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RESEARCH

Assessment of the optimal frequency of insecticide sprays required to manage fall armyworm (*Spodoptera frugiperda* J.E Smith) in maize (*Zea mays* L.) in northern Ghana

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Abstract

Background: Insecticide use is an important component of integrated pest management strategies developed for fall armyworm (FAW), *Spodoptera frugiperda* J.E Smith, control in maize in many African countries. Here, the optimum number of synthetic insecticide and biopesticide applications needed to effectively manage FAW at a minimal cost in maize was studied.

Materials and methods: A 3 × 4 factorial experiment arranged in a split plot design was used. Insecticides [Neem seed oil (NSO), 3% Azadirachtin); Emastar 112 EC (emamectin benzoate 48 g/L + acetamiprid 64 g/L); Eradicoat (282 g/L Maltodextrin)] were on the main plots, while insecticide spraying regimes [untreated control, spraying once (at VE–V5 maize develoment stage), twice (at VE–V5 and V6–V12 stages), thrice (at VE–V5, V6–V12 and V12–VT stages), four times (at VE–V5, V6–V12, V12–VT and R1–R3 stages)] were on the sub-plots.

Results: The results showed that larval infestations were generally lower in Emastar 112 EC treated maize than in those sprayed with Eradicoat or NSO. Infestations were higher in the untreated control (no spray) but decreased with increases in number of spray applications in insecticide treated plots. Again, crop damage was low in Emastar 112 EC treated maize. This variable also decreased with an increase in the number of spray applications. Grain yield was significantly affected by the spraying regime only, with this variable being lowest in the untreated control. In both years, yields were at least 1.5-fold higher in maize sprayed twice, thrice or four times compared to the untreated control. Emastar 112 EC had the highest net economic benefits. A single spray of Emastar 112 EC at the VE–V5 maize development stage resulted in maximum profits, while two sprays (i.e., at VE–V5 and V6–V12 stages) were needed for Eradicoat and NSO.

Conclusion: Hence, synthetic insecticides and biopesticides require different frequency of spray applications for cost effective management of FAW in northern Ghana. These findings are potentially applicable in other sub-Saharan African countries where this pest is present.

Keywords: Biopesticides, Environmentally safe, Fall armyworm, Spray frequency, Grain yield

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Introduction

The fall armyworm (FAW) (*Spodoptera frugiperda* J. E. Smith) is a major pest that attacks many plant species, with a strong preference for maize (Casmuz et al. 2010;

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FAO 2017). In Africa, the maize strain of FAW feeds predominantly on maize causing losses with monetary value of approximately US$ 13 billion *per annum* in maize alone (Day et al. 2017). FAW feeds on young leaf whorls, ears, tassels and eventually kill the whole maize plant by cutting through the base of seedlings (Goergen et al. 2016). This pest has become a serious threat to maize production in Africa, due to the availability of a diverse range of host plants throughout the year and favourable climatic conditions for its growth and development (Montezano et al. 2018). The management of FAW appears challenging due to its short life cycle, wide host range, rapid multiplication and ability to spread across large geographical areas (Day et al. 2017; Prasanna et al. 2018).

Conventionally, management strategies such as insecticides, host-plant resistance, cultural practices, integrated pest management (IPM) approach and crop rotation are used to control FAW (Womack et al. 2018; Tambo et al. 2019). Of these, the use of chemical insecticides for FAW management is the most common among farmers in Africa (Fatoretto et al. 2017). This is mainly due to intervention strategies that have been used by governments on the continent since the outbreak of this pest (Hruska 2019; Kansiime et al. 2019). But this strategy negatively impacts the environment, leads to insecticide resistance and endangers the health of farm operators, animals and consumers (Lewis et al. 2016; Togola et al. 2018). Also, apart from insecticide use resulting in direct mortality of beneficial arthropods, insecticides negatively impact on arthropod behavior (e.g., mobility, sex ratio, feeding behaviour etc.) and physiology (e.g., adult longevity, immunology, fecundity, development etc.) even at sublethal concentrations (Desneux et al. 2007).

Insecticides are generally designed to be toxic and this contributes to they effectively killing target insect species. This notwithstanding, insecticides have off-target toxic effects that result in they harming other species, including human beings (Abreu-Villica and Levin, 2017). Efforts are continuously made to produce safer and more selective insecticides that are less harmful to natural enemies and safe for humans and the environment. Accordingly, most conventional pesticides are being replaced by biorational insecticides (Hara 2000). Some of these insecticides regulate pest populations by acting as ecdysone agonists, juvenile hormone mimic and chitin synthesis inhibitors (Shera et al. 2016; Jansma et al. 1993). A study in Ghana reported that neem seed oil-based biopesticide products (0.17–0.33%) were as effective as synthetic ones containing emamectin benzoate (e.g., Ema 19.2 EC) in the FAW control. In that study, all dose levels of the neem seed oil extract were lethal to FAW (Babendreier et al. 2020). Similar reports of neem seed oil being as effective as synthetic insecticides were reported by Nboyine et al. (2020).

