Crop Protection 176 (2024) 106497

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Efficacy of selected biopesticides on key pests of chilli pepper for increased productivity in Ghana

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ARTICLE INFO

Keywords:
Biopesticides
Chilli pepper
Insect pests
Integrated pest management

ABSTRACT

Chilli pepper is an important food and cash crop in Ghana. Unfortunately, production and marketing are constrained by many insect pests. In this study, the efficacy of five different biopesticides: Neemazal® (Azadirachtin 0.3% w/w EC), Agro blaster® (Pyrethrin I and II 1% w/w), Bypel 1® (*Pieris rapae* 10000PIB/mg + *Bacillus thuringiensis* 16000 IU/mg), Cryptogran® (*Cryptophlebia leucotreta* Granulovirus ≥ 5.10^{10} OBs/ml) and Attack® (Emamectin benzoate 1.9% w/w EC) were assessed against the major insect pests of chilli pepper. These pests included the false codling moth (FCM), thrips, whiteflies and fruit flies. The study was conducted during the minor and major cropping seasons of 2019 and 2020, respectively, using RCBD plot design in two locations (Legon and Begoro) in southern Ghana. All five tested biopesticides reduced the infestation of the target insect pests. Neemazal® and Attack® were more efficacious than the other three biopesticides in controlling FCM. For fruit flies, the infestation in Neemazal® and Attack® treated plots varied between 0.69 ± 0.60 to 12.84 ± 0.91% and 1.40 ± 0.69 to 9.72 ± 1.27%, respectively against 3.82 ± 0.67 to 21.87 ± 2.14% in control plots. Neemazal®, Bypel 1® and Attack® significantly reduced thrips population compared to other biopesticides. Apart from Neemazal® and Attack®, Agro blaster® also reduced whiteflies population compared to control plots. The highest yields were recorded in Neemazal® (3.17 ± 0.33 to 4.35 ± 0.22 t/ha) and Attack® (3.05 ± 0.21 to 4.55 ± 0.25 t/ha) treated plots against 2.12 ± 0.31 to 3.06 ± 0.37 t/ha in the control. Therefore, these two biopesticides are promising and could be used as part of integrated pest management (IPM) against chilli pepper insect pests in Ghana.

1. Introduction

Chilli pepper, *Capsicum* spp. an herbaceous perennial spice crop of the family Solanaceae, and commonly cultivated in tropical zones (Tong and Bosland, 1999). It is an important vegetable widely cultivated over an area of 1776 thousand hectares in the world (Hussain and Abid, 2011). Chilli pepper fruit is highly appreciated for its many culinary attributes, including its taste and ability to stimulate appetite (Bosland and Votava, 2003; Djieto-Lordon et al., 2014). It is consumed fresh or dried, either as whole fruit or ground, and alone or in combination with many other spices (Grubben and El Tahir, 2004). Nutritionally, chilli pepper is cholesterol-free and low in sodium, but rich in vitamins A and C, and it is a good source of potassium, folic acid, and vitamin E (Bosland and Votava, 2003).

In Ghana, chilli pepper is widely cultivated and represents the second most important grown vegetable after tomato (Schippers, 2000). Ghana ranks as the fourth largest chilli pepper producer in Africa, after Egypt, Nigeria, and Algeria (MiDA, 2010; GSS, 2014). Besides its culinary and nutritional benefits, the economic value of chilli pepper is very attractive, representing one of the most important sources of income for the resource–poor farmers involved in its production and other stakeholders along the value chain, especially exporters (Segnou et al., 2013;

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https://doi.org/10.1016/j.cropro.2023.106497
Received 16 July 2023; Received in revised form 24 October 2023; Accepted 27 October 2023
Available online 30 October 2023

Saavedra et al., 2014). A substantial amount of chilli pepper production in Africa targets domestic markets, but a considerable quantity is exported to international markets. In this context, Ghana is the fifth largest exporter of chilli pepper to the European Union, where demand has increased annually by ~17% since 2000 (FAO, 2015).

Although, the nutritional and economic benefits of chilli pepper in Ghana are clear and opportunities to increase production abound, production, however, is currently low and insufficient to meet increasing demands from local and international markets (Gonzalez et al., 2014; MoFA, 2018). Currently, chilli pepper is cultivated by resource-poor smallholder farmers, generally in farms ranging from 0.1 to 1.2 ha, with an average yield of about 8.30 Mt/ha, which is far below the potential yield of 32.30 Mt/ha (MoFA, 2014; MiDA, 2010). The low yield is the result of many factors constraining the production and marketing of chilli pepper in Ghana. These constraints include recurrent unsuitable climatic conditions, poor adoption of good agricultural practices and biotic factors (MiDA, 2010). The biotic factors are mainly represented by diseases and insect pests.

As many as 60 insect pests were recorded in chilli crop in the nursery and in the field worldwide (Shivalingaswamy et al., 2022). The most damaging in Ghana include thrips *Thrips parvispinus* Karny (Thysanoptera: Thripidae), whiteflies *Bemisia tabaci* (Hemiptera: Aleyrodidae), fruit flies *Ceratitis capitata* and *Ceratitis cosyra* (Diptera: Tephritidae), and the false codling moth (FCM), *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) (Segnou et al., 2013; Djieto-Lordon et al., 2014; Fening et al., 2017; Fening and Billah 2019). These insect pests attack and feed on chilli pepper, causing significant reduction in the yield and quality of the produce. Also, some of them such as FCM, fruit flies and whiteflies are of quarantine importance. Hence, a major constraint for the international trade of chilli pepper (Gonzalez et al., 2014; Fening and Billah, 2018). Therefore, proper management of insect pests of chilli pepper is crucial to increase the yield and improve the marketability of the produce.

