesions present on a few whorls and furl leaves, 5 = Several large elongated lesions greater than 2.5 cm in length are present on a few whorls and furl leaves and/or a few small- to midsized uniform to irregularly shaped holes (basement mem-brane consumed) eaten from the whorl and/or furl leaves, 6 = Several large elongated lesions are present on several whorls and furl leaves and/or several large uniforms to irregular-shaped holes eaten from furl and whorl leaves, 7 = Many elongated lesions of all sizes are present on several whorl and furl leaves plus several large uniforms to irregular-shaped holes eaten from the whorl and furl leaves, 8 = Many elongated lesions of all sizes are present on most whorl and furl leaves plus many mid-to large-sized uniform to irregular-shaped holes eaten from the whorl and furl leaves, and 9 = Whorl and furl leave almost destroyed. Each plant was examined after scoring for leaf damage/incidence, and the number of *S. frugiperda* eggs, larvae and adults were recorded. The yield data were obtained by weighing 20 dry cobs from the 20 sampled plants per plot. The fresh cobs were weighed, and their weight and grain moisture content were recorded. Moisture content was recorded using a digital grain moisture meter (SATAKE, Moistex Model SS-7, Satake Eng. Co., Tokyo, Japan).

The recovered egg masses and larvae of FAW were collected from each sampled plant and reared in the laboratory under fluctuating conditions for the emergence of parasitoids. The egg masses were picked up with a piece of maize leaf on which they were found and placed in Petri dishes with humid filter paper in the laboratory until FAW moths or parasitoids emerged. Each larva was kept separately in a plastic vial and provided with maize leaf to sustain until FAW moth or parasitoid emergence in the laboratory under-fluctuating environmental conditions. Leaves collected from 3 to 4 week-old untreated maize plants grown in a screenhouse were used to feed the larvae daily. All parasitoid species that emerged from the samples were preserved in 90% ethanol for morphological and molecular identification.

2.4. Identification of Parasitoids

The emerged parasitoids were examined and identified to the family/genus level using published identification guides for Platygastridae [35], Braconids [36,37], Ichneumonidae [38], and Tachinidae [39,40], also comparing with voucher specimens archived by Otim et al. [41]. The identity of the parasitoids was confirmed using molecular techniques. This was achieved by extracting DNA from individual samples, running a PCR, sequencing the PCR products, and using the Pregap4 and Gap4 sequence analysis programs within the Staden sequence analysis package to analyze trace files and assemble contigs [42]. All

PCR products were then sent to Macrogen Europe B.V. (Amsterdam, The Netherlands) for purification and sequencing. The clean partial mtCOI sequences were compared with sequences in GenBank using the Blast search program against the non-redundant (nr) DNA database [43], and where necessary, we also compared them to the International Barcode of Life (iBoL) database [44] to determine the species.

2.5. Data Analysis

The data were entered into Microsoft Office Excel (version 2019), cleaned, and exported to R-studio (version 1.4.17.17) using R version 4.2.1 (R core team, 2021). The data were summarized to obtain the mean damage per replication, total egg masses, and larvae per 20 sampled plants. The data were analyzed by season for each location. The data on mean damage, damage incidence, number of larvae per 20 plants, and larval infestation were checked for normality using the Shapiro–Wilk test [45]. Since they were not normally distributed even after the Tukey power transformation, they were then analyzed using the Kruskal Wallis test in R studio using the "r companion package". Mean separation was conducted using Dunn's test in Rstudio using the FSA package. Larval parasitism was calculated as a percentage of the total number of larvae collected that had been parasitized, while egg parasitism was calculated as a percentage of the total number of egg masses collected that had been parasitized. Since the number of egg masses and adults were low, they were not subjected to statistical analysis. Damage incidence was calculated as a proportion (%) of the total plants sampled that had leaf damage symptoms.

Grain yield (t/ha) was determined from field weight (Kg) per plot and corrected to 13.5% moisture content as:

$$\text{Grain yield } (\text{t ha}^{-1}) = (\text{FW} \times 0.8 \times (100 - \text{mc}) \times 10{,}000)/(86.5 \times 3.75 \times 1000) \quad (1)$$

where FW is the field weight (kg); mc is the field moisture content of grain per plot; 0.8 is the shelling coefficient; 10,000 m^2 is the area of a hectare; and 3.75 m^2 is the area of the 20 plants per plot.

Grain yield advantage for each treatment was then calculated as the difference between the yield obtained under the treatment (y_t) and the untreated control (y_c), expressed as a percentage- of yield of the untreated control.

$$\%\ Yield\ loss = \frac{y_t - y_c}{y_c} \times 100 \quad (2)$$

Linear regression analysis was performed to establish the relationship between yield and damage score, damage incidence and the number of FAW larvae per 20 plants.

3. Results

3.1. Leaf Damage Due to Spodoptera frugiperda in 2020A

Spodoptera frugiperda leaf damage and the incidence of damaged plants in 2020 are presented in Tables 2 and 3. Leaf damage occurred in both seasons.

Table 2. Mean leaf damage score and incidence of damaged maize plants under different treatments in different locations and seasons of 2020.

		2020			
Location	**Treatments**	**FAW Leaf Damage Score**		**Damage Incidence (%)**	
		2020A	**2020B**	**2020A**	**2020B**
Lira	Amdocs®	1.4 ± 0.10 d	2.8 ± 0.52 bc	89.3 ± 2.93 b	89.3 ± 4.79
	Roket®	2.0 ± 0.148 c	2.5 ± 0.46 cd	97.3 ± 1.43 a	88.8 ± 5.84
	Beauveria bassiana	2.2 ± 0.22 bc	2.7 ± 0.52 bc	93.3 ± 3.11 a	86.5 ± 6.28
	Metarhizium anisopliae	2.4 ± 0.32 ab	3.3 ± 0.55 ab	92.5 ± 3.51 a	89.8 ± 4.95
	Nimbecidine®	2.1 ± 0.27 c	1.9 ± 0.30 d	94.5 ± 2.92 a	86.0 ± 5.80
	Control	3.1 ± 0.49 a	3.7 ± 0.83 a	94.0 ± 3.45 a	85.3 ± 6.73