In spite of the proven efficacy of biopesticides for FAW management (Babendreier et al. 2020; Day et al. 2017; Nboyine et al. 2020), there is limited knowledge on growth stages of maize that critically require insecticide treatments when infestations reach threshold levels. Surveys in Ghana in 2018 showed that households sprayed pesticides, including biopesticides against FAW up to 12 times, during maize growing seasons (Tambo et al. 2019), and this could impact negatively on natural enemies' populations and increase production cost. Hence, this work aimed at determining the optimum number of applications for synthetic insecticides and biopesticides in maize in order to effectively mitigate FAW infestation and damage at a reduced cost. The hypotheses tested in this study were: (i) the efficacy of synthetic insecticides and biopesticides in managing FAW infestation and damage in maize are the same; (ii) the optimum number of sprays required to effectively mitigate FAW infestation and damage in maize does not differ between synthetic insecticides and biopesticides; (iii) the cost associated with FAW management is not affected by the type of insecticide used and number of spray applications.

Materials and methods
Study area
A field experiment was conducted on the research field of the Council for Scientific and Industrial Research—Savanna Agricultural Research Institute (CSIR-SARI) at Dokpong in the Wa Municipality of the Upper West region, Ghana, during the 2019 and 2020 cropping seasons. The location of the trial (N 9° 53′ 9″, W 2° 27′ 49″) is classified into Guinea Savannah ecological zone. This zone has a uni-modal rainfall pattern that commences in May and ends in October, followed by a dry season from November to April each year. Mean annual rainfall ranges between 900 and 1200 mm. The daily mean temperatures in this zone range between 20 and 35 °C. 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 sandy loam (Neumann et al. 2007).

The trial site was tractor ploughed and harrowed to good soil tilth. In both seasons, planting was done in mid-July.

Experimental design, planting and treatments
Treatments comprising three insecticides and four spraying regimes were arranged in split-plots in a randomized complete block design with four replications. The main-plot treatments consisted of the insecticides [Eradicoat (a.i: 282 g/L Maltodextrin), Grow-safe neem seed oil (NSO) (a.i. 3% azadirachtin) and EmaStar 112 EC (a.i. emamectin benzoate 48 g/L + acetamiprid 64 g/L)], while

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the sub-plots consisted of the four spraying regimes, [i.e., no spray (untreated controls), spraying once, twice, thrice and four times. The Emastar 112 EC was the synthetic insecticide while the Eradicoat and NSO were the biopesticides. Maize sprayed once were treated at the first action threshold only which occurred at the VE–V5 stage (i.e., early whorl) (i.e., 2 weeks after emergence). Those sprayed twice were treated at the first and second action thresholds only (i.e., VE–V5 and V8–V12). Maize sprayed thrice were treated at thresholds occurring at the VE–V5, V8–V12 and just before VT (i.e., late whorl) stage. Maize sprayed four times were insecticide treated at the first, second, third and fourth thresholds; the fourth application occurred between the R1 and R3 (i.e., tasseling and silking) stages (Prasanna et al. 2018).

The Eradicoat was obtained from Certis, UK and Ireland, while the NSO was supplied by Green-Gro Ltd., Ghana. The Emastar 112 EC was obtained from Adama West Africa Ltd., Ghana.

Each sub-plot occupied an area of 22.5 m^2 and consisted of 6 rows of maize that were 5 m long. The maize variety used in this experiment was Ewul-boyu. This variety has a maturity period of 110 days, excellent seed quality, drought tolerant, resistant to lodging and diseases such as rust, blight, streak and curvularia. It has a yield potential of 5.4 t/ha and is adapted to the savannah and transitional zones of Ghana (Ghana Variety Release Catalogue 2019).

The maize seeds were sowed at a spacing of 75 cm between rows and 40 cm between plants. The sub-plots were separated by 2 m unsowed alleys. The main-plots each occupied a 117 m^2 area and these were 3 m apart. There was a 3 m separation between blocks of treatments.

Maize plants were sampled for infestation by FAW larvae and action thresholds were 10–30%, 20–50% and 10–30% field infestation levels for the VE–V6, V7–VT and R1–R3 stages, respectively (Prasanna et al. 2018). At these thresholds, insecticides were applied using 15 L capacity knapsacks. The concentration of Eradicoat, NSO and EmaStar 112 EC per knapsack were 0.53%, 0.17% and 0.17%, respectively. Spray applications were done such that each plant was completely covered with the insecticide solution including spraying into the whorl based on approximately 200 l ha^{-1} in the early cropping stage. This was increased to about 300 l ha^{-1} after 36 days of crop establishment.

At 2 weeks after crop emergence, basal fertilizer application with 250 kg/ha NPK (23-10-10) was undertaken followed by top dressing with urea at 125 kg/ha, 3 weeks after basal fertilization. Weed control was done manually at three and six weeks after crop emergence.

Data collection

Data were collected before treatments applications and at 14, 28 and 42 days after first treatment applications from 20 plants randomly selected along two diagonals on each plot. The variables measured from the plants sampled were: number of egg masses per 20 plants and number of larvae per 20 plants (non-destructively). Foliar damage was assessed using the Davis scale (from 0—no damage, to 9—heavy damage) at 42 days after the first spray applications (Davis and Williams 1992).