The use of synthetic chemical insecticides to control agricultural insect pests is very common due to their rapid effects in reducing pests' populations (Donkor et al., 2016). However, chemical insecticides have adverse effects on the structure, functioning and equilibrium of agroecosystems and human health. Overreliance and frequent application of synthetic chemical insecticides can cause the evolution of resistance in pests, resurgence, outbreaks of secondary pests, phytotoxicity, residual toxicity in the food and harm to non-target or beneficial organisms (Wiktelius et al., 1999; Antonious, 2004). Also, high insecticide residue levels in exported foods are one of the serious challenges faced by vegetable export, causing rejections of export commodities due to non-compliance with the pesticide maximum residue limits (MRLs) (Donkor et al., 2016). This calls for the use of novel or the new generation group of chemicals and biopesticides (i.e., botanicals and microbials), which are safer than synthetic pesticides. Several biorational insecticides have been introduced recently into vegetable production in Ghana as an integral part of the Integrated Crop Management (ICM) strategies developed to control various insect pests. However, the efficacies of these biopesticides against insect pests of economic importance including the FCM, thrips, whiteflies, and fruit flies on chilli pepper have not been tested. This study aimed at assessing the efficacy of the biopesticides currently used or introduced for the control of FCM and other major chilli pepper insect pests in Ghana and proffer recommendations for the choice of biopesticides to increase chilli pepper productivity in Ghana.

2. Materials and methods

2.1. Description of study sites

The study was carried out over two years in two regions (Greater Accra and Eastern) regions of Ghana. In the Greater Accra region, we selected the University of Ghana farm (Lat: 5.64639; Long: −0.18198) in Legon, and Begoro (Lat: 6.73869; Long: −0.37687) in the Eastern region. These locations were selected because they constitute two of the main chilli pepper producing areas of Ghana. Legon and Begoro lie in the coastal savannah and semi-deciduous forest ecological zones of Ghana, respectively. Both agro-ecological zones experience bimodal rainfall. In the coastal savannah, the cropping season lasts for 100–110 days during the major rainy season (March to July), and about 50 days in the minor rainy season (September to October). The average annual rainfall is 800 mm. The deciduous forest has an average annual rainfall of 1500 mm with a cropping season of 150–160 and 90 days during the major and minor rainy seasons, respectively (Aquastat Ghana, 2005).

2.2. Experimental design, crop management and biopesticide application

The experiments were conducted during the minor and major chilli pepper cropping seasons of 2019 and 2020, respectively. The chilli pepper, variety ''Legon 18″ was used in the experiment. This variety was selected because it is one of the most commonly cultivated chilli pepper varieties in Ghana, both for local and international markets (MoFA, 2018). The seed was obtained from the University Ghana, Legon farm and nursed on raised beds (3m × 1m). Transplanting of seedlings was done after 30 days of seed germination. A Randomised Complete Block Design (RCBD) with five treatments (5 different biopesticides): (1) - Neemazal®, (2) - Agro blaster®, (3) - Bypel 1®, (4)- Cryptogran®, (5)- Attack® (Table 1), and one untreated control was used and replicated four times. The planting distance was 0.6 m × 0.6 m and each experimental plot measured 3 m × 3 m, giving 25 plants per plot. Inter-plot and inter-block distance were 1.5 m. All regular recommended cultural practices, including weeding and fertilizer application (NPK: 15 15 15 at a rate of 280 kg ha^{-1}, 2 weeks after transplanting) were carried out similarly in each treatment and control plot. No insecticides were applied apart from those pre-selected for the trials. (Please see Table 1 for further details on the tested biopesticides and the application rates). We applied biopesticides (treatments) at the fruiting stage of the crop, using a manually operated knapsack sprayer (Volume: 20 L, Farmguard®) at an interval of 7 days, as practiced by chilli pepper farmers in southern Ghana (Fening et al., 2016). As most of the selected biopesticides are heat sensitive, they were applied in the evening at 4 p.m. The sprayer was thoroughly washed using a local black soap (African black soap made with cocoa pods and shea butter) and well rinsed with water prior to application of each biopesticide type.

2.3. Effects of biopesticides on the infestation levels of FCM and fruit flies

At fruit physiological maturity, 10 weeks after transplanting, nine plants were randomly selected in each plot, while avoiding plants in bordering rows. Eight fruits were randomly harvested from each plant, making a total of 72 fruits per experimental unit. The harvested fruits were examined for FCM and fruit fly damage by dissecting them

Table 1
Biopesticides used in the experiment and the application rates.

Trade name	Active ingredient	Concentration of Active ingredient	Chemical group	Dose (g or ml/15l)
Neemazal®	Azadirachtin	0.3% w/w EC	Botanical	60
Agro blaster®	Pyrethrin I and II	1% w/w	Botanical	90
Bypel 1®	PrGV + Bt[a]	10000PIB/mg + 16000 IU/mg	Microbial	20
Crypogran®	CrleGV [b]	≥ 5.10^{10} OBs/ml [c]	Microbial	5
Attack®	Emamectin benzoate	1.9% w/w EC	Semi-synthetic	15

[a] PrGV = *Pieris rapae* Granulosis Virus, Bt = *Bacillus thuringiensis* Kurstaki.
[b] CrleGV = *Cryptophlebia leucotreta* Granulovirus.
[c] OBs = Occlusion bodies.

longitudinally with a scalpel under a stereomicroscope (Vernon Hills, Illinois 60061, Cole Parmer®). A damaged fruit by FCM was recognised by the presence of FCM larva, the larva exit hole, the frass or broken seeds in the fruit. These are characteristic FCM larval feeding signs (Stibick, 2006; De Jager, 2013). Conversely, fruits damaged by fruit flies were recognised by the presence of fruit fly maggots in a waterlogged and decaying fruit or by the presence of maggot exit holes (Jaya et al., 2022). Each of these parameters (i.e., FCM and fruit flies) were counted and recorded. The infestation levels were determined by the percentage of damaged fruits. The assessment of the infestation level was done during the first two harvesting times of chilli pepper fruits at the 10th and 12th week after transplanting.

2.4. Effects of biopesticides on the population density of thrips and whiteflies

The population levels of thrips and whiteflies were assessed using blue and yellow sticky traps, respectively as thrips are more attracted by blue colour and whiteflies by yellow (Pinto-Zevallos and Vänninen, 2013; Allan and Gillett-Kaufman, 2018; Pobozniak et al., 2020). One yellow and one blue trap of the same shape and size (rectangular; 20 cm × 30 cm) were set in the middle of each experimental unit at the canopy level. The traps were changed weekly on the day of biopesticide application. The trap catches were transported to the laboratory in polyethylene bags and thrips and whiteflies were counted under a stereomicroscope. The population density of thrips and whiteflies was determined by the number/trap/week in each plot. The density of these insect pests was determined during 5 weeks from the 6th to the 11th week after transplanting.

