Comparative effects of biopesticides on fall armyworm management and larval parasitism rates in northern Ghana

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Abstract

The outbreak of the fall armyworm, *Spodoptera frugiperda,* in Africa has led to several recommendations of insecticides, including biopesticides. However, the effects of these products on the environment, especially on parasitoids have not been assessed under field conditions. Here, we investigated the effect of commonly used biopesticides on *S. frugiperda* management and larval parasitoids of *S. frugiperda* in northern Ghana. The experiments were conducted both on-station in Wa and Nyankpala and on-farm in Wa during the 2020 rainy season. Active ingredients tested included neem oil (3% Azadirachtin), maltodextrin (282 g/l), 55% *Bacillus thuringiensis* (*Bt*) combined with 45% Monosultap, and a *Pieris rapae* granulosis virus combined with 5% *Bt*. A chemical insecticide based on emamectin benzoate and acetamiprid was used as positive control while non-treated maize plots were considered as untreated control. The two most abundant parasitoids in Wa were *Coccygidium luteum* and *Chelonus bifoveolatus*, while in Nyankpala they were *C. luteum* and *Meteorus* sp. Total larval parasitism rates on-station were 18.7% and 17.6% in Wa and Nyankpala, respectively, and 8.8% in Wa on-farm. Parasitoid species diversity and evenness indexes did not vary among treatments, but parasitism rates were significantly lower with the chemical on-station in Wa and with the virus and Bt product in Nyankpala. Untreated maize plots showed the highest larval density and plant damage, the highest cob damage, and generated the lowest yields. The other treatments showed hardly any difference in cob damage and yields, suggesting that biopesticides should be preferred over chemical pesticides for *S. frugiperda* control.

Keywords *Spodoptera frugiperda* · Parasitoid species · Maize · Side-effects of pesticides · Environment

Key message

- This study investigated the effect of commonly used biopesticides on *Spodoptera frugiperda* management and its larval parasitoids in Ghana, in comparison with a chemical insecticide based on emamectin benzoate and acetamiprid and untreated control.
- The diversity and evenness indexes of the parasitoid species did not vary among treatments, but parasitism rates were significantly lower with the chemical on-station.
- The highest larval density and cob damage and the lowest yields were recorded in the untreated maize plots while, the biopesicides and the chemical treatments displayed similar cob damage and yields.
- Biopesticides should be preferred over chemical pesticides for *S. frugiperda* control.

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Introduction

The fall armyworm, *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) is a highly destructive pest of cereals, native to tropical and subtropical regions of the Americas (Kenis et al. 2022). The pest invaded Africa, parts of Asia and Australia over the last six years, threatening the food security and income situation of millions of farmers, many of which are small holders relying on maize as their main staple crop (Rwomushana et al. 2018). In addition, the pest, known to be highly polyphagous, is likely to jeopardize the trade and export of other crops from the invaded regions.

Following the invasion of *S. frugiperda* into Africa, emergency responses were geared towards the use of chemical insecticides. The severity of *S. frugiperda* infestation resulted in farmers repeatedly spraying insecticides during the cropping season, often relying on broad spectrum active ingredients of high toxicity, especially in the first years following the outbreak (Tambo et al. 2020a). The frequent application of broad-spectrum insecticides, however, may be unsustainable because it increases production costs, risk for the development of insecticide resistance, health risks to the growers and consumers, as well as impacts on biodiversity and the environment (Pimentel and Andow 1984; Yu 1991; Togola et al. 2018). Broad spectrum pesticides further have high potential to disrupt natural biological control in maize fields, which, in Africa and other regions, are mostly not or hardly treated with insecticides (Hruska 2019).

There are over 150 parasitoid species that are reported to parasitize *S. frugiperda* from its native range in the Americas (Molina-Ochoa et al. 2003). Studies conducted in Africa have recently shown over 27 species of parasitoids and the numbers are likely to increase due to species being overlooked and others that will still need to adapt to this new invasive pest (Laouali et al. 2018; Sisay et al. 2019; Agboyi et al. 2020; Laminou et al. 2020; Durocher-Granger et al. 2021; Otim et al. 2021; Abang et al. 2021). Similarly, studies in China and India have shown a considerable number of natural enemies, both looking at predators and parasitoids (Firake and Behere 2020). Already in the first or second year after invasion of fall armyworm, combined parasitism and predation rates were reported to exceed 50% in some locations, suggesting that the local community of natural enemies could play a significant role in controlling this invasive pest (Kenis et al. 2022). However, the use of highly hazardous and broad-spectrum insecticides might threaten these local natural enemies and it is important to minimize their use by developing, promoting and deploying proven and sustainable biopesticides against *S. frugiperda*, under Integrated Pest Management (IPM) strategies.

Several biopesticides are available for control of *S. frugiperda*, for instance, the oil extracted from seeds of the neem tree (*Azadirachta indica* L.) has recently been shown to be effective and even relatively cheap at controlling this pest (Babendreier et al. 2020). Products based on *Bacillus thuringiensis* (Bt) have also been shown to be effective and generally a considerable number of biopesticides are available in African countries, with numbers increasing over the last few years (Bateman et al. 2021).

In Ghana, the Ministry of Food and Agriculture initiated a programme to promote the use of biopesticides for the control of this pest by smallholder farmers since 2018, subsidizing in particular products based on *Bacillus thuringiensis*, Azadirachtin and Maltodextrin (vegetable oil and starch) as active ingredients (Asare-Nuamah 2020; Tambo et al. 2020a). These products are reported to be effective against *S. frugiperda* by farmers, extension agents and researchers, however, there is no information about their compatibility with natural enemies of *S. frugiperda* occurring in the country and reported in our previous study (Agboyi et al. 2020). The objectives of this study were to assess the effectiveness of biopesticides for *S. frugiperda* management but in particular their effect on locally present parasitoids of *S. frugiperda* in northern Ghana, and to identify the most sustainable products compatible with conservation and augmentation biocontrol of *S. frugiperda*.