Table 2. *Cont.*

Location	Treatments	FAW Leaf Damage Score		Damage Incidence (%)	
		2020			
		2020A	2020B	2020A	2020B
	Mean ± SE	2.2 ± 0.14	2.8 ± 0.23	93.5 ± 2.07	87.6 ± 4.47
	X^2	38.24	28.89	11.93	1.24
	p value	<0.001	<0.001	0.036	0.941
Wakiso	Amdocs®	2.0 ± 0.17 c	2.1 ± 0.12 c	95.3 ± 2.39	97.0 ± 2.33
	Roket®	3.3 ± 0.13 b	2.3 ± 0.15 c	99.0 ± 0.59	96.8 ± 1.51
	Beauveria bassiana	4.8 ± 0.39 a	3.4 ± 0.51 ab	99.5 ± 0.34	95.0 ± 2.46
	Metarhizium anisopliae	4.7 ± 0.66 a	3.8 ± 0.58 ab	98.8 ± 0.71	94.3 ± 4.51
	Nimbecidine®	4.5 ± 0.38 a	3.1 ± 0.36 b	99.3 ± 0.55	97.5 ± 2.25
	Control	5.2 ± 0.67 a	4.3 ± 0.70 a	99.8 ± 0.25	96.0 ± 2.42
	Mean ± SE	4.1 ± 0.27	3.2 ± 0.22	98.6 ± 0.56	96.1 ± 1.39
	X^2	62.29	40.98	9.02	2.79
	p value	<0.001	<0.001	0.108	0.733

For each variable, means within a column followed by different letters are significantly different at $p < 0.05$. The letters A and B after a year denote first and second rainy seasons, respectively. Spray applications were performed at 10, 20 and 30 DAE.

Table 3. Mean leaf damage score, and incidence of damage maize under different treatments in Lira and Wakiso during the long and short rainy season of 2021.

Location	Treatments	FAW Leaf Damage Score		Damage Incidence (%)	
		2021			
		2021A	2021B	2021A	2021B
Lira	Amdocs®	3.6 ± 0.20 d	2.9 ± 0.53 c	100 ± 0.00	100 ± 0.00
	Roket®	4.6 ± 0.30 c	3.4 ± 0.35 bc	100 ± 0.00	100 ± 0.00
	General Biopesticide Cocktail	5.9 ± 0.62 a	4.5 ± 0.06 a	100 ± 0.00	100 ± 0.00
	Metarhizium anisopliae ICIPE 7	5.3 ± 0.51 b	4.3 ± 0.08 a	99.8 ± 0.25	99.8 ± 0.25
	Metarhizium anisopliae ICIPE 78	5.4 ± 0.62 b	4.6 ± 0.14 a	99.5 ± 0.50	100 ± 0.00
	Metarhizium anisopliae	5.6 ± 0.66 ab	4.8 ± 0.16 a	99.8 ± 0.25	100 ± 0.00
	Beauveria bassiana	5.2 ± 0.55 b	4.7 ± 0.10 a	99.8 ± 0.25	100 ± 0.00
	Nimbecidine®	4.2 ± 0.33 cd	4.2 ± 0.10 ab	100 ± 0.00	100 ± 0.00
	Control	5.8 ± 0.59 ab	4.7 ± 0.16 a	100 ± 0.00	100 ± 0.00
	Mean ± SE	5.1 ± 0.19	4.2 ± 0.12	99.9 ± 0.07	100.0 ± 0.03
	X^2	59.66	62.12	5.09	8.0
	p value	<0.001	<0.001	0.748	0.434
Wakiso	Amdocs®	1.5 ± 0.08 d	2.1 ± 0.27 c	94.5 ± 3.107	98.5 ± 0.90
	Roket®	1.7 ± 0.14 d	2.9 ± 0.17 bc	93.5 ± 3.37	97.5 ± 1.33
	General Biopesticide Cocktail	3.7 ± 0.62 ab	4.3 ± 0.49 a	94.0 ± 3.00	99.3 ± 0.55
	Metarhizium anisopliae ICIPE 7	3.0 ± 0.34 c	4.0 ± 0.52 a	97.3 ± 1.56	98.8 ± 1.02
	Metarhizium anisopliae ICIPE 78	3.1 ± 0.53 bc	3.7 ± 0.41 ab	94.3 ± 2.82	98.3 ± 1.27
	Metarhizium anisopliae	3.7 ± 0.70 ab	3.7 ± 0.44 ab	93.5 ± 3.35	97.0 ± 2.33
	Beauveria bassiana	3.7 ± 0.57 abc	3.5 ± 0.30 ab	93.5 ± 3.41	98.0 ± 1.38
	Nimbecidine®	3.0 ± 0.51 c	3.7 ± 0.50 ab	94.8 ± 3.02	98.8 ± 0.80
	Control	4.0 ± 0.66 a	4.4 ± 0.638 a	95.0 ± 2.49	97.0 ± 1.60
	Mean ± SE	3.0 ± 0.20	3.6 ± 0.16	94.5 ± 1.70	98.1 ± 0.59
	X^2	61.55	53.49	0.93	3.28
	p value	<0.001	<0.001	0.999	0.916

For each variable, means within a column followed by different letters are significantly different at $p < 0.05$. The letters A and B after a year denote first and second rainy seasons, respectively. Spray applications were performed at 10, 20 and 30 DAE.

In 2020A, plots sprayed with Amdocs® had the lowest leaf damage in both districts, with a reduction in leaf damage above 50% compared with the untreated plots, which registered the highest level of damage. The level of damage in the remaining four treatments was similar for Roket®, *B. bassiana* and Nimbecidine® in Lira. The two biopesticide treatments had similar damage levels. In Wakiso, plots treated with Roket® followed those treated with Amdocs®, which had lower leaf damage, but leaf damage did not differ significantly between the rest of the treatments and control plots (Table 2).

In 2020B, in Lira, leaf damage was lowest in plots treated with Nimbecidine®. In the same district, lower damage levels were observed in plots treated with Amdocs®, Roket® and *B. bassiana*. The damage in the *M. anisopliae*-treated plot was higher and similar to that of the untreated control. In Wakiso, similar—and the lowest—damage levels were recorded in plots treated with Amdocs® and Roket®, whilst the control registered the highest damage. Damage in the plots treated with the two biopesticides and Nimbecidine® were similar (Table 2).

Generally, the percentage of damaged plants was very high (>85%) in both locations and seasons (Table 2). The percentage of damaged plants only differed significantly in 2020A in Lira; Amdocs® had a significantly lower percentage of damaged plants in 2020A, while there were similarities in the other treatments and control.

3.2. Leaf Damage Due to Spodoptera frugiperda in 2021A

The severity of leaf damage differed significantly between treatments in all the seasons and locations (Table 3). In 2021A, Amdocs® and Roket® were superior in reducing leaf damage in both districts and seasons, although Amdocs® outperformed Roket® in 2021A in Lira (Table 3). In Lira, *M. anisopliae* ICIPE 7 and 78, *M. anisopliae* and *B. bassiana* had similar damage levels in 2021A, whilst the highest damage was recorded in the untreated control. In 2021B, however, all the other treatments and the untreated control registered similar levels of damage.