At harvest, the percentage of cobs with characteristic signs of FAW damage was assessed based on 20 randomly selected cobs per plot; this was followed by computing the proportion of damaged cobs. Grain yield was assessed per plot by threshing dry cobs and winnowing the resulting grains using plants in the 4 inner rows (i.e., excluding the outer two from the total of 6 rows per plot). The weight of grains per plot after sun-drying to 12–13% moisture content was measured and converted to yield on kg per ha basis.

Data analyses

For each of the two years, data on number of egg masses and larvae per 20 plants were subjected to repeated measures analysis of variance (ANOVA) in GenStat® statistical programme (12th edition). This was because the variances of the data from each date of sampling were dependent. In these analyses, the treatment structure was Insecticide treatments × Spaying regimes, and blocking structure was the replications. Box's tests were used to assess the symmetry of the covariance matrix of the data before undertaking the repeated measures ANOVA. Whenever the data lacked sphericity, they were adjusted using the Greenhouse–Geisser epsilon estimate. Means were separated at the 5% probability level using their least significant differences (LSD).

The homogeneity of foliar and cob damage data for each season were first assessed before subjecting them to analyses of variance (ANOVA) for split-plots design. In these analyses, insecticides were the main-plot treatments and spraying regimes were the sub-plot treatments. Grain yield data for each season were also subjected to ANOVA for split-plots design. Afterwards, a combined-years ANOVA using treatment means from each season and for each variable measured were performed. In these analyses, Year was used as the blocking factor, Insecticides as main-plot and spraying regimes as sub-plot factors. Whenever Year effects were significant, the means from each Year were presented separately. Means that were significant at 5% probability threshold were separated using Tukey's test.

Partial budget analysis

Partial budget analysis was used to assess the net benefit due to insecticides application and net returns to

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FAW management. This aimed at assessing the economic viability of investment in FAW control compared to no protection. Market prices of both maize and the insecticides were used in arriving at the value of production and cost of production, respectively. It was assumed that all other costs were constant and the costs that vary were therefore used to calculate the input cost. The value of increased yields due to insecticide applications were calculated using the following:

$$\text{Value of increased yield due to spraying} = \text{Price} \times \text{Increased yield over control}$$

$$V_{yield} = P_{makt} \times (Q_{treatment} - Q_{control})$$

where P_{market} is the market price of maize (Ghana cedi, GHS) and $Q_{treatment}$ is the output of treated plot (kg/ha) and $Q_{control}$ is the output of control plot (kg/ha).

The total variable cost of insecticide application was calculated as:

$$TVC_{faw} = (P_{mi} \times Vol_i) + Lab_{spraying}$$

where TVC_{faw} is the total variable cost (GHS), P_{mi} is the market price of insecticides used, Vol_i is the volume of insecticide used (l ha^{-1}) and $Lab_{Spraying}$ is the labor cost for insecticide applications (GHS/ha).

The net benefit was calculated using the following:

$$\text{Net benefit due to spraying} = V_{yield} - TVC_{faw}$$

where V_{yield} is the value of increased yield due to spraying and TVC_{faw} is total variable cost of insecticides and its application.

The returns to spraying were then calculated using the following:

$$\text{Returns to insecticide use}$$
$$= \frac{\text{Value of increased yield over control } (GHS/\text{ha})}{\text{Total variable of insecticide application } (GHS/\text{ha})}$$

Results
Fall armyworm egg masses and larval infestations
First cropping season (2019)
The number of egg masses counted was not significantly affected by insecticides, spraying regimes or their interactions ($p > 0.05$). The mean number of egg masses during this cropping period and across all treatments was 0.25/20 plants (Table 1). This variable was however, significantly affected by dates of sampling ($F_{3,135} = 14.94$; $p < 0.001$). The highest number of egg masses was recorded at the first sampling; afterwards, there were no significant differences between dates of sampling for this variable (Fig. 1).

There were significant differences in spraying regime ($F_{4,42} = 3.7$; $p = 0.011$) and dates of sampling ($F_{3,135} = 37.79$; $p < 0.001$) for mean larval infestations. There were no significant insecticides × spraying regime interaction ($p > 0.05$) effect for this variable. Among spraying regimes, untreated maize had the highest level of infestation while those sprayed 4 times were lowest. Infestation levels were not significantly different between the latter and those sprayed either 2 or 3 times. Also, infestations in untreated maize were not significantly different from that sprayed once (Table 1).