Materials and methods

Study sites

This work was conducted in the Guinea Savannah zone of northern Ghana from June to November 2020. The climate in this zone is classified as tropical savannah climate with non-seasonal or dry-winter characteristics (Geiger 1961) and annual daily maximum temperatures of between 26 and 45 °C. The region has a uni-modal rainfall pattern that starts in May and ends in October, followed by a dry season from November to April (mean annual rainfall is about 1100 mm). The soil in the experimental area belongs to the Savannah Ochrosol type, with a relatively thin layer of top soil (about 25 cm deep) consisting of greyish brown loamy sand.

Both on-station and on-farm trials were undertaken. The on-station studies were implemented at the research fields belonging to the Council for Scientific and Industrial Research-Savanna Agricultural Research Institute (CSIR-SARI) near Wa (Longitude: −2.5058; Latitude: 10.0783) in Upper West region and Nyankpala (Longitude: −0.9899; Latitude: 9.4022) in Northern region. The on-farm

Fig. 1 Map of the study sites in Upper West and Northern regions of Ghana
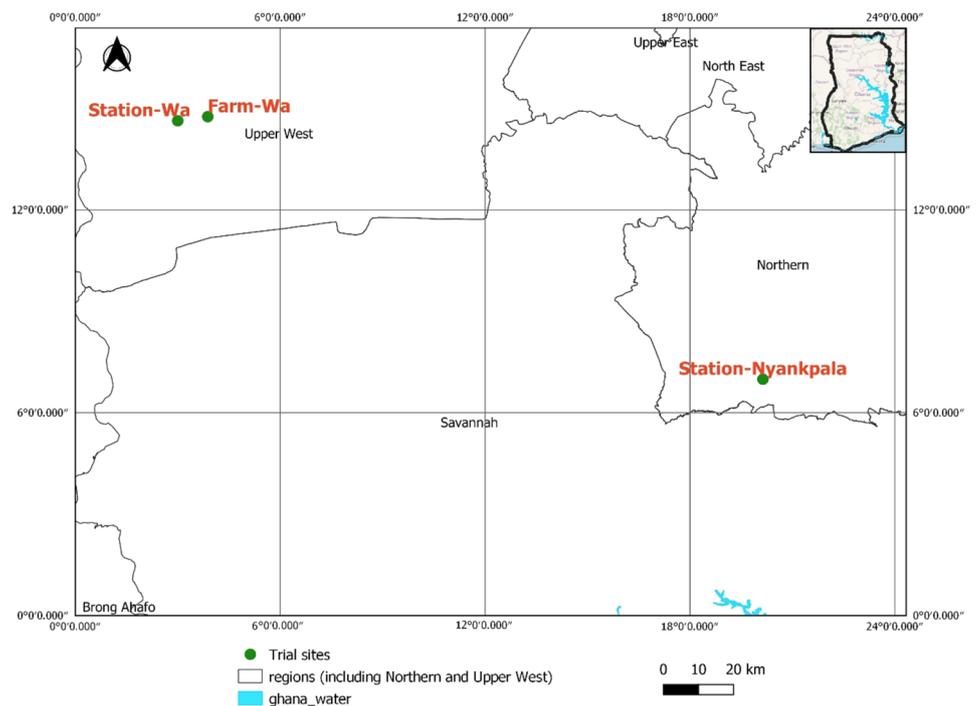
studies were conducted on farmers' fields in Wa (Longitude: −2.4281; Latitude: 10.0891) (Fig. 1).

Experimental design

On-station trial

At Wa and Nyankpala stations, the experimental design was a randomized complete block design (RCBD) with 5 replications each. The plots measuring 4.5 m × 5 m were separated by 2 m alleys within a block while blocks were 3 m apart. At both sites, the fields were tractor ploughed followed by harrowing. The maize variety used was Sansalsima, a drought tolerant variety commonly planted in northern Ghana. It was planted at a spacing of 75 cm between rows and 40 cm between plants within a row, with two seeds per hole. The sowing dates were 29 June and 21 July 2020 for Wa and Nyankpala, respectively. Treatments included four biopesticides, one synthetic insecticide (positive control) and an untreated control (see Table 1 for treatments and application rates). Treatment applications were carried out two weeks after crop emergence, and were repeated at three weeks intervals thereafter, with three applications in total. All treatments were applied early in the morning, using CP–15 knapsack sprayers (capacity: 15 l). One sprayer was used for the synthetic insecticides spraying and another one for spraying biopesticides. The latter was thoroughly cleaned between application of the different biopesticides. The whole maize plants were sprayed, during the treatment. In order to reduce product drift, a physical barrier made up of a plastic tarpaulin was placed around each given plot prior to the application of insecticides. The volume of spray solution

Table 1 Treatments tested under on-station and on farm conditions in Upper West and Northern region, Ghana

Treatment/Trade name	Producer	Active ingredient	Product rate (per 15 l of water)
Grow-Safe neem oil	Green Grow Ltd. Ghana	3% Azadirachtin	25 ml
Eradicoat	Certis Europe	282 g/l Maltodextrin	60 ml
Agoo	Wuhan Kernel Bio-Tech Co. Ltd. China	55% *Bacillus thuringiensis* (*Bt*) + 45% Monosultap	50 g
Bypel 1	Wuhan Unioasis Biological Technology Co. Ltd. China	*Pieris rapae granulosis* virus + 5% *Bt*	15 g
Ema Star 112 EC (positive control)	Adama West Africa Ltd, Ghana	48 g/l Emamectin benzoate + 64 g/l acetamiprid	25 ml
Control		No application of insecticide	

used during the first, second and third spray applications was 0.5 l, 1 l and 2 l, respectively, for a total of 5 plots (replications) for each treatment.