2.5. Effects of biopesticides on the population of the beneficial arthropods

The population density of beneficial arthropods, such as ants, ladybird beetles, bees and spiders, was determined in each plot during the trial. One yellow pan trap was set in each plot after every insecticide application and removed after 24 h. All the beneficial arthropods were removed from the trap, preserved in vials containing 70% ethanol, and then transported to the laboratory for identification and counting. The beneficial arthropods caught by the yellow and blue traps were also counted. The abundance of each predatory species was determined for each plot.

2.6. Effects of biopesticides on chilli pepper yield

At maturity, all chilli pepper plants in each plot were harvested and weighed using a weighing scale (Salter metal-body kitchen® scale). Only two harvests were done during the experimental period. The yield determined in this study was the sum of the two harvests.

2.7. Identification of collected organisms

The identity of FCM adults emerged from sampled chilli pepper fruits was confirmed according to the identification keys developed by Gilligan et al. (2011). All other insect pests and beneficial arthropods were identified using reference specimens at the Museum of the Department of Animal Biology and Conservation Science, University of Ghana, Accra. Samples of the immature stages of the collected organisms were cultured in the laboratory to the adult life stage to allow identification by comparison with labelled specimens in the museum.

2.8. Data analysis

All statistical analyses were conducted in R foundation environment for statistical analyses (R Core Team, 2022). Each of the data sets was subjected to normality and homogeneity of variances tests, using Shapiro and Barttlett's tests, respectively. Most of the data sets did not violate the assumptions of parametric tests. Therefore, an Analysis of variance (ANOVA) test was performed to assess the significant effects of the treatments (i.e., the five insecticides applied) for each data set. Student-Newman-Keuls was used to separate means wherever a significant test was detected. However, the beneficial arthropods data did not satisfy the assumptions of ANOVA. A generalised linear model with a Poisson distribution and log-link function was applied to test the interactions between the treatments, seasons, and abundance of beneficial arthropods in the study sites. Following the indication of a significant test, we used Tukey's HSD test to identify homologous subsets.

3. Results

3.1. Effect of biopesticides on the infestation level of FCM

The infestation level of FCM on chilli pepper was not significantly different at Begoro and Legon ($F_{1,\ 72} = 0.0001; P = 1.0000$). However, FCM infestation varied significantly between the major and minor cropping seasons ($F_{1,\ 72} = 95.07; P < 0.0001$). Overall, FCM infestation levels was higher during the major cropping than in the minor cropping season in both study locations (Tables 2 and 3). Also, infestation levels of FCM differed significantly among the plots treated with the various insecticides ($F_{5,\ 72} = 17.02; P < 0.0001$), and the highest infestation was recorded in the control plots in both study locations and cropping seasons. The efficacy of the various biopesticides did not significantly differ between locations ($F_{5,\ 72} = 0.30; P = 0.910$) but it varied across cropping seasons ($F_{5,\ 72} = 2.62; P = 0.0310$) and between harvest times ($F_{5,\ 72} = 2.05; P = 0.0400$) (Tables 2 and 3). In both study locations, the infestation level of FCM was significantly lower in Neemazal® and Attack® treated plots than in the other insecticide-treated plots. The efficacy of Neemazal®, Attack® and Cryptogran® was consistent across cropping seasons and harvest times. However, Agro blaster® and Bypel 1® was inconsistent in efficacy (Tables 2 and 3).

3.2. Effects of biopesticides on the infestation level of fruit flies

The infestation level of fruit flies on chilli pepper differed significantly in both study locations ($F_{1,\ 72} = 18.57; P < 0.0001$). The infestation level in Legon was higher than Begoro during the minor and major cropping seasons. However, in both locations, the occurrence of fruit flies was significantly higher during the major cropping season than in the minor cropping season ($F_{1,\ 72} = 18.57; P < 0.0001$). Overall, the infestation levels of fruit flies differed significantly among the plots treated with the five biopesticides and the highest infestation levels were recorded in Cryptogran treated plots and in control plots in both locations and cropping seasons ($F_{5,\ 72} = 18.57; P < 0.0001$). The efficacy of

Table 2
Mean (±SE) of FCM infestation level (%) recorded in the different treatments during the minor cropping season, 2019 and major cropping season, 2020 in Begoro.

Treatments	Minor cropping season		Major cropping season	
	First harvest	Second harvest	First harvest	Second harvest
Neemazal®	0.00 ± 0.00 a	0.70 ± 0.70a	1.04 ± 0.66a	2.78 ± 1.27 ab
Agro blaster®	2.40 ± 0.30bc	2.08 ± 0.40 ab	2.77 ± 0.56 ab	4.16 ± 1.00abc
Bypel 1®	1.40 ± 0.60 ab	1.74 ± 1.04 ab	4.17 ± 0.57 ab	5.21 ± 1.20c
Cryptogran®	2.10 ± 0.90abc	1.04 ± 1.04a	2.43 ± 0.66 ab	4.51 ± 0.66bc
Attack®	0.30 ± 0.20 ab	0.00 ± 0.00a	1.38 ± 0.80a	2.43 ± 0.66a
Control	3.80 ± 0.70c	4.26 ± 0.57b	4.86 ± 1.20b	5.21 ± 0.87c

Means within a column followed by the same letter for each cropping season, are not significantly different (Student-Newman-Keuls, $P < 0.05$).

Table 3
Mean (±SE) of FCM infestation level per treatment recorded during the minor cropping season, 2019 and major season cropping, 2020 in Legon.