In 2021A in Wakiso, the levels of damage in plots treated with Ma ICIPE 7 and 78 and Nimbecidine® were similar; they were lower than those registered for the General Biopesticide Cocktail, *M. anisopliae*, *B. bassiana* and the untreated control. In Wakiso in 2021B, except in Amdocs®- and Roket®-treated plots, damage severity was similar in all the other remaining treatments, plus the untreated control (Table 3). In 2021, the incidence of damaged plants was high (>93%) and did not differ significantly between treatments in all the seasons in the respective districts (Table 3).

3.3. Larval Abundance and Incidence of Plants Infested with Spodoptera frugiperda in 2020

The mean number of *S. frugiperda* larvae per 20 plants and the level of infestation differed significantly between treatments in 2020A in Lira ($p < 0.01$) and all seasons in Wakiso (Table 4). In 2020A, the number of larvae was lower in Amdocs®-treated plots but similar in all other treatments (almost more than two-fold the number registered in Amdocs®-treated plots). In 2020A in Wakiso, Amdocs® had the lowest larval infestation. This was followed by Roket®- and Nimbecidine®-treated plots, which registered almost three and four times more larvae than Amdocs®, respectively. The rest of the treatments did not differ significantly. In 2020B in Wakiso, save for Amdocs®- and Roket®-treated plots, the rest of the treatments did not differ significantly in larval numbers.

Table 4. Number of *Spodoptera frugiperda* larvae and percentage of plants infested under different treatments in Lira and Wakiso during the long and short rainy season of 2020.

2020					
Location	**Treatments**	**Number of Larvae per 20 Plants**		**Larval Infestation (%)**	
		2020A	**2020B**	**2020A**	**2020B**
Lira	Amdocs®	3.6 ± 1.38 b	4.0 ± 1.15	15.0 ± 7.76 b	18.8 ± 9.34
	Roket®	8.1 ± 1.64 a	3.3 ± 0.85	30.0 ± 8.34 a	16.0 ± 8.75
	Beauveria bassiana	6.9 ± 1.42 a	3.7 ± 1.09	28.5 ± 9.15 a	17.5 ± 9.43
	Metarhizium anisopliae	9.3 ± 2.12 a	4.8 ± 1.25	35.3 ± 11.41 a	23.0 ± 11.94
	Nimbecidine®	7.4 ± 1.26 a	1.5 ± 0.76	30.3 ± 6.77 a	7.30 ± 4.62
	Control	10 ± 1.63 a	6.4 ± 1.55	41.3 ± 8.96 a	30.0 ± 14.87
	Mean ± SE	7.5	3.9	30.0	18.8
	SE	0.67	0.48	3.60	4.04
	X^2	15.78	9.99	15.30	10.02
	p value	0.008	0.075	0.009	0.075
Wakiso	Amdocs®	5.4 ± 1.570 c	4.7 ± 1.326 c	22.8 ± 10.639 c	21.3 ± 11.011 c
	Roket®	14.4 ± 2.173 b	5.4 ± 1.022 bc	52.0 ± 6.430 b	25.5 ± 7.144 bc
	Beauveria bassiana	23.0 ± 3.064 a	8.6 ± 1.491 ab	72.3 ± 11.669 a	40.3 ± 10.676 ab
	Metarhizium anisopliae	22.4 ± 2.630 ba	10.5 ± 1.781 ab	73.3 ± 7.475 a	48.0 ± 15.287 ab
	Nimbecidine®	20.6 ± 2.332 ab	7.9 ± 1.270 ab	73.8 ± 6.835 a	37.8 ± 10.364 ab
	Control	26.4 ± 2.728 a	12.8 ± 1.915 a	83.5 ± 4.650 a	56.3 ± 13.773 a
	Mean ± SE	18.7 ± 1.17	8.3 ± 0.65	62.9 ± 4.87	38.2 ± 4.88
	X^2	40.77	17.10	43.94	17.79
	p value	<0.0001	0.004	<0.0001	0.003

For each variable, means within a column followed by different letters are significantly different at $p < 0.05$. The letters A and B after a year denote first and second rainy seasons, respectively. Spray applications were performed at 10, 20 and 30 DAE.

3.4. Larval Abundance and Incidence of Plants Infested Spodoptera frugiperda in 2021

The abundance of larvae of *S. frugiperda* did not differ significantly between treatments in Lira in 2021A and B (Table 5). In Wakiso, however, the abundance of larvae differed significantly between the treatments in both seasons, when Amdocs®-treated plots registered the lowest larval numbers. This was followed by plots treated with Roket®. *Metarihzium anisopliae* ICIPE 7 and 78 and Nimbecidine® also registered slightly lower numbers of larvae when compared to the untreated control in 2021A. In 2021B, except in Amdocs®- and Roket®-treated plots, the rest of the treatments did not differ significantly in the level of larval infestation.

Table 5. Number of *Spodoptera frugiperda* larvae and percentage of maize infested under different treatments in Lira and Wakiso during the long and short rainy season of 2021.

2021					
Location	**Treatments**	**Number of Larvae per 20 Plants**		**Larval Infestation (%)**	
		2021A	**2021B**	**2021A**	**2021B**
Lira	Amdocs®	6.3 ± 1.98	5.6 ± 2.27	27.5 ± 16.92	19.3 ± 15.99
	Roket®	9.1 ± 2.13	6.1 ± 2.05	39.3 ± 15.93	24.3 ± 16.17
	General Insecticidal Cocktail	12.0± 2.59	11.6 ± 2.72	47.8 ± 18.68	40.0 ± 17.49
	Metarhizium anisopliae ICIPE 7	10.8 ± 2.27	9.7 ± 2.15	45.3 ± 16.78	35.8 ± 15.46
	Metarhizium anisopliae ICIPE 78	9.5 ± 2.36	11.2 ± 2.33	37.8 ± 16.31	41.8 ± 17.37
	Metarhizium anisopliae	10.4 ± 2.31	12.6 ± 2.60	43.0 ± 16.53	45.5 ± 18.93
	Beauveria bassiana	8.9 ± 2.02	11.4 ± 2.44	38.3 ± 15.44	43.5 ± 17.85
	Nimbecidine®	7.9 ± 2.13	9.9 ± 2.18	33.0 ± 15.90	37.3 ± 15.36
	Control	11.4 ± 2.130	10.8 ± 2.67	48.5 ± 16.65	37.5 ± 14.98