For dates of sampling, larval numbers were significantly higher during the 1st sampling and lower in subsequent samplings. The lowest infestation was recorded during the 3rd sampling (Fig. 1).
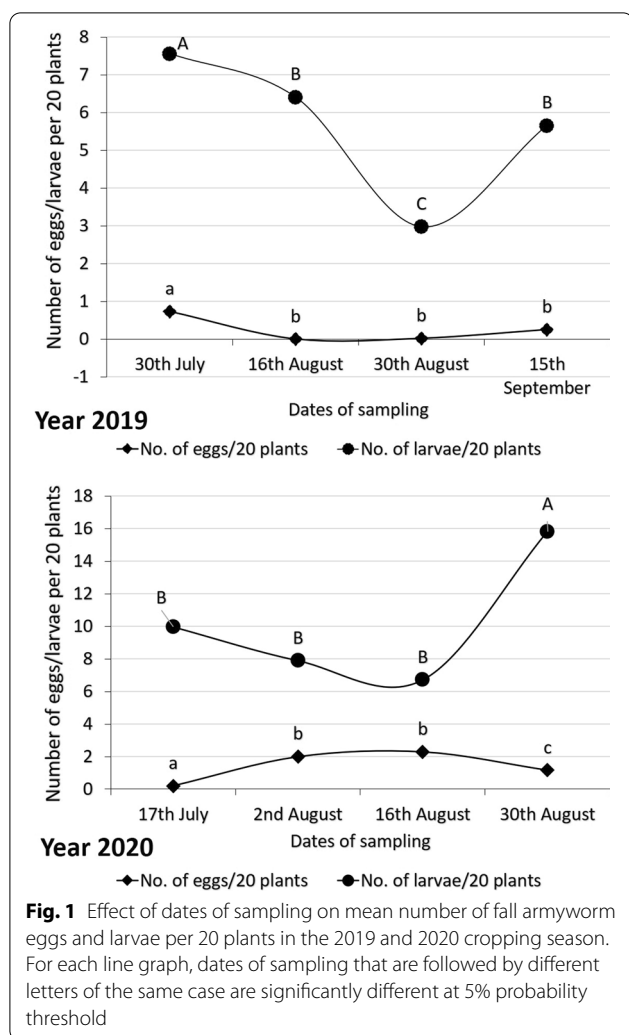
Second cropping season (2020)
There were significant differences for the effects of insecticides ($F_{2,42} = 5.77$; $p = 0.006$) and spraying regimes ($F_{4,42} = 4.80$; $p = 0.003$) on number of egg masses; there was no insecticides × spraying regimes interactions effect ($p > 0.05$). Dates of sampling also significantly affected the abundance of egg masses ($F_{3,135} = 23.17$; $p < 0.001$). Of insecticides tested, abundance of egg masses was lowest in maize treated with Eradicoat and highest in those treated with Emastar 112 EC. There were no significant differences in egg masses between Emastar 112 EC and NSO treated plants. Among the spraying regimes, number of egg masses was lowest in the untreated control and highest in those sprayed once. There was no

Table 1 Effect of insecticides and spraying regimes on mean number of egg masses and larvae per 20 plants in 2019 cropping season

Variable	No. of egg masses/20 plants	No. of larvae/20 plants
Insecticides		
Emastar 112 EC	0.17 ± 0.07 a	5.17 ± 0.46 a
Eradicaot	0.28 ± 0.06 a	5.88 ± 0.48 a
NSO	0.30 ± 0.15 a	5.92 ± 0.33 a
P-value	0.618	0.352
Spraying regimes		
Untreated control	0.22 ± 0.07 a	6.97 ± 0.62 a
Once	0.19 ± 0.10 a	6.39 ± 0.53 ab
Twice	0.31 ± 0.10 a	5.25 ± 0.39 ab
Thrice	0.39 ± 0.25 a	5.25 ± 0.58 ab
Four times	0.14 ± 0.08 a	4.42 ± 0.45 b
P-value	0.711	0.011

Means in a column that are followed by different letters are significantly different at 5% probability threshold; NSO: neem seed oil

Fig. 1 Effect of dates of sampling on mean number of fall armyworm eggs and larvae per 20 plants in the 2019 and 2020 cropping season. For each line graph, dates of sampling that are followed by different letters of the same case are significantly different at 5% probability threshold

Table 2 Effect of insecticides and spraying regimes on mean number of egg masses and larvae per 20 plants in 2020 cropping season

Variable	No. of egg masses	No. of larvae/20 plants
Insecticides		
Emastar 112 EC	1.69 ± 0.19 a	8.12 ± 0.88 b
Eradicaot	1.00 ± 0.11 b	12.24 ± 0.92 a
NSO	1.56 ± 0.27 a	9.95 ± 0.74 a
P-value	0.006	< 0.001
Spraying regimes		
Untreated control	0.83 ± 0.20 b	14.29 ± 1.46 a
Once	1.88 ± 0.27 a	10.88 ± 0.85 b
Twice	1.81 ± 0.33 a	8.79 ± 0.84 bc
Thrice	1.27 ± 0.29 a	8.90 ± 0.88 bc
Four times	1.29 ± 0.12 a	7.67 ± 0.84 c
P-value	0.003	< 0.001

Means in a column that are followed by different letters are significantly different at 5% probability threshold; NSO: neem seed oil

significant difference in egg masses between the single and double spayed plants. The number of egg masses collected in maize sprayed thrice and four times were also significantly higher than those in the untreated control (Table 2). Except the 3rd sampling date which recorded higher egg masses, there were significantly lower numbers of egg masses in the 1st and 4th dates of sampling (Fig. 1).

Larval infestation levels were significantly affected by insecticides ($F_{2,42} = 9.14$; $p < 0.001$) and spraying regimes ($F_{4,42} = 8.80$; $p < 0.001$); there were no insecticides × spraying regimes interactions effects ($p > 0.05$). Of the insecticides tested, mean larval infestation was lowest in Emastar 112 EC and highest in Eradicoat. There were no differences between the former and NSO treated maize for this variable. Among the spraying regimes, untreated maize had the highest infestation and those sprayed 4 times were lowest. There were no significant

differences between the latter treatment and maize sprayed twice or thrice (Table 2).