In this experiment, 250 kg/ha of granular fertilizer, NPK (23-10-10), were placed in holes dibbled near the maize plants as basal fertilizer, two weeks after germination. This was followed by top dressing with 125 kg/ha urea (46% N), 4 weeks after the basal fertilization. All plots were hand weeded twice before the maize ear filling stage. No other crop management or plant protection measure was applied in the plots until harvesting.

On-farm trial

A total of 42 maize farms located in seven communities (6 maize farms per community) in the Upper West region were selected and georeferenced for this on-farm study (Fig. 1). All fields were tractor ploughed and harrowed before sowing. In each community, the maize farms belonged to six farmers who agreed to collaborate. They each offered a field measuring at least one acre and the minimum distance between the maize fields was 50 m. The farmers selected in each community were randomly supplied with one of the five insecticides (biopesticides/synthetic insecticide) to be tested (Table 1). All fields, including the control plots, were established between 29 June and 13 July 2020 using the maize variety Sansalsima and all treatments were applied as described above for the on-station trials by farmers with the assistance of technical advisors (Table 1).

Data collection

Initial background data were collected from all plots two weeks after crop emergence, directly before the first treatment. For the on-station trials, data were collected six days after the first treatments, one day before the second and the third application of treatments and six days after the third application date, respectively, so five times in total. For the on-farm studies, the farms were sampled fortnightly starting again directly before treatments were applied for the first time, and five times in total (Fig. 2).

Data were collected from 30 randomly selected plants per plot following a "W" pattern for the two on-station trials and on 50 plants per farm following a "W" pattern for the on-farm studies where plots were larger. For all plots, data were collected by staff from CSIR—SARI. During data collection, the plants were carefully inspected for the presence of *S. frugiperda* larvae. All *S. frugiperda* larvae present were counted but only younger ones (L1-L3) were carefully removed from the plant and transferred into ventilated plastic cups (V: 80 ml) containing some tissue paper to assess the diversity and the relative abundance of larval parasitoids. Only young instars were collected because earlier studies (Agboyi et al. 2020) showed that all the abundant larval parasitoids of *S. frugiperda* in Ghana are koinobiont hymenopteran parasitoids attacking eggs and young larvae. The *S. frugiperda* larvae collected were kept in the same cups in the laboratory under room conditions (average temperature: 27 °C; average relative humidity: 76%; photoperiod: 12 h light:12 h dark) and checked daily for emergence of parasitoids. Larvae were provided with maize leaves collected from 3–4 weeks old untreated maize until either the emergence of parasitoids or *S. frugiperda* moth. Parasitoid adults that emerged from the samples were preserved in 96% ethanol and identified by comparison with barcoded voucher specimens deposited in GenBank (Agboyi et al. 2020; Durocher-Granger et al. 2021). New species not included in the lists were identified based on the morphology by the author MK. The relative abundance of the parasitoid species was calculated by dividing the number of individuals of each parasitoid species by the total number of parasitoids obtained from the sample collected and expressing this value as a percentage. Parasitism rates were calculated by dividing the number of parasitized larvae by the sum of the parasitized larvae and unparasitized larvae reaching the pupal stage (Agboyi et al. 2020).

Crop damage caused by *S. frugiperda* was assessed on 30 and 50 maize plants on-station and on-farm, respectively, using the Davis and Williams (1992) damage score scale (from 0—no damage, to 9-very heavy damage). Cob damage was assessed for the on-station trials by selecting 10 cobs at random from each plot, while 30 cobs were selected from the on-farm plots. The cobs were separated into damaged
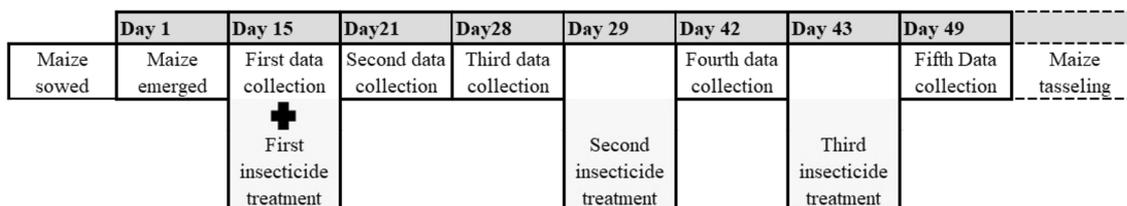
	Day 1	Day 15	Day21	Day28	Day 29	Day 42	Day 43	Day 49	
Maize sowed	Maize emerged	First data collection	Second data collection	Third data collection		Fourth data collection		Fifth Data collection	Maize tasseling
		First insecticide treatment			Second insecticide treatment		Third insecticide treatment		

Fig. 2 Overview on the timing for the data collection and the treatments

and undamaged cobs; damaged cobs were those that had symptoms of *S. frugiperda* larvae feeding on the grains. Cob damage was computed as a proportion of the number of cobs damaged from the total number of cobs observed.

Yield estimates for the farmer fields were generated by first demarcating a 10 m × 10 m area in the centre of each of the maize plots. All maize cobs within that 100 m^2 area were harvested, dried, threshed, winnowed and the grains were weighed. For the on-station trials, all maize cobs from the inner four rows of the plots (area: 15 m^2) were harvested and treated like those from the farmer fields. The grain weight from each plot was converted into yield per ha.