Treatments	Minor cropping season		Major cropping season	
	First harvest	Second harvest	First harvest	Second harvest
Neemazal®	0.00 ± 0.00a	0.70 ± 0.70	0.69 ± 0.40a	3.12 ± 1.04a
Agro blaster®	2.83 ± 0.90 ab	0.70 ± 0.70	2.78 ± 0.98 ab	4.86 ± 0.40b
Bypel 1®	0.00 ± 0.00a	1.04 ± 0.68	6.25 ± 0.89c	5.55 ± 0.57b
Cryptogran®	1.04 ± 1.04 ab	1.39 ± 0.98	4.16 ± 0.80bc	5.90 ± 1.18b
Attack®	0.00 ± 0.00a	0.00 ± 0.00	0.34 ± 0.34a	3.47 ± 0.90a
Control	2.78 ± 0.57b	1.73 ± 0.35	5.90 ± 1.04c	6.25 ± 1.74b

Means within a column followed by the same letter for each cropping season, are not significantly different (Student-Newman-Keuls, $P < 0.05$).

the five insecticides did not significantly vary across locations ($F_{5,\,72} = 0.12; P = 0.9900$), but varied across cropping seasons ($F_{5,\,72} = 6.31; P < 0.0001$). During the minor cropping season, the efficacy of Neemazal®, Agro blaster®, Bypel 1® and Attack® did not significantly differ. However, all four insecticides reduced the infestation of fruit flies significantly more than Cryptogran® having similar fruit flies infestation as in control plots. Conversely, the efficacy of Bypel 1® was significantly lower in the major cropping season (Tables 4 and 5).

3.3. Effects of biopesticides on the population density of thrips

The five insecticides had significantly varying efficacies in reducing thrips' population in both locations and time of application ($F_{5,\,72} = 89.43; P < 0.0001$). Although the efficacy of each insecticide was similar at both locations ($F_{5,\,72} = 2.14; P = 0.55$), their efficacies significantly varied at the 1st ($F_{5,\,90} = 6.7; P < 0.0001$), 2nd ($F_{5,\,90} = 10.8; P < 0.0001$), 3rd ($F_{5,\,90} = 10.2; P < 0.0001$), 4th ($F_{5,\,90} = 3.8; P < 0.0001$) and 5th ($F_{5,\,90} = 5.6; P < 0.0001$) weeks of application. At the 1st, 2nd and 3rd weeks of application, Neemazal®, Attack® and Bypel 1® significantly reduced thrips population than in control plots. However, thrips in the control plots were similar to those in Agro blaster® and Cryptogran® treated plots. At the 4th week, only Neemazal® reduced thrips abundance over the control. In the 5th week, Neemazal® and Attack® significantly reduced thrips population over the control, which had similar populations as in the other treatments (Fig. 1).

The efficacy of the insecticides was affected by the cropping season ($F_{5,\,72} = 5.59; P < 0.0001$). All five insecticides had a higher efficacy in

Table 4
Mean (±SE) of fruit flies infestation level per treatment recorded during the minor cropping season, 2019 and major cropping season, 2020 in Begoro.

Treatments	Minor cropping season		Major cropping season	
	First harvest	Second harvest	First harvest	Second harvest
Neemazal®	0.69 ± 0.69a	1.74 ± 0.67a	5.55 ± 1.50 aA	10.07 ± 2.50bB
Agro blaster®	2.78 ± 1.00b	1.39 ± 0.57a	4.86 ± 0.40 aA	9.02 ± 1.74bB
Bypel 1®	1.39 ± 1.00 ab	0.35 ± 0.35a	10.42 ± 1.84bA	13.89 ± 3.25bA
Cryptogran®	4.167 ± 0.57b	4.86 ± 0.90b	15.28 ± 3.26 cA	19.10 ± 3.47 cA
Attack®	1.40 ± 0.69 ab	1.04 ± 0.30a	5.90 ± 1.19 aA	8.33 ± 0.98 aB
Control	3.82 ± 0.67b	4.51 ± 0.66b	15.63 ± 2.15 cA	18.06 ± 4.05cbB

Means within a column followed by the same lowercase letter and in a row followed by the same.
Uppercase letter for each cropping season are not significantly different (Student-Newman-Keuls, $P < 0.05$).

Table 5
Mean (±SE) of fruit flies infestation level per treatment recorded during the minor cropping season, 2019 and major cropping season, 2020 in Legon.

Treatments	Minor cropping season, 2019		Major cropping season, 2020	
	First harvest	Second harvest	First harvest	Second harvest
Neemazal®	1.04 ± 0.69a	1.73 ± 0.88a	8.33 ± 2.04a	12.84 ± 0.91b
Agro blaster®	3.87 ± 1.20 ab	2.78 ± 0.57a	6.94 ± 0.98a	11.08 ± 0.74 ab
Bypel 1®	2.43 ± 0.67 ab	2.08 ± 0.40a	12.15 ± 2.80 ab	17.01 ± 1.62c
Cryptogran®	4.51 ± 0.67 ab	5.20 ± 1.43 ab	20.13 ± 4.59b	22.22 ± 2.45d
Attack®	1.74 ± 0.67 ab	2.08 ± 0.90a	7.64 ± 1.75a	9.72 ± 1.27a
Control	5.20 ± 1.19b	6.60 ± 0.67b	19.09 ± 3.02b	21.87 ± 2.14d

Means within a column followed by the same letter for each cropping season are not significantly different (Student-Newman-Keuls, $P < 0.05$).

the major rainy season than in the minor season. The efficacies of the insecticides were also affected by the time of application ($F_{5,\,72} = 1.85; P = 0.0230$). However, the effects of the insecticides at the different application times varied between locations ($F_{5,\,72} = 1.90; P = 0.0180$). At the 1st week of the application, Attack® ($F_{1,\,14} = 7.60; P = 0.1600$) and Neemazal® ($F_{1,\,14} = 8.8; P = 0.0100$) significantly reduced thrips population in Legon than in Begoro. At 4th week the population levels in Cryptogran® treated plots in Begoro was higher than Legon ($F_{1,\,14} = 6.60; P = 0.0220$). Similarly, the population of thrips in Bybel 1® treated plots in Begoro was higher than in Legon at the 5th week of application ($F_{1,\,14} = 4.90; P = 0.0430$) (Fig. 1).

3.4. Effects of biopesticides on the population density of whiteflies

The difference in the efficacy of the various insecticides in reducing the whiteflies population was significant in Begoro ($F_{5,\,228} = 24.00; P < 0.0001$) as well as in Legon ($F_{5,\,228} = 38.24; P < 0.0001$). The efficacy of the insecticides was similar across cropping seasons in Begoro ($F_{5,\,228} = 0.84; P = 0.5200$) but not in Legon ($F_{5,\,228} = 5.610; P < 0.0001$), where all five insecticides were significantly more efficacious in the major season than the minor season (Fig. 2).