Table 5. *Cont.*

Location	Treatments	Number of Larvae per 20 Plants 2021A	Number of Larvae per 20 Plants 2021B	Larval Infestation (%) 2021A	Larval Infestation (%) 2021B
	Mean ± SE	9.6 ± 0.73	9.9 ± 0.80	40.0 ± 5.10	36.1 ± 5.18
	X^2	7.92	6.54	7.59	7.15
	p value	0.442	0.587	0.475	0.520
Wakiso	Amdocs®	0.5 ± 0.17 d	3.2 ± 0.98 c	2.3 ± 1.34 d	15.0 ± 9.289 c
	Roket®	2.1 ± 1.18 cd	5.3 ± 0.69 bc	7.5 ± 2.74 cd	25.0 ± 3.56 bc
	General Insecticidal Cocktail	6.2 ± 1.27 a	14.6 ± 2.57 a	27.3 ± 8.92 a	52.3 ± 11.80 a
	Metarhizium anisopliae ICIPE 7	3.1 ± 1.07 bc	10.2 ± 1.89 ab	13.5 ± 5.67 bc	38.3 ± 11.47 ab
	Metarhizium anisopliae ICIPE 78	3.6 ± 1.15 abc	11.1 ± 1.69 ab	15.3 ± 7.22 abc	44.3 ± 9.10 ab
	Metarhizium anisopliae	6.1 ± 1.43 ab	10.3 ± 1.86 ab	25.3 ± 9.79 ab	39.3 ± 8.24 ab
	Beauveria bassiana	5.4 ± 1.33 ab	10.0 ± 1.14 ab	22.3 ± 8.28 ab	39.8 ± 3.22 ab
	Nimbecidine®	3.7 ± 1.07 abc	10.3 ± 2.36 abc	16.8 ± 6.79 abc	37.8 ± 11.72 abc
	Control	8.3 ± 2.02 ab	16.0 ± 2.53 a	29.5 ± 11.65 ab	56.8 ± 8.79 a
	Mean ± SE	4.3 ± 0.45	10.1 ± 0.67	17.7 ± 2.64	38.7 ± 3.29
	X^2	31.41	37.27	30.83	37.41
	p value	0.0001	<0.0001	0.0001	<0.0001

(All columns: 2021.)

For each variable, means within a column followed by different letters are significantly different at $p < 0.05$. The letters A and B after a year denote first and second rainy seasons, respectively. Spray applications were performed at 10, 20 and 30 DAE.

The percentage of plants infested with larvae did not differ significantly between treatments in both seasons of 2021 in Lira (Table 5). However, there were significant differences between treatments in both seasons in Wakiso (Table 5), where Amdocs®- and Roket®-treated plots registered significantly lower percentage of infested plants; the percentage of infested plants did not differ significantly between the remaining treatments.

3.5. *Abundance of Spodoptera frugiperda Egg Mass and Adults*

The total numbers of egg masses are presented in Supplementary Tables S1 and S2. We recovered a total of 360 egg masses from the different locations. Although not analyzed statistically, we recorded more egg masses in Lira and Waksio in 2020 than in 2021. There were more egg masses in the treated plots than in the untreated plots in Lira in 2020A and in Wakiso in both seasons of 2020 (Supplementary Table S1). The untreated control had higher egg mass numbers in Lira in both 2021 seasons and in 2021B in Wakiso (Supplementary Table S2). There were no discernible patterns in the number of adults between treatments, but Wakiso also registered a higher number of *S. frugiperda* moths (46 individuals), while only 14 adult moths were recovered from Lira in the 4 seasons.

3.6. *Variation in Leaf Damage Severity with the Age of Maize Plants under Different Treatments*

Leaf damage severity generally increased in all treatments between 10 DAE and 20 DAE and peaked between 20 and 40 DAE in most treatments (Figure 1). There were significant ($p < 0.05$) differences in leaf damage severity between treatments on all sampling dates, except at 10 DAE in all locations and seasons in 2020 and 2021 and 20 DAE in 2020B in Lira. Amdocs® and Roket® were the most superior in reducing leaf damage at the different stages of maize growth in both locations and seasons (Figure 1). Nimbecidine®-treated plots performed well in Lira; this was not significantly different from Amdocs®- and Roket®-treated plots at 30 and 40 DAE in 2020B and at 20, 30 40 and 50 DAE in 2021A. The biopesticides did not always lead to a significant leaf reduction when compared with the untreated control. The only exceptions occurred in Lira at 40 DAE (2020A), at 30 and 40 DAE (2020B), and in Wakiso at 50 DAE (2020A) when *B. bassiana*-treated plots had significantly lower damage levels compared with the untreated control (Figure 1). In 2021, the two registered ICIPE products significantly reduced leaf damage severity when compared with the untreated control in Wakiso: *Metarhizium anisopliae* ICIPE 7 significantly reduced leaf damage at 40 and 50 DAE (2021A) and *M. anisopliae* ICIPE 78 reduced leaf damage at 20 DAE (2021A and 2021B). *Beauveria bassiana* also had a significantly lower leaf damage level at 20 DAE in Wakiso in 2021B.