Data analysis

Parasitoids species diversity was analysed by calculating the Shannon's diversity index (H') and Pielou evenness index (E). The Shannon's diversity index is function of the population proportions of all species. It is the population value of the average diversity and it is calculated by using the following formula:

$$H' = \sum\nolimits_{i=1}^{s} \left(\frac{q_i}{Q}\right) ln\left(\frac{q_i}{Q}\right)$$

where q_i = the number of individuals in the *i*th specie, and $Q = \sum_{i=1}^{s} q_i$

The Pielou evenness index was used to assess the parasitoid species population evenness in the parasitoid community. It is calculated using the formula:

$$E = H'/ln(S)$$

where H' = Shannon's diversity index, S = total number of species in the community.

Data on fall armyworm infestation levels, maize plant damage and larval parasitism rates were analysed using generalized linear models with a binary logistic response variable (i.e. coding parasitized larvae as '1' and unparasitized larvae as '0') and the Logit link function. This was conducted separately for the three different sites and not including data of the first sampling date which was done before the treatments were applied. An overall analysis (again based on binary generalized linear models) was conducted to compare parasitism rates among the three sites. Means were separated using LSD tests at 5% probability threshold.

Data on cob damage and maize grain yield were analysed using ANOVA, with means separated based on Tukey's HSD post-hoc tests and a 5% probability threshold. All data were analysed using SPSS Statistics 27.

Results

Larval parasitoid relative abundance

The species *Coccygidium luteum* (Brulle) (Hymenoptera: Braconidae) and *Chelonus bifoveolatus* Szépligeti (Hymenoptera: Braconidae) were the most abundant species occurring in Wa, both on-farm and on-station, followed by *Charops* sp. (Hymenoptera: Ichneumonidae), *Cotesia icipe* Fernandez-Triana and Fiaboe (Hymenoptera: Braconidae) *and Meteorus* sp. (Hymenoptera: Braconidae) (Table 2). The species *Chelonus curvimaculatus* Cameron (Hymenoptera: Braconidae) and *Drino* sp. (Diptera: Tachinidae) were rarely collected in Wa. In the on-station trial in Nyankpala, *C. luteum*, was the most abundant parasitoid, followed by *Meteorus* sp., *Ch. bifoveolatus, Charops* sp., *Drino* sp. and *C. icipe* in decreasing order. *Chelonus curvimaculatus* was absent from the samples collected from different treatments in Nyankpala (Table 2). No statistical analysis was conducted on these abundance data because of low numbers in some of the species and also because of a bias due to the difference in the number of hosts per treatment, reflecting different levels of efficacy of the pesticides tested.

Larval parasitoid species diversity and evenness

In general, the values of Shannon's diversity index were low and varied between sites but were overall similar between treatments. Regardless of the treatments, lower values of the Shannon's diversity index were recorded on-station in Wa (0.46 ≤ H' 0.67), compared to the on-farm trial in Wa (0.89 ≤ H' ≥ 1.08) and the on-station trial in Nyankpala (0.85 ≤ H' ≥ 1.48) (Table 3). No consistent effects could be observed; however, the biopesticide Agoo and the negative control plot displayed higher Shannon's diversity index values in Nyankpala when compared to the chemical positive control Ema Star. The Pielou evenness index values were similar between the treatments at the different sites and ranged between 0.28–0.42, 0.64–0.88 and 0.71–0.92 on-station and on-farm in Wa and on-station in Nyankpala, respectively (Table 3).

Effect of insecticides on larval parasitism of *S. frugiperda*

A total of 2482 *S. frugiperda* larvae were collected over five sampling dates for the on-station trial in Wa. Of these, 242 larvae died in the laboratory from unknown cause and 481 were parasitized resulting in an overall pooled parasitism rate of 21.5% (Table 4). Differences were found among treatments in parasitism rate for the on-station trials in Wa ($\chi^2_{5,15}$ = 12.2, p = 0.033). This was mostly driven by

Table 2 Parasitoid species reared from *S. frugiperda* larvae and their relative abundance in different pesticides' treatments applied to maize fields on-station and on-farm in northern Ghana

Site	Treatment	*Spodoptera frugiperda* parasitoid species' relative abundance (%)						
		Coccygidium luteum	*Charops* sp	*Cotesia icipe*	*Chelonus bifoveleotus*	*Chelonus curvimaculatus*	*Meteorus* sp	*Drino* sp
On-station in Wa, Upper West region, Ghana	Control (n=110)	2.7	2.7	2.7	87.3	1.8	2.7	0
	Agoo (n=96)	4.2	3.1	6.3	83.3	0	3.1	0
	Bypel (n=43)	4.7	2.3	0	88.4	0	4.7	0
	Emastar (n=34)	2.9	2.9	8.8	85.3	0	0	0
	Eradicoat (n=129)	3.9	0.8	12.4	79.8	0.8	1.6	0.8
	Grow Safe (n=69)	4.3	1.5	1.5	89.9	0	2.9	0
	Average species relative abundance (±SD)	3.8±0.8	2.2±0.9	5.3±4.8	85.7±3.7	–	2.5±1.6	0.1±0.3
On-farm in Wa	Control (n=46)	30.4	6.5	2.2	56.5	–	4.3	–
	Agoo (n=43)	48.8	9.3	0	39.5	–	2.3	–
	Bypel (n=44)	43.2	11.4	0	45.5	–	0	–
	Emastar (n=23)	30.4	4.3	0	60.9	–	4.3	–
	Eradicoat (n=52	69.2	15.4	1.9	13.5	–	0	–
	Grow Safe (n=56)	46.4	3.6	1.8	48.2	–	0	–
	Average species relative abundance (±SD)	44.8±14.4	8.4±4.5	1±1.1	44±16.8	–	1.8±2.1	–
On-station in Nyankpala, Northern region, Ghana	Control (n=87)	49.4	14.9	13.8	0	–	17.2	–
	Agoo (n=71)	42.3	19.7	8.5	1.4	–	21.1	–
	Bypel (n=28)	39.3	21.4	10.7	0	–	17.9	–
	Emastar (n=34)	67.7	0	14.7	0	–	17.6	–
	Eradicoat (n=108)	51.9	12.0	11.1	0.9	–	23.1	–
	Grow Safe (n=67)	59.7	13.4	11.9	0	–	13.4	–
	Average species relative abundance (±SD)	51.7±10.7	13.6±7.6	11.8±2.3	0.4±0.6	–	18.4±3.4	–