Dates of sampling ($F_{3,135} = 36.43$; $p < 0.001$) significantly affected larval abundance. This variable was lowest in 3rd sampling and highest at the 4th sampling date. The overall mean larval infestation levels in the first sampling date were not significantly higher than that in 2nd and 3rd sampling dates. Also, there were no significant differences between infestation levels in the 2nd and 3rd samplings (Fig. 1).

Foliar damage by fall armyworm (FAW)
FAW damage to maize plants was significantly affected by year ($F_{1,24} = 16.39$; $p < 0.001$). This variable was higher in 2020 (1.92) than in 2019 (1.11) season. There were significant insecticides ($F_{2,36} = 84.90$; $p < 0.001$), spraying regimes ($F_{4,36} = 16.64$; $p < 0.001$) and insecticides × spraying regimes interactions effect ($F_{8,36} = 2.98$; $p = 0.012$) in 2019 season for damage. This variable was lowest when Emastar 112 EC was sprayed four times and higher in untreated ones. Except the untreated maize, there were no significant differences among all spraying regimes in Emastar 112 EC treatments. Similarly, there were no significant differences among NSO treatments, except the untreated control. Damage in Eradicoat treatments were not significantly different among the spraying regimes (Fig. 2).

In 2020, this variable was significantly affected by insecticides ($F_{2,36} = 38.14$; $p < 0.001$) and spraying regimes ($F_{4,36} = 26.53$; $p < 0.001$); there was no interactions effect ($p > 0.05$). Damage to maize plants was lower in Emastar 112 EC treated maize but highest in
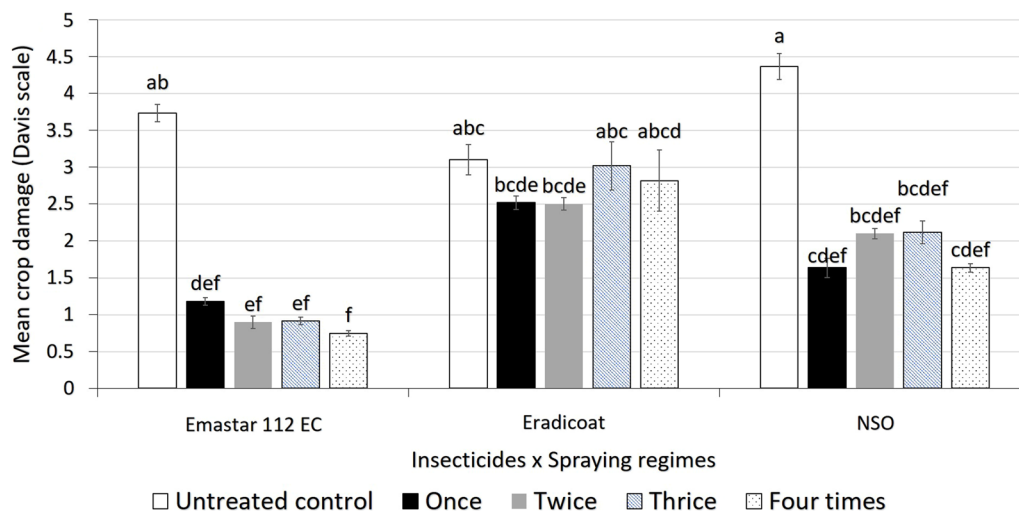
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Fig. 2 Interaction effect of insecticides and spraying regimes on mean FAW damage to maize plants in the 2019 cropping season. Data are means ± standard error of mean (SEM); LSD: least significant difference at 5% probability threshold; NSO: neem seed oil. Bars that are followed by different letters are significantly different at 5% probability threshold; NSO: neem seed oil

Table 3 Effect of insecticides and spraying regimes on mean maize foliar damage in 2020 season

Variable	Foliar damage
Insecticides	
Emastar 112 EC	2.92 ± 0.33 b
Eradicaot	4.55 ± 0.23 a
NSO	4.07 ± 0.30 a
P-value	< 0.001
Spraying regimes	
Untreated control	5.45 ± 0.26 a
Once	4.53 ± 0.34 b
Twice	3.37 ± 0.35 c
Thrice	3.19 ± 0.31 cd
Four times	2.69 ± 0.31 d
P-value	< 0.001

Means in a column that are followed by different letters are significantly different at 5% probability threshold; NSO: neem seed oil

those sprayed with Eradicoat. There was no significant difference between the latter and NSO treated maize. Among the spraying regimes, the untreated control had the highest damage while maize sprayed four times was lowest (Table 3).

Cob damage and yield

A combined-years analysis showed significant year effects ($F_{1,12} = 18.97$; $p = 0.049$) for cob damage. Cob damage was higher in 2019 (0.40) than in 2020 (0.25)

cropping season. In 2019, cob damage was not significantly affected by insecticides ($p > 0.05$), spraying regimes ($p > 0.05$) and their interactions ($p > 0.05$) (Fig. 3A). In contrast, damage was significantly affected by spraying regime only ($F_{4,36} = 4.27$; $p = 0.006$) with no significant insecticides ($p > 0.05$) and insecticide × spraying regimes interactions effects ($p > 0.05$) in 2020 season. Of the spraying regimes tested, proportion of damaged cobs were highest in untreated control and lowest in plants sprayed thrice. There were no significant differences between the proportion of damaged cobs in maize sprayed thrice and four times (Fig. 3B).