Application time had an impact on the effects of the five insecticides on the population density of whiteflies in Legon and Begoro across seasons. No significant difference was recorded in the 1st week of insecticide application ($F_{5,\,90} = 2.00; P = 0.0900$). However, significant differences were recorded at the 2nd ($F_{5,\,90} = 12.90; P < 0.0001$), 3rd ($F_{5,\,90} = 7.00; P < 0.0001$), 4th ($F_{5,\,90} = 8.70; P < 0.0001$) and 5th weeks ($F_{5\,90} = 8.8; P < 0.0001$) of insecticide application in both locations during both seasons. At the 2nd and 4th weeks of insecticide application, Neemazal®, Agro blaster®, Bypel 1® and Attack® were significantly effective than Cryptogran®. At the 3rd week, Neemazal® and Agro blaster® had the greatest effects. The performance of the insecticides at the 5th week of insecticide application was similar to the 2nd and 4th weeks, except that Attack® was more efficacious than Bypel 1®, which did not differ from Cryptogran® (Fig. 2).

3.5. Effects of biopesticides on the population of beneficial arthropods

Four different beneficial arthropods groups were recorded during the trials: 1- bees: included honey bee *Apis* spp. and bumble bee *Bombus* spp. (Hymnopetra: Apidae), 2- black ants: included *Crematogaster* spp. and *Camponotus* spp. (Hymnopetra: Formicidae), 3- ladybird beetles: included *Cheilomenes* spp. and *Coccinella* spp. (Coleoptera: Coccinellidae), and 4- spiders (Araneae). Only the population of bees ($\chi 2_{5,\,92} = 4.63; P < 0.0001$) and ladybird beetles ($\chi 2_{5,\,92} = 3.09; P = 0.0140$) were negatively affected by insecticide application. However, the effect of the

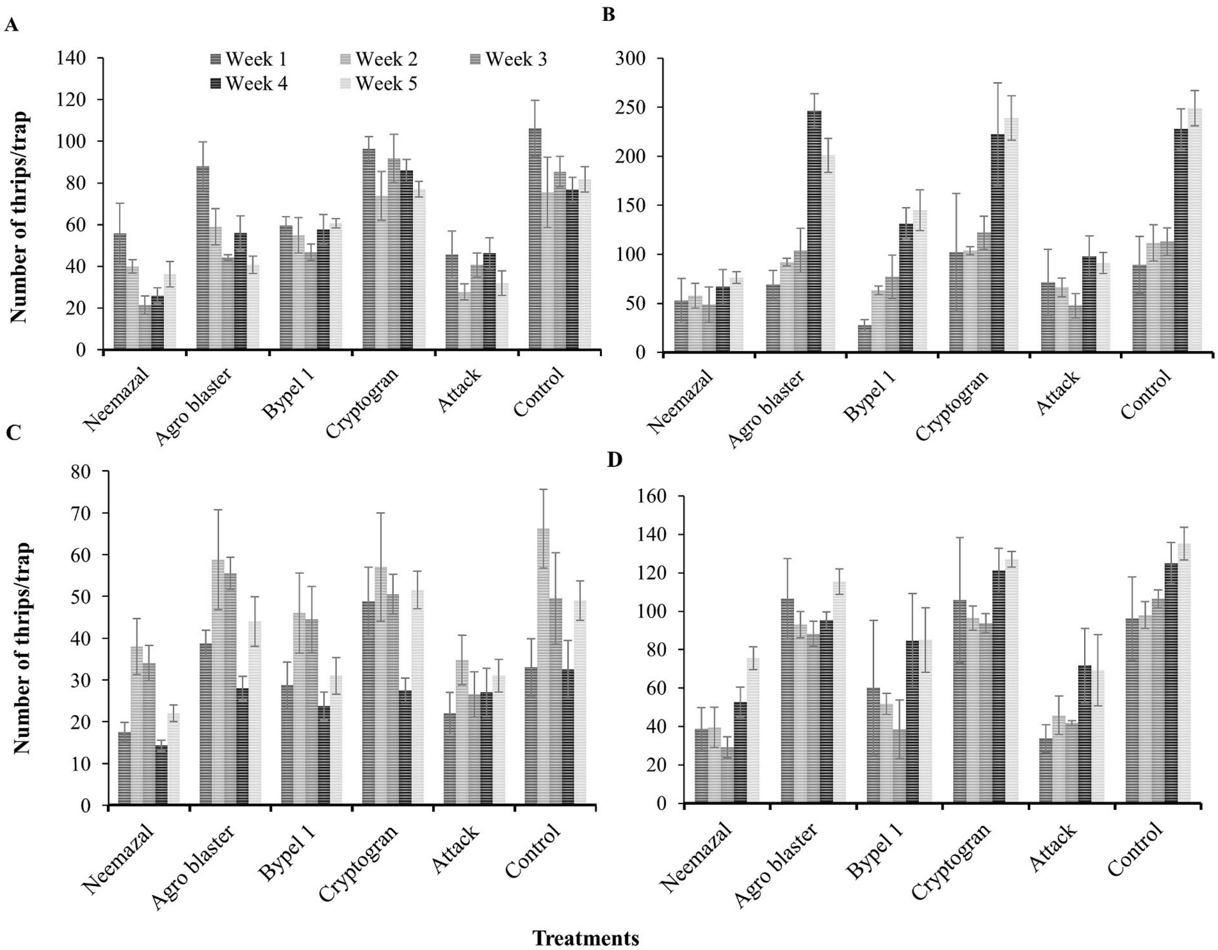

Fig. 1. Weekly mean (±SE) count of thrips on traps per treatment; A = minor cropping season in Begoro; B = major cropping season in Begoro; C = minor cropping season in Legon and D = major cropping season in Legon.

insecticides on these arthropods varied across both locations and cropping seasons. Agro blaster® was more detrimental for bees' population than the other four insecticides. Conversely, Cryptogran® did not significantly affect the population of any the four beneficial insects. (Table 6 and Table 7).