–: Parasitoids species absent from the collection; n: total number of parasitoids; For each treatment, pooled data for the plots sampled were used to estimate the relative abundance

significantly lower parasitism rates in the Ema Star treatment when compared to all other treatments except Grow Safe (all $p < 0.05$). Significant differences were also observed among the different dates ($\chi^2_{3,15} = 77.6$, $p < 0.001$).

From the 42 farmer plots sampled on-farm in Wa, 3,266 larvae were collected for parasitism assessment, of which 368 died before reaching pupal stage due to unknown reasons. The overall pooled parasitism rate for farmer's fields

was 9.4% (Table 4) and no difference was found among treatments in parasitism rates ($\chi^2_{5,15} = 2.22$, $p = 0.82$). Similar to Wa on station, significant differences were observed among the different dates ($\chi^2_{3,15} = 39.3$, $p < 0.001$).

In Nyankpala, a total of 3,163 larvae were collected of which 485 died due to unknown reasons and 395 of them were parasitized. The overall mean larval parasitism rate in Nyankpala was 14.7%. Significant differences in parasitism

Table 3 Diversity of larval parasitoids of *S. frugiperda* under different pesticides' treatments applied to maize fields on-station and on-farm in northern Ghana

Location	Diversity indexes	Treatment					
		Control	Agoo	Bypel	Ema Star	Eradicoat	Grow Safe
On-station in Wa	Shannon's diversity index (H')	0.58	0.67	0.48	0.56	0.66	0.46
	Pielou evenness index (E)	0.36	0.42	0.35	0.40	0.41	0.28
On-farm in Wa	Shannon's diversity index (H')	1.08	1.03	0.97	0.94	0.89	0.90
	Pielou evenness index (E)	0.67	0.74	0.88	0.68	0.64	0.65
On-station in Nyankpala	Shannon's diversity index (H')	1.35	1.47	1.48	0.85	1.26	1.16
	Pielou evenness index (E)	0.84	0.82	0.92	0.78	0.71	0.72

Table 4 Larval parasitism rates in *S. frugiperda* collected in maize fields treated with different pesticides on-station and on-farm in northern Ghana

Sites	Treatment	Parasitism rate (%)				
		Vegetative stage			Tasseling	Fruiting
		8 July	15 July	23 July	5 Aug	12 Aug
On-station, Wa (n = 5)						
	Control	25.0	39.0	9.0	29.5	6.7
	Agoo	20.7	28.9	14.0	21.2	16.0
	Bypel1	8.6	–	3.1	–	–
	Ema Star	12.5	0.0	4.0	16.8	–
	Eradicoat	23.9	50.1	7.4	19.5	9.7
	Grow Safe	12.7	4.2	12.3	18.7	13.9
		6 Aug	13 Aug	28 Aug	4 Sep	17 Sep
On-farm, Wa (n = 7)						
	Control	13.4	6.5	1.7	15.5	11.6
	Agoo	24.5	11.8	2.7	6.4	2.6
	Bypel1	10.5	9.0	1.4	14.6	3.0
	Ema Star	2.3	11.8	0.9	8.4	–
	Eradicoat	11.3	13.9	3.7	10.3	–
	Grow Safe	15.9	9.1	3.1	17.4	4.2
		24 July	7 Aug	21 Aug	4 Sep	18 Sep
On-station, Nyankpala (n = 5)						
	Control	21.6	16.3	25.6	17.9	21.8
	Agoo	9.8	6.9	26.1	19.4	21.9
	Bypel1	9.9	–	17.0	–	–
	Ema Star	8.9	–	32.8	–	–
	Eradicoat	30.6	14.3	31.5	–	29.5
	Grow Safe	16.1	13.2	27.4	–	28.4

–: missing values indicate that the number of larvae found was too low to calculate parasitims rates

rate were found among treatments ($\chi^2_{5,15} = 14.1$, $p = 0.015$; Table 4) which were due to significantly lower parasitism rates in the Bypel 1 treatment when compared to all other treatments (all $p < 0.005$). Significant differences were again observed among the different dates ($\chi^2_{3,15} = 39.2$, $p < 0.001$).

Significant effects were found among the three locations ($F_{2,61} = 206.5$, $p < 0.001$) with parasitism rates being significantly higher in Wa on-station compared to Nyankpala on-station ($p < 0.001$) and higher in Nyankpala on-station compared to Wa on-farm trials ($p < 0.001$).

Effect of insecticides on larval numbers, plant and cob damage and yield

Highly significant differences were found among the different pesticides in terms of the number of *S. frugiperda* larvae collected ($F_{5,402.501} = 11.9$, $p < 0.001$). All treatments significantly reduced the number of larvae compared to the control ($p < 0.018$). The number of larvae found in the Bypel and Ema Star treatments was significantly lower than in the other three biopesticides treatments ($p < 0.012$, see Table 5). Slightly significant differences were also found among the three locations ($F_{2,402.810} = 3.59$, $p = 0.029$) with Wa on-station showing slightly lower numbers of *S. frugiperda* larvae compared to Nyankpala on-station ($p = 0.029$) and Wa on-farm ($p = 0.013$), whereas no difference in larval numbers were found between Nyankpala on-station and Wa on farm ($p = 0.90$).