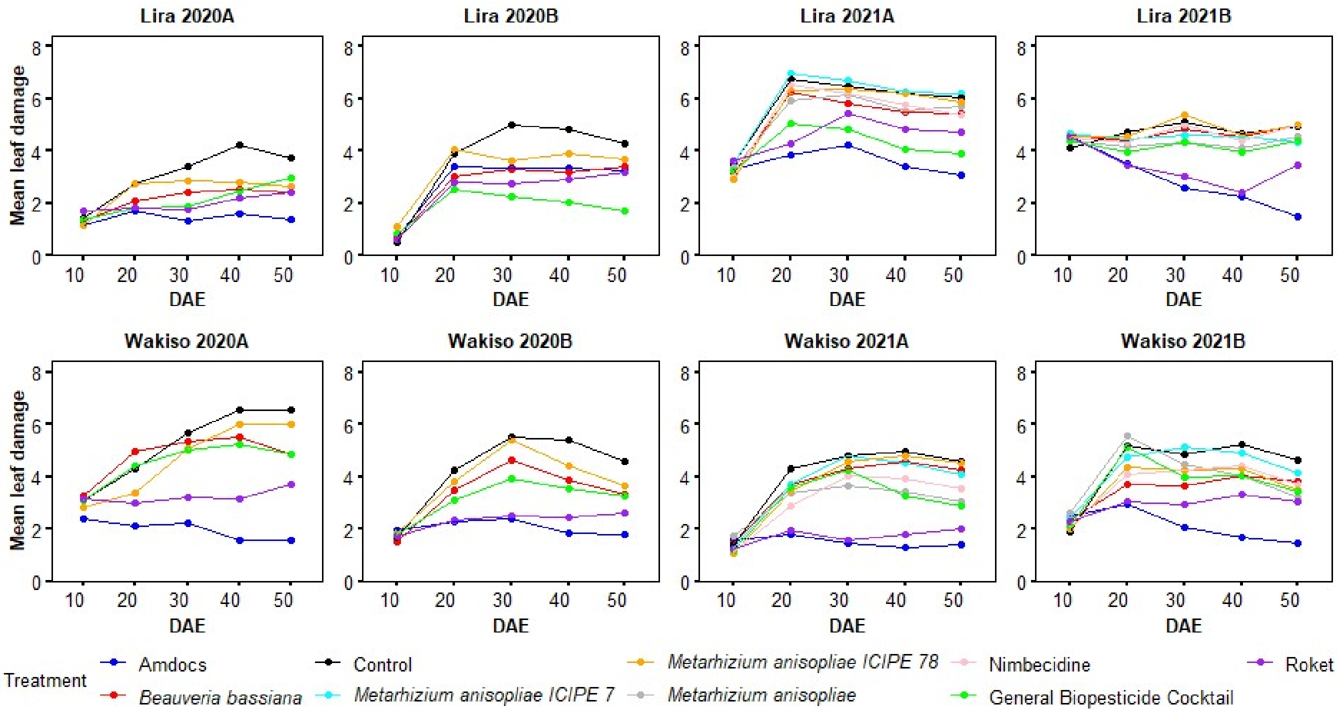

Figure 1. Mean leaf damage under different treatments over the days after seedling emergence. The letters A and B after a year denote first and second rainy seasons, respectively. Spray applications were performed at 10, 20 and 30 DAE.

3.7. Variation in the Abundance of Larvae of Spodoptera frugiperda with the Age of Maize Plants under Different Treatments

There were significant ($p < 0.05$) differences in larval abundance between the treatments in Lira at 30 and 40 DAE (2020A), 30 DAE (2020B and 2021A), and at 20 and 30 DAE (2021B). In Wakiso, significant differences occurred in larval abundance between the treatments at 30 to 50 DAE (2020A), 30 and 40 DAE (2020B), 40 DAE (2021A), and 20 and 40 DAE (in 2021B) (Figure 2).

In Lira, statistically lower and similar larval abundance occurred between the untreated control, the biopesticides, and Amdocs®- and Nimbecidine®-treated plots at 30 and 40 DAE, whilst Roket®-treated plots had the highest abundance in 2020A. In 2020B in Lira, *M. anisopliae*-treated plots had significantly higher larval abundance, while the abundance of larvae was similar to the control. In 2021A, only *M. anisopliae* and *M. anisopliae* ICIPE 78 had the lowest larval abundance at 30 DAE, while *M. anisopliae*, *M. anisopliae* ICIPE 78, Roket® and Nimbecidine® had larval abundance not significantly different from the control at 40 DAE; the rest of the treatments had significantly higher larval abundance. In 2021B, the lowest larval abundance was observed in *M. anisopliae* ICIPE 78 and the control at 20 DAE, and in the control only at 40 DAE.

In Wakiso in 2020A, *M. anisopliae*- and Amdocs®-treated plots had the lowest larval abundance at 30 DAE, while *M. anisopliae*-, Amdocs®- and Roket®-treated plots had the lowest larval abundance at 40 DAE. (Figure 2). In 2020B, Roket®- and Nimbecidine®-treated plots had the lowest and similar larval abundance to the untreated control, while the other treatments had significantly higher larval abundance at 30 and 40 DAE. In 2021A, *M. anisopliae* ICIPE 78, *M. anisopliae*, Nimbecidine® and Roket® had the lowest and similar damage levels to the untreated control at 40 DAE. In 2021B in Wakiso, Nimbecidine®-

and *M. anisopliae*-treated plots had the lowest larval abundance at 20 DAE, while Roket®, Nimbecidine®- and *M. anisopliae*-treated plots had the lowest larval abundance at 24 DAE (Figure 2).

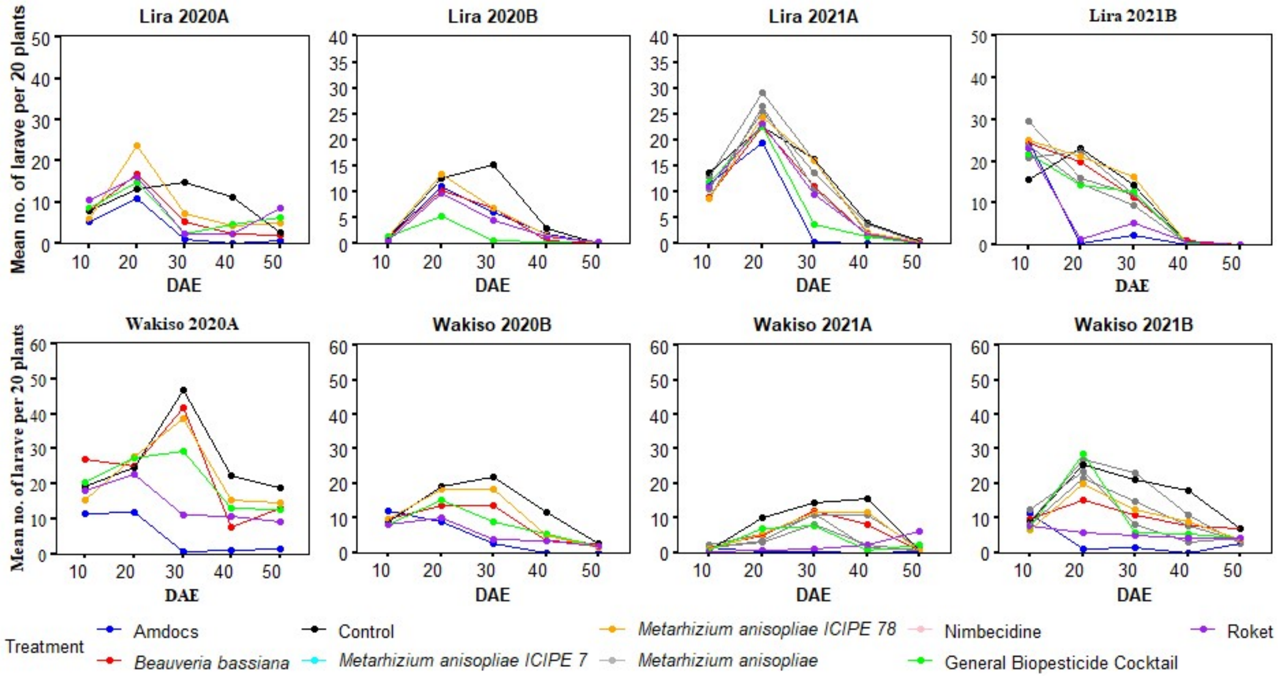

Figure 2. Variation in the number of *Spodoptera frugiperda* larvae under different treatments over the different growth stages (days after seedling emergence). The letters A and B after a year denote first and second rainy seasons, respectively. Spray applications were performed at 10, 20 and 30 DAE.

3.8. Grain Yield of Maize in Different Locations and Seasons

Grain yield was not significantly different between the treatments ($p > 0.05$) in all seasons in both locations (Table 6). In some instances, the untreated control outyielded some insecticide-treated plots, as seen in 2020B in Lira and 2021B in the Wakiso district. The overall yield gain across treatments and locations averaged 9.2%. The highest gain was 38.7%.