3.6. Effects of biopesticides on the chilli pepper yield

The total yield of the two harvests varied significantly between locations ($F_{1,\ 72} = 4.62; P = 0.035$) and across seasons ($F_{1,\ 72} = 54.99; P < 0.0001$). Application of insecticides significantly increased chilli pepper yield in both locations and seasons ($F_{5,\ 72} = 17.03; P < 0.0001$). However, the efficacy in improving the yield did not vary between locations ($F_{5,\ 72} = 1.29; P = 0.2800$) and seasons ($F_{5,\ 72} = 0.96; P = 0.2800$). The highest yield was recorded in Attack® treated plots, followed by Neemazal® and Bypel 1®. The lowest was recorded with Cryptogran® treated plots and control plots (Table 8).

4. Discussion

The infestation level of FCM on chilli pepper during the experimental period was generally low in both study locations (Begoro and Legon), especially during the minor cropping season of 2019. Nevertheless, the effect of Neemazal® (azadirachtin) in reducing FCM infestation was significant. Previous studies in Ghana, have underscored the efficacy of neem-based products in reducing or completely suppressing FCM populations on pepper and eggplant (e.g., Fening et al., 2016). Neemazal® also reduced the population of thrips, whiteflies and fruit flies. The toxicity of azadirachtin against these pests has been previously highlighted. For example, the application of neem oil (2%), neem leaf extract (5%) and neem seed extract (3%) can reduce the population of thrips and their associated damage by more than 60% in cotton plantations (Khattak et al., 2006; Wawdhane et al., 2020). In a greenhouse study, Kumar and Poehling (2007) reported 100% mortality of sweet potato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae) after nine days of NeemAzal-T/S® (azadirachtin) application on tomato. Several laboratory studies have revealed that azadirachtin induces sublethal effects in fruit flies by affecting their physiology and behaviour. For example, in field studies in India, neem-based insecticides were able to control fruit flies' infestation in bottle gourd, cucumber and ridged gourd (Sawai et al., 2014; Abrol et al., 2019). The high and consistent efficacy of neem-based products against many insect pests as reported in previous and this study could be explained by the fact that the active ingredient azadirachtin, possesses multiple modes of action including anti-feedant, deterrent and growth perturbance (Mordue and Nisbet, 2000).

Like Neemazal®, Attack® also induced significant reductions in FCM infestation during the trial. Both insecticides (i.e., Neemazal® and Attack®) were equally efficacious in reducing FCM populations, corroborating the findings of Gayi et al. (2016). These authors reported that Nimbecine® (azadirachtin) and Amdoc® (Emamectin benzoate and abamectin) performed similarly in reducing populations of the cotton bollworm *Helicoverpa. armigera* (Hübner) (Lepidoptera: Noctuidae) on cotton. The potential of emamectin benzoate in controlling a wide range of insect pests including the larva stages of Lepidoptera and various thrips, whitefly, and fruit fly species is well-documented (e.g., White

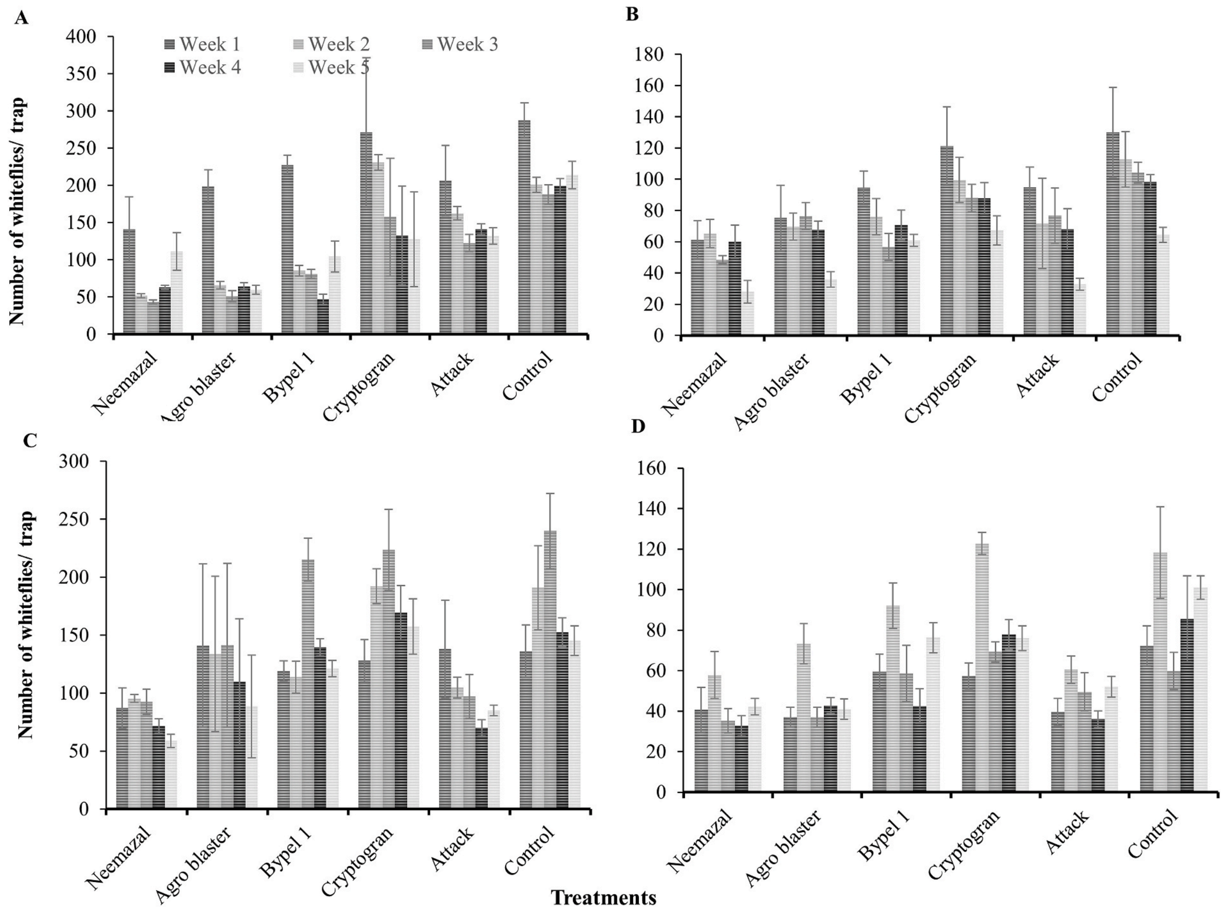

Fig. 2. Weekly mean (±SE) count of whiteflies on traps per treatment; A = minor cropping season in Begoro; B = major cropping season in Begoro; C = minor cropping season in Legon and D = major cropping season in Legon.