Significant differences among treatments were also found for maize plant damage caused by *S. frugiperda*

($F_{5,171,499} = 3.45$, $p = 0.005$). In line with the results obtained for larvae, the lowest damage rates were found in the Bypel and Ema Star treatments (Table 6).

Regarding cob damage, highly significant differences were found among treatments in a global analysis over all sites ($F_{5,74} = 13.3$, $p < 0.001$) (Fig. 3a). Cob damage rates were significantly higher in the control than in all other treatments ($p < 0.05$ for all comparisons). In addition, the positive control Ema Star showed significantly lower cob damage levels than Agoo ($p = 0.044$), Eradicoat ($p = 0.002$) and Grow Safe ($p = 0.048$). Significant differences in the proportion of damaged cobs were also found among locations ($F_{2,74} = 10.8$, $p < 0.001$) with lower cob damage rates in Nyankpala compared to Wa on-station and Wa on-farm ($p < 0.001$). For cob damage, a significant interaction was obtained between the pesticide treatments and locations ($F_{10,74} = 3.57$, $p < 0.001$).

Finally, highly significant differences were found among treatments for maize grain yield ($F_{5,72} = 8.4$, $p < 0.001$). Results were mainly driven by significantly lower yields

Table 5 Density of *Spodoptera frugiperda* larvae in maize fields treated with different pesticides on-station and on-farm

Sites	Treatment	Number of *Spodoptera frugiperda* larvae (per 30 maize plants on-station and 50 plants on-farm) ($\overline{X} \pm SD$)				
		Vegetative stage			Tasselling	Fruiting
		08-Jul	15-Jul	23-Jul	05-Aug	12-Aug
On-station, Wa (n = 5)						
	Control	15.2 ± 4.03	9.8 ± 3.27	15.4 ± 4.04	18.8 ± 10.26	16.6 ± 3.78
	Agoo	17.6 ± 3.36	7.4 ± 6.77	17 ± 4.3	15 ± 5.43	8.8 ± 3.35
	Bypel1	20 ± 3.61	1.2 ± 1.3	15.6 ± 8.14	3.8 ± 1.79	2 ± 0.71
	Ema Star	16.8 ± 5.81	4 ± 4.64	15.6 ± 7.13	10.2 ± 6.22	1 ± 0.71
	Eradicoat	16.8 ± 4.44	6.2 ± 4.5	17.6 ± 5.46	16.6 ± 7.33	13.75 ± 3.1
	Grow Safe	21.8 ± 1.64	8.2 ± 10.33	16.4 ± 6.23	12.4 ± 4.67	8.8 ± 2.95
		06-Aug	13-Aug	28-Aug	04-Sep	17-Sep
On-farm, Wa (n = 7)						
	Control	21 ± 4.24	23.71 ± 4.42	22 ± 6.58	17.14 ± 7.15	9.57 ± 4.96
	Agoo	14.86 ± 10.99	21.14 ± 5.73	19.71 ± 6.47	17.43 ± 5.8	7.57 ± 6.65
	Bypel1	13.57 ± 8.85	20.86 ± 6.94	14.14 ± 8.28	13 ± 7.07	6.57 ± 4.61
	Ema Star	20.71 ± 6.16	18.86 ± 7.18	15.29 ± 5.47	10.57 ± 8.2	3 ± 3.92
	Eradicoat	20.14 ± 6.67	19.14 ± 8.82	13.86 ± 8.8	15.43 ± 8.26	5.71 ± 6.16
	Grow Safe	16.29 ± 8.44	23.14 ± 2.97	19.71 ± 4.72	16.71 ± 8.34	5.71 ± 4.89
		24-Jul	07-Aug	17-Jan	04-Sep	18-Sep
On-station, Nyankpala (n = 5)						
	Control	16.4 ± 10.41	29.4 ± 11.97	46.8 ± 11.01	30.2 ± 14.31	14.4 ± 8.85
	Agoo	22.4 ± 23.33	14 ± 1.87	39.4 ± 8.41	10.6 ± 6.58	19.4 ± 11.06
	Bypel1	14.6 ± 7.13	2.4 ± 1.67	22.2 ± 12.38	1 ± 1	3.4 ± 4.72
	Ema Star	17.4 ± 4.93	1.4 ± 0.55	36.2 ± 18.85	1 ± 1.41	3.4 ± 1.67
	Eradicoat	9.2 ± 7.26	11.2 ± 7.76	47.2 ± 10.99	6.2 ± 2.49	10.2 ± 6.72
	Grow Safe	16.8 ± 15.16	35.8 ± 21.31	42.6 ± 4.88	2.2 ± 1.1	14.2 ± 6.72

n: number of replications

Table 6 Plant damage scores caused by *S. frugiperda* in maize fields treated with different pesticides on-station and on-farm