There was significant year effect ($F_{1,12} = 20.74$; $p = 0.045$) when the two seasons' data were combined and analyzed for grain yield. Yield was higher in 2020 (3540 t/ha) than in 2019 (2644 t/ha) season. In 2019, it was only spraying regime ($F_{4,36} = 28.19$; $p < 0.001$) that significantly affected yield. There were no significant insecticides ($p > 0.05$) and insecticides × spraying regimes interactions effects ($p > 0.05$). Among the spraying regimes, untreated control had the lowest yield while maize sprayed thrice was highest. There were no significant differences between maize sprayed thrice and 4 times, in terms of yield (Fig. 3C).

Again, it was only spraying regime that significantly affected yield in 2020 ($F_{4,36} = 6.23$; $p < 0.001$); there were no significant insecticides ($p > 0.05$) and insecticides × spraying regimes interactions effects ($p > 0.05$). Untreated maize had the lowest yield while those sprayed twice had the highest. There was no significant difference between the latter and those sprayed thrice or 4 times (Fig. 3D).
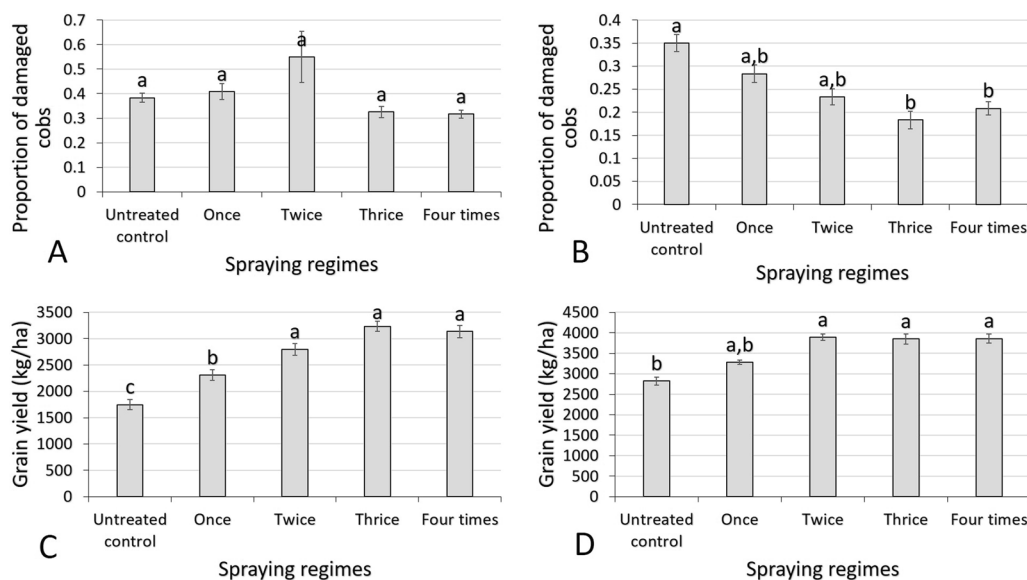
Fig. 3 Effect of spraying regimes on proportion of damaged cobs and grain yield in 2019 and 2020 season. Data are means ± standard error of means (SEM). Bars followed by different letters are significantly different at 5% probability threshold. **A** Proportion of damaged cobs in 2019 season; **B** proportion of damaged cobs in 2020 season; **C** grain yield in 2019 season; **D** grain yield in 2020 season

Partial budget analysis

The results of a partial budget analysis showed a positive value of increased yield for all treatments compared to the untreated controls. The net benefit of using insecticides (synthetic or biopesticides) to manage FAW were positive and these net returns on investing in insecticides applications were higher than unity. Among the insecticides used, Emastar 112 EC had the highest net benefit compared to NSO and Eradicoat (Table 4).

For Emastar 112 EC, there was a return of GHS 14.00 for every GHS 1.00 investment in its application compared to untreated controls, for maize plots that were sprayed only once. Afterwards, the returns decreased to GHS 11.00, GHS 8.00 and GHS 6.00 compared to the untreated controls, for every GHS1.00 invested in those sprayed twice, thrice and four times, respectively (Table 4).

The net returns for maize treated with Eradicoat once, twice, thrice and four times were GHS 1.20, GHS 3.00, GHS 2.00 and GHS2.00, respectively, for every GHS 1.00 invested compared to the untreated controls. In the case of NSO, the returns increased with an increase in number of spray applications but decreased in maize sprayed thrice or four times (Table 4).

Discussion

In general, semi-synthetic derivatives of the natural product abamectin in the avermectin family such as emamectin benzoate are reported to have ovicidal effects because of their low molecular weight (Jansson et al. 1998; Moscardini et al. 2013). This allows for their penetration into the chorion, thereby acting on the embryo and changing its rate of development (Moscardini et al. 2013). For NSO, a study by Hassan (1999) reported egg mortality and deformation of subsequent larvae as some effects of treating eggs of the lepidopteran, *Helicoverpa armigera* (Hübner), with extracts of neem seeds. In contrast, Eradicoat is not known to have any ovicidal effects. Although this work did not directly measure the ovicidal effects of the insecticides tested, we infer that the reduction in neonates/larval abundance, especially in Emasrtar 112 EC treatments and to a limited extent NSO was partly contributed by this property of those insecticides. Apart from these insecticides directly killing the larvae, they might have also reduced the hatchability of the eggs, thereby reducing larval numbers particularly in Emastar 112 EC and NSO treated maize.