Table 6. Grain yield and yield advantage under different treatments in Lira and Wakiso during the long and short rainy seasons of 2020 and 2021.

Location	Treatments	Grain Yield (t/ha)				Yield Advantage over Control (%)			
		2020A	2020B	2021A	2021B	2020A	2020B	2021A	2021B
Lira	Amdocs®	8.6 ± 0.63	5.1 ± 0.21	4.3 ± 0.37	5.1 ± 0.33	7.5	−13.6	38.7	27.5
	Roket®	7.8 ± 0.39	6.1 ± 0.14	4.3 ± 0.39	4.0 ± 0.68	−2.5	3.4	38.7	0.0
	General Biopesticide Cocktail			4.3 ± 0.40	3.6 ± 0.14			38.7	−10.0
	Metarhizium anisopliae ICIPE 7			3.3 ± 0.10	3.9 ± 0.72			6.5	−2.5
	Metarhizium anisopliae ICIPE 78			4.1 ± 0.12	3.7 ± 0.21			32.3	−7.5
	Metarhizium anisopliae	9.3 ± 0.54	6.0 ± 0.50	4.3 ± 0.61	3.6 ± 0.61	16.3	1.7	38.7	−10.0
	Beauveria bassiana	9.5 ± 0.46	6.0 ± 0.39	4.2 ± 0.50	3.2 ± 0.67	18.8	1.7	35.5	−20.0
	Nimbecidine®	8.8 ± 0.66	5.0 ± 0.24	3.1 ± 0.53	4.1 ± 0.29	10.0	−15.3	0.0	2.5
	Control	8.0 ± 0.42	5.9 ± 0.30	3.1 ± 0.30	4.0 ± 0.47				
	Mean ± SE	8.67 ± 1.11	5.68 ± 0.40	3.88 ± 0.65	3.9 ± 1.01				
	Lsd	2.519	1.519	2.0302	2.532				
	%cv	12.17	11.182	20.769	25.729				
	p value	0.202	0.085	0.125	0.442				

Table 6. *Cont.*

Location	Treatments	Grain Yield (t/ha)				Yield Advantage over Control (%)			
		2020A	2020B	2021A	2021B	2020A	2020B	2021A	2021B
Wakiso	Amdocs®	2.8 ± 1.00	6.2 ± 0.50	6.4 ± 0.60	5.5 ± 0.39	21.7	19.2	−9.9	10.0
	Roket®	2.8 ± 0.50	4.5 ± 0.54	6.1 ± 0.66	6.0 ± 0.85	21.7	−13.5	−14.1	20.0
	General Biopesticide Cocktail			6.3 ± 0.62	5.7 ± 0.46			−11.3	14.0
	Metarhizium anisopliae ICIPE 7			7.4 ± 0.64	5.6 ± 0.45			4.2	12.0
	Metarhizium anisopliae ICIPE 78			6.9 ± 0.86	5.8 ± 0.67			−2.8	16.0
	Metarhizium anisopliae	2.4 ± 0.53	6.0 ± 0.51	7.0 ± 0.29	5.4 ± 1.10	4.3	15.4	−1.4	8.0
	Beauveria bassiana	2.9 ± 0.87	5.5 ± 0.83	7.3 ± 0.39	6.0 ± 0.26	26.1	5.8	2.8	20.0
	Nimbecidine®	3.1 ± 0.53	5.8 ± 0.89	6.7 ± 0.87	6.6 ± 0.27	34.8	11.5	−5.6	32.0
	Control	2.3 ± 0.42	5.2 ± 1.12	7.1 ± 0.55	5.0 ± 1.00				
	Mean ± SE	2.70 ± 1.79	5.5 ± 2.36	6.81 ± 1.60	5.7 ± 1.81				
	Lsd	3.195	3.668	3.190	3.391				
	%cv	49.36	27.825	18.591	23.482				
	p value	0.933	0.652	0.823	0.881				

The letters A and B after a year denote first and second rainy seasons, respectively. Spray applications were performed at 10, 20 and 30 DAE.

3.9. The Relationship between Grain Yield and Leaf Damage

The regression between grain yield and leaf damage was generally insignificant ($p > 0.05$), except for 2021B in Lira $\left(Y = 6.7 - 0.67x; R^2 = 0.69; P = 0.005\right)$, where a significant negative relationship was observed between the two variables. Although not significant, negative relationships were observed in four cases, whilst non-significant positive relationships between grain yield and leaf damage were observed in two cases.

3.10. The Relationship between Grain Yield and Larval Numbers

Although insignificant, the relationship between grain yield and larval numbers was negative in three of four seasons in each location. A significant negative relationship was observed between grain yield and larval abundance only in Lira in 2021B $\left(Y = 0.62 - 0.17x; R^2 = 0.62; P = 0.012\right)$.

3.11. The Relationship between Grain Yield and Percentage of Infested Plants

The relationship between grain yield and the percentage of infested plants was negative in three of four seasons in both locations. A significant negative relationship was observed between grain yield and the percentage of infested plants only in Lira in 2021B $\left(Y = 5.7 - 0.051x; R^2 = 0.72; P = 0.004\right)$.

3.12. Parasitoids Recovered from Spodoptera frugiperda Eggs and Larvae

During the study, we reared eight species of parasitoids from *S. frugiperda*—one from eggs (*Telenomus remus*) and seven from the larvae (*Coccygidium* spp., *Cotesia icipe*, *Chelonus* sp., *Micranisa* sp., *Charops* cf. *diversipes* and an unidentified Tachinidae) (Table 7). Three other species of parasitoids (an unidentified *Eurytomidae*, *Parapanteles*. and *Dolichogenidea* sp.) were recovered from cocoons on maize plants.

Table 7. Parasitoid species recovered from eggs and larvae of *Spodoptera frugiperda* collected from maize fields in Uganda, host stage attacked, and their sequence identity as compared with publicly available sequences from GenBank and iBoL entries.