Table 6
Number of beneficial arthropods collected in different treatments in Begoro.

Cropping season	Beneficials arthropods	Treatments					
		Neemazal®	Agro blaster®	Bypel 1®	Cryptogran®	Attack®	Control
Minor	Bees	1.2 ± 0.33a	1.54 ± 0.48 a	1.04 ± 0.45a	2.95 ± 0.21b	1.39 ± 0.47a	3.41 ± 0.37b
	Black ants	6.42 ± 0.94	5.33 ± 0.26	4.87 ± 0.50	5.75 ± 1.00	5.29 ± 0.93	6.29 ± 0.67
	Ladybirds	4.66 ± 0.65	4.01 ± 1.33	4.29 ± 0.91	3.83 ± 0.98	3.58 ± 0.58	4.20 ± 0.81
	Spiders	3.83 ± 0.35	2.10 ± 0.44	3.50 ± 0.50	3.70 ± 0.69	3.16 ± 0.56	3.58 ± 0.71
Major	Bees	3.04 ± 0.37 ab	2.04 ± 0.51a	5.04 ± 0.10c	4.54 ± 0.26bc	3.54 ± 0.55abc	4.04 ± 0.53bc
	Black ants	2.87 ± 0.47	3.29 ± 0.42	3.25 ± 0.34	4.08 ± 0.59	3.62 ± 0.61	3.75 ± 0.55
	Ladybirds	2.50 ± 0.31 ab	2.45 ± 0.31 ab	2.12 ± 0.31a	2.91 ± 0.37 ab	2.54 ± 0.36 ab	3.83 ± 0.37b
	Spiders	2.54 ± 0.10	1.79 ± 0.28	2.66 ± 0.28	2.58 ± 0.22	2.41 ± 0.48	2.50 ± 0.20

Means within a row followed by the same letter for each cropping season are not significantly different following a generalised linear model and Tukey HSD $P < 0.05$.

Table 7
Number of beneficial arthropods collected in different treatments in Legon.

Cropping season	Beneficial arthropods	Treatments					
		Neemazal®	Agro blaster®	Bypel 1®	Cryptogran®	Attack®	Control
Minor	Bees	1.20 ± 0.33	1.54 ± 0.48	1.04 ± 0.45	2.95 ± 0.21	1.39 ± 0.47	3.41 ± 0.37
	Black ants	6.14 ± 0.94	5.33 ± 0.26	4.87 ± 0.50	5.75 ± 1.03	5.29 ± 0.92	6.29 ± 0.67
	Ladybirds	4.67 ± 0.65 ab	4.04 ± 1.33 ab	4.29 ± 0.91 ab	3.83 ± 0.97b	3.58 ± 0.58a	4.20 ± 0.80b
	Spiders	3.83 ± 0.35	2.10 ± 0.44	3.50 ± 0.58	3.70 ± 0.69	3.17 ± 0.56	3.58 ± 0.71
Major	Bees	4.37 ± 0.26	2.79 ± 0.55	3.25 ± 0.91	4.08 ± 0.95	3.54 ± 0.59	5.75 ± 1.00
	Black ants	2.33 ± 0.26	2.12 ± 0.47	2.50 ± 0.26	2.37 ± 0.53	2.29 ± 0.26	2.41 ± 0.34
	Ladybirds	3.67 ± 0.15	3.58 ± 0.32	4.29 ± 0.28	5.12 ± 0.29	3.83 ± 0.51	4.04 ± 0.47
	Spiders	4.33 ± 0.44	3.17 ± 0.47	5.08 ± 0.79	4.25 ± 0.32	3.67 ± 0.28	5.04 ± 0.47

Means within a row followed by the same letter for each cropping season are not significantly different following a generalised linear model and Tukey HSD $P < 0.05$.

Table 8
Mean (±SE) of fresh unripe pepper yield (t/ha) recorded in the different treatments during the minor and major cropping seasons in Begoro and Legon.

Treatments	Legon		Begoro	
	Minor season	Major season	Minor season	Major season
Neemazal®	3.17 ± 0.33 aA	4.13 ± 0.38 aB	3.23 ± 0.26 aA	4.35 ± 0.22 aB
Agro blaster®	2.30 ± 0.30bcA	2.58 ± 0.25bcA	2.50 ± 0.13bA	3.61 ± 0.16bB
Bypel 1®	2.70 ± 0.27bA	3.80 ± 0.34 aB	2.37 ± 0.54bA	3.40 ± 0.20 cB
Cryptogran®	2.00 ± 0.12 cA	2.12 ± 0.15 cA	2.19 ± 0.08 cA	3.02 ± 0.69 cB
Attack®	3.05 ± 0.21 aA	4.37 ± 0.34 aB	3.41 ± 1.71 aA	4.55 ± 0.25 aB
Control	2.12 ± 0.31 cA	2.33 ± 0.15 cA	2.22 ± 0.22 cA	3.06 ± 0.37 cB

Means within a column followed by the same lowercase letter and in a row followed by the same uppercase letter for each location are not significantly different (Student-Newman-Keuls, $P < 0.05$).

et al., 1997; Kumar and Poehling, 2007; Muthukrishnan et al., 2012; Vanisree et al., 2017; Lad et al., 2020; Wawdhane et al., 2020). Emamectin benzoate acts by preventing feeding in the insect pests between 1 and 4 h after application, resulting in starvation and death after 2–4 days (Dunbar et al., 1998).