Effective management of FAW in maize fields in Africa using synthetic active ingredients has been reported by several authors (Babendreier et al. 2020; Hardke et al. 2011; Nboyine et al. 2020; Sisay et al. 2019). The general effectiveness of the insecticides tested in this study corroborates previous studies which found emamectin benzoate, acetamiprid, azadirachtin and maltodextrin as active ingredients that are effective at managing FAW under SSA conditions (Babendreier et al. 2020; Nboyine et al. 2020; Sisay et al. 2019). However, Emastar 112 EC was more effective at reducing

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Table 4 Partial budget analysis for the effect of insecticides used to manage fall armyworm in maize at different spraying regimes

Insecticides	Spraying regimes	Output			Inputs			Net benefit due to spraying (GHS/ha)	Net Returns to spraying
		Yield (kg/ha)	Increased yield due to spay over control (kg/ha)	Value of increased yield (GHS)/ha	Cost of insecticide (GHS/ha)	Labor charges for spraying (GHS/ha)	Total cost (GHS/ha)		
Emastar 112 EC	Untreated control	2158.93							
	Once	3070.36	911.43	1458.29	45.00	50.00	95.00	1363.29	14.35
	Twice	3568.33	1409.40	2255.05	90.00	100.00	190.00	2065.05	10.87
	Thrice	3732.98	1574.05	2518.48	135.00	150.00	285.00	2233.48	7.84
	Four times	3711.07	1552.14	2483.43	180.00	200.00	380.00	2103.43	5.54
Eradicoat	Untreated control	2332.98							
	Once	2566.79	233.81	374.10	120.00	50.00	170.00	204.10	1.20
	Twice	3140.48	807.50	1292.00	240.00	100.00	340.00	952.00	2.80
	Thrice	3300.95	967.98	1548.76	360.00	150.00	510.00	1038.76	2.04
	Four times	3157.62	824.64	1319.43	480.00	200.00	680.00	639.43	0.94
NSO	Untreated control	2357.98							
	Once	2748.81	390.83	625.33	20.00	50.00	70.00	555.33	7.93
	Twice	3327.62	969.64	1551.43	40.00	100.00	140.00	1411.43	10.08
	Thrice	3589.76	1231.79	1970.86	60.00	150.00	210.00	1760.86	8.39
	Four times	3709.64	1351.67	2162.67	80.00	200.00	280.00	1882.67	6.72

NSO: neem seed oil; GHS: Ghana cedi; price of 1 kg maize: GHS 1.60; Emastar 112 EC: GHS 45.00 per 250 ml bottle; NSO: GHS 60 per l bottle; Eradicoat: GHS 120 per l bottle

larval infestations than Eradicoat and NSO. Though less effective than those with synthetic active ingredients, one of the major benefits of using these biopesticides is that their active components act on multiple sites in the target pest, thus making it more difficult for the pest to develop resistance (Mostert 2018). For instance, neem seed oils control lepidopteran pest through its anti-feedant effects and increased larvae mortality (Assefa and Ayalew 2019; Nicoletti et al. 2012; Tavares et al. 2010) while Eradicoat has a physical mode of action—it blocks the spiracles of the pest leading to suffocation. In contrast, emamectin benzoate in Emastar 112 EC controls lepidopteran pest by acting as a gamma-amino-obutyric acid (GABA)—and glutamate-gated chloride channel agonist (Jansson et al. 1998). Also, the acetamiprid, included in Emastar 112 EC formulation, acts on the central nervous system of insects by quickly knocking them down (Yamada et al. 1999).

Although the modes of action of biopesticides result in delayed resistance development, their main disadvantage is that they require frequent applications to attain maximum effects. This increases the cost associated with their use. For example, the azadirachtin in neem-based pesticides are highly photosensitive and it isomerizes quickly under sunlight (Forim et al. 2010; Schmutterer 1990);

hence a need for repeat applications in order to attain maximum pest control in tropical climates, especially under high infestation pressure. Similarly, Eradicoat, just like other biopesticides, is easily washed off the body of target pest by rain water (Mostert 2018). Thus, its efficacy is reduced by frequent and heavy rainfalls. In contrast, synthetic active ingredients are generally fast acting and cause larval mortality within a short period time (Jansson et al. 1998). These properties of the different insecticides used in the current study explains the lower larval infestation levels reported in Emastar 112 EC treated maize compared to those sprayed with Eradicoat and NSO.