Sites	Treatment	Plant damage score ($\overline{X} \pm$ SD)				
		Vegetative stage			Tasselling	Fruiting
		08-Jul	15-Jul	23-Jul	05-Aug	12-Aug
On-station, Wa (n = 5)						
	Control	2.33 ± 0.63	2.58 V 1.71	3.1 ± 3.75	5.97 ± 1.93	7.16 ± 1.92
	Agoo	0.99 ± 0.52	2.66 ± 1.43	1.64 ± 1.43	6.37 ± 1.05	7.83 ± 1.00
	Bypel1	1.71 ± 0.69	2.93 ± 1.13	2.72 ± 1.90	6.54 ± 1.73	6.87 ± 1.12
	Ema Star	1.17 ± 0.78	2.49 ± 1.58	1.81 ± 0.96	6.6 ± 1.11	5.24 ± 1.11
	Eradicoat	1.04 ± 0.30	2.99 ± 73	1.62 ± 1.63	6.14 ± 1.51	7.27 ± 2.7
	Grow Safe	1.53 ± 0.56	1.92 ± 1.78	2.35 ± 2.59	6.37 ± 1.10	6.47 ± 1.59
		06-Aug	13-Aug	28-Aug	04-Sep	17-Sep
On-farm, Wa (n = 7)						
	Control	3.78 ± 2.34	3.13 ± 0.56	3.76 ± 1.49	3.5 ± 2.15	–
	Agoo	3.21 ± 0.51	2.72 ± 1.40	3.34 ± 1.48	3.54 ± 2.28	–
	Bypel1	3.48 ± 0.43	3.59 ± 0.71	4.68 ± 1.47	4.52 ± 2.14	–
	Ema Star	2.75 ± 0.51	2.99 ± 0.86	2.74 ± 2.00	2.28 ± 1.87	–
	Eradicoat	2.86 ± 0.33	3.47 ± 0.35	3.82 ± 1.55	3.52 ± 2.04	–
	Grow Safe	2.89 ± 0.48	3.09 ± 0.51	3.08 ± 1.77	3.11 ± 2.42	–
		24-Jul	07-Aug	21-Aug	04-Sep	18-Sep
On-station, Nyankpala (n = 5)						
	Control	2.03 ± 0.86	3.42 ± 1.25	8.36 ± 1.23	5.09 ± 5.72	1.19 ± 0.40
	Agoo	2.14 ± 1.17	1.98 ± 0.74	8.74 ± 0.80	1.13 ± 0.32	1.49 ± 0.89
	Bypel1	1.43 ± 0.47	0.4 ± 0.40	2.7 ± 1.56	0.23 ± 0.13	0.18 ± 0.20
	Ema Star	1.68 ± 0.45	0.46 ± 0.40	4.12 ± 2.06	0.3 ± 0.23	0.22 ± 0.16
	Eradicoat	1.4 ± 0.78	1.6 ± 0.39	8.6 ± 0.66	1.21 ± 0.37	0.79 ± 0.62
	Grow Safe	1.65 ± 0.68	4.52 ± 2.20	8.99 ± 1.50	0.38 0.39	0.9 0 ± 0.38

–: missing values indicate that the plant damage score was not assessed; n: number of replications

in the control as compared to all other treatments, especially on-station (Fig. 3b). Yield was significantly different among locations ($F_{2,72} = 264.8$, $p < 0.001$) with higher yields found for Wa on-station when compared to Nyankpala and Wa on-farm ($p < 0.001$).

Discussion

Chemical pesticide applications against *S. frugiperda* have been recommended in most invaded areas, resulting in various levels of control. However, it is a well-known fact that the use of chemical pesticides may have serious health and environmental impacts (PAN UK 2007; Miah et al. 2014), including on beneficial organisms such as natural enemies relevant for pest control (Pimentel 1995; Desneux et al. 2007). On the other hand, there is general belief that biopesticides are less harmful to natural enemies, although evidence from field studies on *S. frugiperda* is lacking (Kenis et al. 2022). In this study, we assessed the

impact of commonly used biopesticides recommended and distributed by the government of Ghana to farmers against *S. frugiperda* on the local parasitoids associated with this pest, in comparison with the most used chemical pesticide, Ema Star, and a negative control. In general, parasitism was lower in the fields treated with Ema Star and Bypel 1 as compared to untreated plots and those treated with the other biopesticides, although the tendency was not consistently significant throughout the sites and dates. This may be due to the fact that the parasitoid complex varied with sites and dates and it well known that different parasitoid species may react differently to pesticide and biopesticide treatments. For example, it was shown in Florida that the braconid egg-larval parasitoid *Chelonus insularis* Cresson was much less present in maize fields sprayed with insecticides than in untreated fields, which was not the case for the larval parasitoid *Cotesia marginiventris* (Cresson) (Meagher et al. 2016). Another possible reason for the relatively low impact of pesticides and biopesticides on parasitism is the size of the plots and the ability of parasitoids to quickly