Order and Family	Species	Location	Host Stage Attacked	Species with the Closest Nucleotide Sequence Match	Percentage Identity, and Reference GenBank Accession Number and iBoL Entries
Hymenoptera: Platygastridae	*Telenomus remus* Dixon	Wakiso and Lira	Eggs	*Telenomus remus*	100% (ON923739.1) [29]
Hymenoptera: Eurytomidae	*Unidentified*	Wakiso	Egg/Larval	*Eurytoma asphodeli*	87.16% KT623736.1 [46]

Table 7. *Cont.*

Order and Family	Species	Location	Host Stage Attacked	Species with the Closest Nucleotide Sequence Match	Percentage Identity, and Reference GenBank Accession Number and iBoL Entries
Hymenoptera: Braconidae	*Coccygidium luteum*	Wakiso and Lira	Larvae	*Coccygidium luteum*	99.64% MT784187 [41]
	Coccygidium sp.	Wakiso and Lira	Larvae	*Coccygidium* sp.	
	Cotesia icipe	Wakiso and Lira	Larvae	*Cotesia icipe*	100% MN900735.1 [26], 100% MT780217 [41]
	Unidentiified.	Wakiso	Larvae	*Parapanteles athamasae*	100% HM397613.1 [47]
	Chelonus sp.	Wakiso and Lira	Egg/Larval	*Chelonus insularis*	97.42% XM_035078068
	Dolichogenidea sp.	Wakiso	Larval	*Dolichogenidea* sp.	93.28% JF271344.1 [48]
Hymenoptera: Pteromalidae	*Micranisa* sp	Wakiso	Larvae	*Micranisa* sp.	87.34% MK530760.1 [49]
Hymenoptera: Ichneumonidae	*Charops* cf. *diversipes*	Wakiso and Lira	Larvae	*Charops* cf. *diversipes*	100% (MT784182.1), 100% (MT784181.1), 100% (MT784179.1) [41], 100% (MT784183.1) [26]
Diptera: Tachinidae	Unidentified	Wakiso and Lira	Larvae/pupae	Tachinidae sp.	99.35% (MT784176.1) [41]

3.12.1. Egg Parasitism of *Spodoptera frugiperda*

All the recovered eggs of *S. frugiperda* were parasitized by *T. remus*. Irrespective of treatment, egg parasitism was 15.2% (in 2020A), 19.2% (2020B), and 5.7% (2021A), and there was no parasitism in 2021B in Lira. The corresponding values for Wakiso were 21.7% (2020A), 4.4% (2020B), and 13.6% (2021A), and there was no parasitism in 2021B. The variation in egg parasitism across treatments was not consistent between seasons for each location (Supplementary Tables S1 and S2).

In 2020 in Lira, the highest egg parasitism levels were recorded in the untreated control in 2020A and plots treated with Amdocs® in 2020B (Supplementary Table S1). In the same year in Wakiso, the highest egg parasitism level was recorded in plots spayed with Nimbecidine® in 2020A and those treated with *B. bassiana* in 2020B. Combined over locations and seasons, egg mass parasitism averaged 10%.

In 2021, egg parasitism was only recorded in two treatments in both locations in 2021A, whereas no parasitism was recorded in both locations in 2021B (Supplementary Table S2). The highest egg parasitism level was recorded in a plot treated with *M. anisopliae* in Lira, whilst both plots that registered egg parasitism in Wakiso had 100% egg mass parasitism.

3.12.2. Parasitism of Larvae of *Spodoptera frugiperda*

Larval parasitism in the different locations and seasons is presented in Supplementary Tables S3 and S4. A total of seven (7) larval parasitoid species were recovered in 2020 (Supplementary Table S3), and six (6) were recovered in 2021 (Supplementary Table S4).

In 2020, we recovered *Charops* cf. *diversipes*, *C. luteum* and *C. icipe* from Lira. In Wakiso, we reared seven species from *S. frugiperda larvae*. These included *C.* cf. *diversipes*, *Chelonus* sp., *C. luteum*, *Coccygidium* sp., *C. icipe*, *Micranisa* sp. and the Tachinidae When pooled over locations and seasons, larval parasitism averaged 5.3%. Larval parasitism was 0.7% and 1% in 2020A and 2020B, respectively, in Lira, and 21.1% and 4.7% in the respective seasons in Wakiso.

In 2021, we recovered four larval parasitoid species from Lira (*Chelonus* sp., *C. icipe*, the Tachinidae and *C. cf diversipes*) and six species from Wakiso (*Chelonus* sp., *C. luteum*, *Coccygidium* sp., the Tachinidae, *C. cf diversipes*, and *C. icipe*) (Supplementary Table S4). Irrespective of treatment, larval parasitism was 0.7% and 3% in Lira and 7.4% and 3.4% in Wakiso in 2021A and 2021B, respectively.

4. Discussion

We conducted this study to investigate the effectiveness of different insecticides in controlling *S. frugiperda* infestation and damage, and to document the parasitoids and parasitism of this pest in two different locations. The results of our study have shown significant differences in leaf damage among treatments in all seasons and locations. Comparatively, plots treated with Amdocs® (emamectin benzoate 2% + abamectin 1%), a synthetic insecticide, had significantly lower leaf damage, damage incidence, and larval infestation. This was followed closely by the plots treated with the synthetic insecticide, Roket® (profenofos 40% + cypermethrin 4% EC.). Nimbecidine®, a botanical, was sometimes as superior as Roket® and at times reduced leaf damage just the same as the EPFs. Control plots generally had higher damage and larval infestation levels. The EPFs performed better or at the same level as the untreated control. We recovered eight species of parasitoids from *S. frugiperda*; *Telenomus remus* from eggs; and seven egg/larval or larval parasitoids from *Coccygidium* spp., *Cotesia icipe*, *Chelonus* sp., *Micranisa* sp., *Charops* cf. *diversipes* and the Tachinidae. Three other unidentified parasitoids (*Eurytomidae*., *Parapanteles* and *Dolichogenidea*) were reared from cocoons on maize plants. Despite the diversity of parasitoids, parasitism was generally low, averaging 10% in eggs and 5.3% in larvae. Because of the low number of parasitoids encountered, no discernible association could be made between parasitoid abundance/parasitism and the treatments.

The results of this study have shown that the application of insecticides, especially the synthetics and the botanical, reduced infestation and damage, and this could explain why farmers in Uganda use insecticides as a key measure to control *S. frugiperda* [41]. The superiority of insecticides may be attributed to their high potency in *S. frugiperda*. The effectiveness of avermectins such as emamectin benzoate to control *S. frugiperda* has been reported in laboratory and field studies [31,50,51]. Their effectiveness is attributed to ovicidal and larval effects and translaminar uptake, which ensures a long presence in the parenchyma tissue of sprayed plants [52], resulting in an extended protection duration. Neem, on the other hand, is known to have antifeedant, ovicidal, insect growth regulation, repellant, and mating disruption activity [53,54]. Our findings corroborate earlier reports where emamectin benzoate caused a higher mortality of *S. frugiperda* than organophosphates or pyrethroids [51,55,56]. Similarly, the reported effectiveness of Nimbecidine® is in tandem with earlier reports that show the good effectiveness of neem in controlling *S. frugiperda* [31,50,57]. Although the tested biopesticides showed some reduction in leaf damage, they were not always better than the untreated control and performed below the synthetic and botanical pesticides. This is consistent with earlier work in which the moderate effectiveness of biopesticides was reported when compared to synthetic pesticides [32,50]. Environmental factors such as humidity, rainfall and temperature are reported to influence the effectiveness of biopesticides, leading to their poor performance [58].