Contrary to Neemazal® and Attack®, the efficacy of Bypel 1® (Bt + PrGV) in reducing FCM infestation was not consistent in this study. The efficacy of *Bacillus thuringiensis* (Bt) either as an insecticide or as Bt transgenic plant, against many other pests such as thrips, whiteflies and fruit flies has been proven (Graham et al., 2019; Liu et al., 2020; Gebremariam et al., 2021). The use of Bt products such as Baciguard® 16WDG 15g/20L and Dipel DF® is recommended for the control of FCM (Ostojá-Starzewski et al., 2017; CABI, 2018). Azmi et al. (2015) found that Bt bioinsecticides can cause more than 80% larvae mortality of the fruit fly *B. dorsalis*. The synergistic effect of *Bacillus thuringiensis* (Bt) and *Pieris rapae* granulovirus may have contributed to the efficacy of Bypel 1® on various insect pests as suggested by Ngosong et al. (2021).

Agro blaster® was less efficacious than the other four insecticides in reducing FCM infestation. To our knowledge, no previous studies have reported the toxicity of natural pyrethrin to FCM. However, its efficacy in controlling lepidopterous pests on various crops has been reported (Bayindir et al., 2014; de Castro et al., 2018). Agro blaster® was also poorly effective against thrips. Although some previous studies have reported that pyrethrin is effective in controlling many thrips species, other studies have however found it not effective (Seal and Baranowski, 1992; Yang et al., 2012; Vassiliou, 2011). For example, Seal and Baranowski (1992) reported that pyrethrin did not affect melon thrips affecting vegetables. However, in this study, Agro blaster® significantly reduced the population of whiteflies which agrees with Simmonds et al. (2002). Pyrethrins have been reported to exert an antifeeding effect on whiteflies, resulting in death (Prota et al., 2014). It has also been reported effective against fruit flies (Flores-Estévez et al., 2013), as recorded in this study.

Although Cryptogran® was able to reduce FCM infestation, its performance was inconsistent and not as efficacious as the other four insecticides. However, Cryptogran® was reported very effective against FCM in citrus orchards in South Africa (Moore et al., 2015). Thus, constituting a component of a systems approach, an IPM strategy for FCM control in South Africa (Kirkman, 2007; Moore et al., 2015; Moore, 2017). The relatively poor efficacy of Cryptogran observed in this study may be due to unsuitable climatic conditions. Indeed, *Cryptophlebia granulovirus*, the active ingredient of Cryptogran® is UV-sensitive and rapidly destroyed by high temperatures. Therefore, the microorganism is usually protected against UV light by adding an adjuvant such as molasse or Nu-Film 17TM to the spray mix (Kirkman, 2007) which was not done in this trial (mainly because it is not the practice of smallholder growers in Ghana), and this may have affected its performance.

Regarding the effect of the insecticides on the four beneficial arthropod species recorded in this study, Neemazal® and Attack® were least inimical on bees and ladybird beetles. These results are similar to previous studies, showing that azadirachtin and emamectin benzoate have little or no side effects on the predators, especially ladybird beetles, ants and spiders (Sinzogan et al., 2006; Ravi et al., 2008; Gayi et al., 2016). However, some other studies have reported the detrimental effects of azadirachtin products on some predators such as spiders (Řezáč et al., 2010). These disparities in the effect of azadirachtin products on the beneficial organisms could be due to the differences in the concentration of the product applied and perhaps the time of application (Mansour and Nentwig, 1988; Punzo, 1997).

Agro blaster® was inimical to bees in Begoro during both seasons but not in Legon. The observed difference could be due to the different biotypes of bees that occur in these locations (Peng et al., 1989; Kükrer et al., 2021). One population may have evolved resistance to the pyrethrum class of insecticides, while the other is sensitive, although this was not investigated in the current study. Moreover, this effect could be also explained by the fact that the coastal savanna (Legon) has more sunshine than the forest (Begoro), so the pyrethrin which is photosensitive is likely to be readily broken down by the hot sun, thereby, allowing natural enemies to recuperate.

The Bypel 1® and Cryptogran® did not show any effect on the population density of predators. Microbial insecticides are highly selective and rarely affect non-target species such as predators and parasitoids (Kalha et al., 2014). Pujiastuti et al. (2019) found that microbial insecticides did not affect the population of several coccinellid species in intercropped farms in India.

In summary, the application of Neemazal®, Attack® and Bypel 1® reduced the infestation levels of all the major insects, consequently increasing the yield of chilli pepper. The application of azadirachtin, emamectin benzoate and microbials have been reported to improve different crop yields (Furlong et al., 2008; Gayi et al., 2016).

5. Conclusion

Judicious use of insecticides is critical for IPM of insect pests, especially for quarantine pests such as FCM with zero tolerance in international markets and invasive pests such as *B. dorsalis* and several species of thrips. Our investigations revealed significant variations in the efficacy of the five biopesticides when applied against FCM, thrips, fruit flies, and whiteflies in smallholder chilli pepper growers' farms in southern Ghana. These differences in efficacy were reflected in both the population density of each of the pest species and chilli pepper yield in each of the insecticide treated plots. Neemazal® and Attack® were the most effective in reducing the population density of all the major chilli pepper insect pests. Agro blaster® was very effective in controlling only whiteflies. Although Bypel 1® was also able to control all the pests, its performance was inconsistent as well as Cryptogran® in controlling FCM. Therefore, Neemazal® and Attack® are the most promising insecticides that smallholder pepper growers may consider an integral part of an IPM programme to manage the major insect pests on chilli pepper. The botanical neemazal (Azadiractin) could be used and interchanged with the semi-synthetic insecticide Attack® (emamectin benzoate) for effective control. During fruiting, it will be more prudent to use the neem-based product to ensure food safety and to promote the activities of beneficial arthropods. Emamectin benzoate could also be used by strictly observing the preharvest interval.

Author contributions

Project conceptualization and methodology: MA, KOF, MKB, DDV.
Investigation and original draft: MA.
Data curation; visualization and formal analysis: MA, POA.
Manuscript review and editing: KOF, MKB, POA, DDV.

Supervision: KOF, MKB, DDV.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We are thankful to the German Academic Exchange Service (DAAD) for supporting financially the PhD programme of the first author. We are grateful to the Centre for Agriculture and Biosciences International (CABI/Ghana) for some financial support during data collection. We also appreciate the assistance of Ghana Association of Vegetable exporters (GAVEX) and their out growers.

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