Fig. 3 Mean maize cob damage rates (± SD) (top) and mean maize grain yield (bottom) caused by *S. frugiperda* under different pesticide treatments on-station (n = 5) and on-farm in Northern Ghana (n = 7). Treatments showing the same letter above bars are not significantly different from each other for a given site (Tukey's HSD post-hoc tests; p < 0.05)
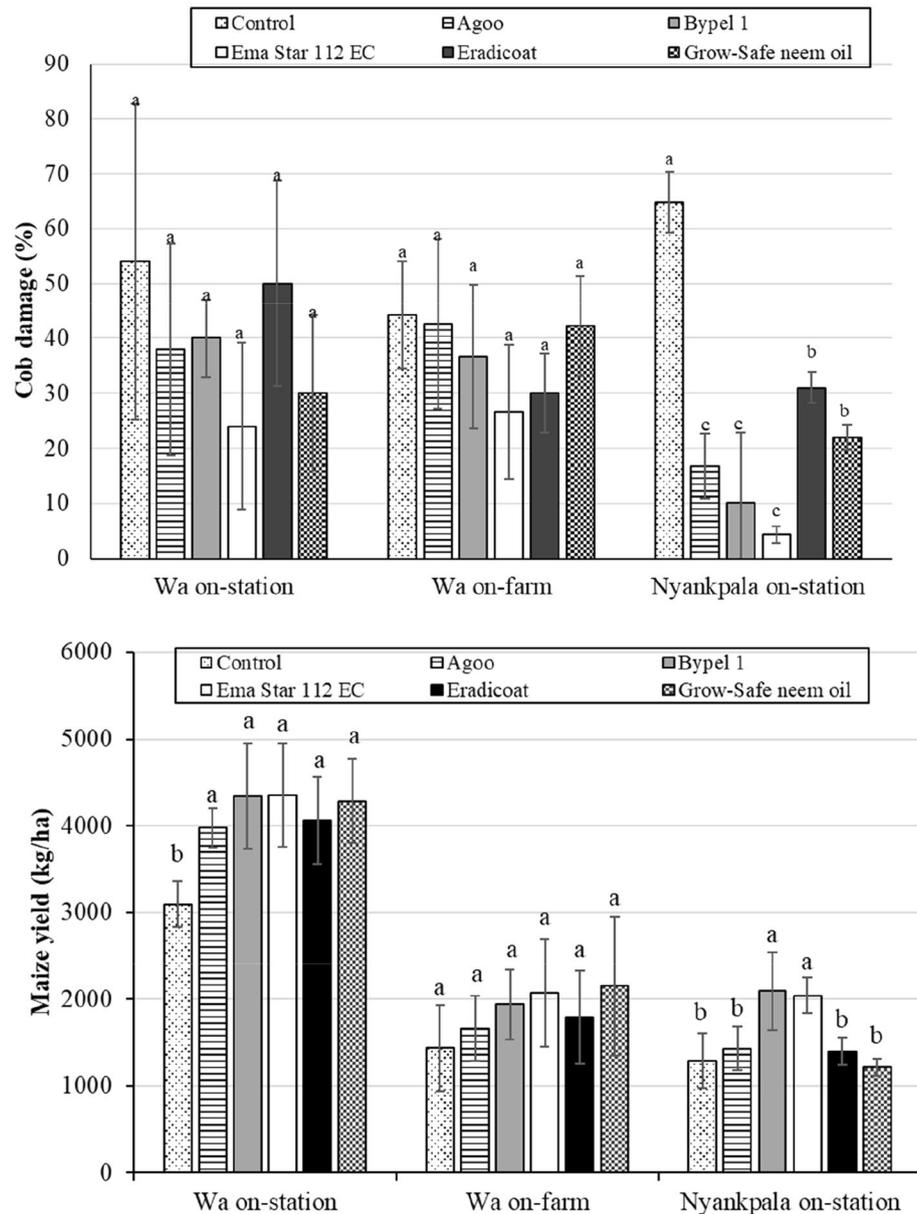
move from adjacent, untreated fields or vegetation to the previously treated plots. The three-week interval between applications may be long enough to allow for significant restoration of the parasitoid populations after each treatment. The parasitoid species attacking *S. frugiperda* in Ghana are known to parasitize other Lepidoptera in many agroecosystems (Agboyi et al. 2020; Koffi et al. 2020). At plot level, the use of pesticides against a pest is probably more detrimental to less mobile natural enemies such as non-flying predators (earwigs, ants, spiders, etc.), whereas more mobile parasitoids are likely more affected by massive uses of pesticides at landscape scale during a longer period.

Furthermore, the insecticide used in this study, Ema Star, is surely not the most detrimental to natural enemies.

Its active ingredients, emamectin benzoate and acetamiprid, are both classified as moderately hazardous (Class II) technical grade active ingredients (WHO 2019), whereas, in Africa, a whole list of more hazardous pesticides are used against *S. frugiperda* (Tambo et al. 2020b). The WHO class I products are phased out in many important markets such as the EU and pressure is high also on the class II products, e.g. for most neonicotinoids. WHO class II products are also generally aimed to be reduced or avoided as much as possible in different types of IPM standards. Still, the effects of emamectin benzoate and acetamiprid on natural enemies may be less severe than expected based solely on the WHO class system. For instance, Sechser et al (2003) found a relatively low hazard of emamectin

benzoate on natural enemies, after studying its effects on predators of sucking pests of cotton. For acetamiprid, after assessing the risk quotient for different chemicals belonging to the neonicotinoid family, Jiang et al. (2019) considered that acetamiprid was the only relatively safe neonicotinoid insecticide for the egg parasitoids *Trichogramma* spp. Acetamiprid was also found to have low effect on some predators' population dynamics, such as the true bug *Orius sauteri* (Poppius) (Lin et al. 2020).

It is unclear how a product such as Bypel 1, based on *Pieris rapae* granulosis virus and Bt, could potentially affect parasitoids, other than through an indirect effect via the mortality of their host. Although the effect was not consistent among sites, there is probably a need for further studies to clarify the effect that such a biopesticide formulation has on parasitoids.

Maize sprayed thrice with Bypel 1 or Ema Star also induced the strongest reductions in *S. frugiperda* larval density, which probably leads to a reduction in cues that attract female parasitoids present in the area. This potentially leads to a density dependence of the parasitism rate in *S. frugiperda* larvae, as observed in Zambia (Durocher-Granger et al. 2021). The density dependence of parasitism on *S. frugiperda* needs to be further assessed.

The untreated plots showed the highest larval density and plant damage, the highest cob damage, and generated the lowest yields, suggesting that the treatments were at least partly efficient to control the pest. There was no consistent difference in cob damage and yields among the chemical pesticide and the biopesticides. In such situations, biopesticides should be preferred to minimize negative effects on human health, natural control and the environment in general.

Author contributions

LKA, DB and MK conceptualized the work. LKA, DB and MK wrote the methodology. JAN, EA, BKB, LKA and PB conducted the trials. DB analysed the data. LKA, DB and JAN prepared the original draft. All authors read, reviewed and approved the manuscript.

Data availability and materials The datasets generated in this study are available from the corresponding author on reasonable request.

Declarations

Ethical approval No approval of research ethics committees was required to accomplish the goals of this study because experimental work was conducted with an unregulated invertebrate species.

Competing interests The authors declare no competing interests.

Consent to participate Not applicable.

Consent to publish Not applicable.

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