This study also reports that a single round of insecticide spray to protect maize during the first infestation threshold of FAW at the early whorl stage (VE–V5) and perhaps, a repeat spray at the initial phase of the late whorl stage (V6–V12) were adequate to fully protect the crop. Studies show that FAW infestations that occur from early to late whorl stages are the most damaging in terms of their impact on yield (Assefa and Ayalew 2019; Hruska and Gould 1997). Thus, farmers in Sub-Saharan African countries may not need to spray insecticides against this pest at the VT stages and beyond (though these later applications slightly reduce larval numbers). Generally, feeding on leaf by FAW larvae/neonates depends on the

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leaf age and quality because these factors impact on their establishment, growth and survival. The age of maize leaf influences quality parameters such as water availability, toughness and nitrogen; these may lead to high neonate mortality even if the same leaves are suitable for older instars (Bernays and Chapman 1994; Cockfield and Mahr 1993; Pannuti et al. 2015). Hence, after the VT and reproductive growth stages, maize leaves are not suitable for the development of early instars (Pannuti et al. 2016) and farmers do not have to spray the crop against damage by this pest. Most adult FAW may therefore, not invest in laying their eggs in such fields.

Studies show that FAW larvae inflict higher leaf feeding damage in unprotected maize compared to those protected with insecticides (Babendreier et al. 2020; Nboyine et al. 2020; Sisay et al. 2019). In this work, all insecticides tested effectively reduced feeding damage though Emastar 112 EC was more effective. Similar reports of reduced foliar damage in maize treated with insecticides containing the active ingredients in Emastar 112 EC was reported by Babendreier et al. (2020). The relatively slow rate of causing larval mortality by neem-based biopesticides and Eradicoat resulted in maize treated with these products sustaining some significant amount of damage than those treated with synthetic insecticides (Schmutterer 1990). Also, additional insecticides spray applications better protected plants from damage by FAW as these repeat applications contributed to further reductions in larval numbers and feeding on the plants.

Feeding on reproductive parts of maize by FAW larvae negatively impacts on fertilization and grain formation, thereby reducing grain yield (Tambo et al. 2019). FAW is also capable of partially or totally damaging maize cob and this reduces grain quality and yield (Harrison et al. 2019). The efficacy of the insecticide treatments and spraying regimes in reducing cob damage was inconclusive from this study. However, all insecticides appeared effective at protecting cobs from damage. Cob damaged can be effectively managed in maize sprayed thrice and four times; as these spray applications occur between the VT and R3 growth stages. Hence, the insecticides applied contributed to reducing larval numbers in the silk and cobs, thereby reducing their damage to the cobs.

Grain yield is affected by FAW feeding damage that mostly occur at vegetative growth stage although damage to reproductive parts and cobs also contribute to yield reductions (Tambo et al. 2019; Harrison et al. 2019). Yield losses due to feeding damage at the vegetative stages is reported to range between 15 and 73% (Assefa and Ayalew 2019; Nboyine et al. 2020). Again, all insecticides used in this work were effective at managing FAW consequently increasing yields compared to the untreated controls. However, it was found that managing FAW with two rounds of insecticides (either synthetic or biopesticides) was sufficient to mitigate the damaging effects of this pest on grain yield resulting in at least 1.5-fold yield increment in these treatments over the untreated control. The first insecticide spray was to be applied at the first FAW infestation threshold which occurred between VE and V6 (i.e., early whorl) stage while the second was applied at the late whorl stage. After these, the findings of the current study suggests that any additional insecticide application by farmers is a waste of resources. Yield differences were observed between the two seasons and this was possibly because the trial in 2020 was established on a field previously cropped to a legume. The maize in the 2020 season might have therefore effectively utilized the residual nitrogen fixed into the soil by the previous season's crop.

There is a strong positive relationship between grain yield and pest management practices (Kansiime et al. 2019). In an attempt to increase yield through effective management of pest such as FAW on farmers field, several rounds of insecticides are sometimes applied; this is usually expensive and the cost is sometimes prohibitive (Kumela et al. 2019). As expected, the results of the current study showed positive net benefits for all insecticides used to manage FAW. However, it was interesting to note that resource-poor farmers can maximize their net profits with just a single round of Emastar 112 EC application at the VE to V5 stage. In contrast, farmers required a maximum of two spray applications to maximize profits when Eradicoat or NSO were used to protect maize from FAW damage. Biopesticides are generally slow acting (Mostert 2018) and this probably explains the higher number of spray applications required to attain outcomes similar to those attained when synthetic insecticides such Emastar 112 EC are used. These notwithstanding, they are mostly benign to the environment.

Conclusions
In conclusion, the results of the present study confirms that biopesticides are as effective as synthetic ones in mitigating FAW damage in maize. FAW infestation thresholds that occur at the early (VE–V5) and late whorl (V6–VT) stages are the critical ones which require implementation of control measures; beyond these, any additional investment in FAW control by farmers has no significant impact on the productivity of the crop. However, while farmers who protect their maize crop with synthetic insecticides may require a single round of spray application to effectively mitigate FAW damage, those using biopesticides will require two rounds in order to maximize profits. When adopted by farmers, this reduction in insecticide use might also mitigate the negative

consequences of insecticides on human health and the environment.

Authors' contributions
JAN, FK, LKA and BKB conceived and designed the experiment. JAN, EA and GA conducted the experiment, statistical analysis, and interpretation of field data. IY performed economic analysis for the treatments and wrote that section of the manuscript. JAN, EA, FK, LKA, IY and BKB wrote the manuscript. All authors read and approved the final manuscript.

Availability of data and materials
The authors are willing to share all data and additional information on materials used in this study upon a written request to the corresponding author.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no conflict of interests.

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