The diversity of parasitoids reported in this study is similar to that reported in different parts of Uganda [41], with one exception. Here, we report for the first time that *Micranisa* sp. is associated with *S. frugiperda* in Uganda. The recovered larval parasitoids included *Charops* cf. *diversipes*, *Coccygidium luteum*, *Coccygidium* sp., *Cotesia icipe*, *Chelonus* sp. *Micranisa* sp. and an unidentified tachinid. These are consistent with previous studies on the parasitoid complex of *S. frugiperda* across Africa, and specifically in Uganda [41]. The parasitoids *C. luteum* and *C. icipe* have also been recorded on *S. frugiperda* in other East African countries [59]. In our study, we found that Wakiso had a higher parasitoid species richness than Lira; all seven parasitoid species were recovered from larvae, while only five species were recovered from Lira. The reasons for this are not clear but may be attributable to several factors, including landscape factors. Among the other parasitoids recovered from maize plants, Eurytomids are known parasitoids of the African stem borer, *Busseola fusca* [60]. Parapanteles spp. are reported as parasitoids of *S. frugiperda* in Zambia [27].

The parasitism of field-collected eggs and larvae was low, averaging 10% for egg masses and 5.3% for the larvae. These suggest that the levels of parasitism are still low, but nevertheless, this demonstrates the important role that parasitoids can play in the integrated management of *S. frugiperda*. The levels of parasitism of eggs of *S. frugiperda* by *T. remus* in our study are less than the figures reported in other countries: 69.3% (in Kenya), 58.5% (in Tanzania) [61] and 34.4% in Cameroon [62] for maize, and 78 and 64% in laboratories and sorghum fields in Niger, respectively [28]. Similarly, the overall larval parasitism reported in this study is lower than that reported earlier in Uganda [41], where parasitism averaged 9.2%. In Ghana, the parasitism of *S. frugiperda* larvae ranged from 0% to 35.6% [26]. In the previous study, we performed single sampling in several locations (almost 20), while the present study was conducted in only 2 locations. Thus, location differences may account for the differences between parasitism levels. The parasitism level reported in this study is lower than the 9.5% reported in Mozambique [63]. Among the parasitoids, *Ch. cf diversipes*, *Chelonus* sp., *C. luteum*, *C. icipe* and the Tachinidae were more abundant, especially in Wakiso, and are candidates for mass production and release.

Our interest was also in comparing the parasitism of *S. frugiperda* under different treatments. Although the abundance of parasitoids was low or at times absent, our 2020A results in Wakiso show a generally higher number of parasitoids, based on which we can provide some preliminary observations. Plots treated with Amdocs® and Roket® recorded lower abundance and richness of parasitoids, suggesting that these treatments could potentially have negative effects on the abundance of the parasitoids. The reduction in abundance could be attributed to an indirect reduction in the abundance of the host or detrimental effects on specific species of parasitoids. It is evident from these results that *Ch.* cf *diversipes* and *C. luteum* were not recovered from Amdocs®-treated plots in 2020A in Wakiso, while Chelonus sp. was not recovered from Roket®-treated plots. Ironically, however, the percentage of parasitism was generally lowest in the untreated control, lending credence to the observation that the percentage of parasitism by certain parasitoids is not affected by the different treatments. The lowest parasitism of *S. frugiperda* larvae by *C. icipe* was observed in plots treated with *M. anisopliae* in 2020A in Wakiso, suggesting that this EPF could have a negative effect on the parasitoid. Whereas *M. anisopliae* ICIPE 7 and 78 were reported to reduce parasitism by *C. icipe* [32,33], we did not observe this because of the low abundance of parasitoids in the seasons in which we used the two products. Further observations will thus be needed to conclude the effects of the two EPFs on the parasitism of *S. frugiperda*.

Grain yield was generally higher in insecticide-treated plots than in the untreated plots, increasing to 38.7% yield advantage over the untreated control. This is evidence that the reduction in leaf damage led to higher yields, as reported earlier by some authors [50]. Although this was the case, our data also showed that the untreated control at times had higher yields when compared with the treated plots, despite succumbing to high damage levels. This is consistent with a previous report stating that the relationship between foliar damage by *S. frugiperda* and grain yield does not usually result in significant yield reduction due to the compensation effect [64,65]. Severe losses, however, occur when the whorl is destroyed; this is because of a reduced photosynthetic area and thus compromised grain yield [66]. One of the reasons for the recovery is good rainfall and crop management practices in research plots, which enhance crop vigor.

5. Conclusions

Our findings have demonstrated that synthetic pesticides reduce *S. frugiperda* damage and larval abundance more than biopesticides, often resulting in higher yield when compared with the untreated control. The botanical Nimbecidine® was also good at reducing damage and larval numbers. We recovered one egg parasitoid and seven larval parasitoids that were directly associated with *S. frugiperda*. Because of the low population of parasitoids, we were unable to pinpoint the effect of the treatments on their abundance and parasitism. Nevertheless, we recovered many parasitoids in one season, and the results appear to show that the application of Amdocs® and Roket® reduced the population of parasitoids but not the percentage of parasitism. It may thus be possible that a reduction in the number of parasitoids resulted both from a decrease in the number of hosts and the direct effects of the pesticides.

While pesticide application reduces infestation and damage, the yield did not necessarily differ significantly when there was high rainfall. Thus, it will be prudent to recommend an Integrated Pest and Crop Management Strategy that incorporates good agronomic practices such as early planting, fertilizer application, proper weeding, and scouting, and applying pesticides based on infestation/damage thresholds. Unfortunately, we do not have thresholds that are recommended for maize farmers in Uganda. These, therefore, need to be determined. While considering the tactics to integrate, it will be necessary to assess practices that are more compatible with biological practices. We recommend conducting more studies on the natural enemies of *S. frugiperda* in Uganda, and their interaction with other control practices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16083118/s1, Table S1: Total number of egg masses collected, total number of *Telenomus remus* recovered, and parasitism of *Spodoptera frugiperda* egg masses under different treatments in 2020, Table S2: Total number of egg masses collected, total number of *Telenomus remus* recovered, and parasitism of *Spodoptera frugiperda* egg masses under different treatments in 2021, Table S3: Total number of larvae collected, total number of larval parasitoids recovered, and parasitism of *Spodoptera frugiperda* larvae under different treatments in Lira and Wakiso during the long and short rainy season of 2020, Table S4: Total larvae collected, number of larval parasitoids recovered, and parasitism of *Spodoptera frugiperda* larvae under different treatments in Lira and Wakiso during the long and short rainy season in 2021.

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