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RESEARCH

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Effects of insecticides and cultivars on panicle-feeding insect pest infestations and grain yield of sorghum (*Sorghum bicolor* (L.) Moench) in northern Ghana

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Abstract

Background: Panicle-feeding insects are a challenge in sorghum (*Sorghum bicolor* (L.) Moench) cultivation but most farmers do not protect the crop. Here, the effects of pest management in different sorghum cultivars on grain yields and the financial returns after protecting the crop from panicle-feeding insects was studied.

Results: There were significant insecticide treatments × cultivars/genotypes interaction effects for *Stenodiplosis sorghicola, Clavigralla tomentosicollis, Nezara viridula, Dysdercus fasciantus* and *Riptortus dentipes*. Generally, pest infestations were higher in the untreated control compared to K-Optimal- or NSO-treated sorghum. Infestations were also higher in compact-headed cultivars (Dorado and Kapaala) compared to those with open heads (CSSOR 08-V01 and CSSOR 10-V07). Damage was approximately 1.7-fold higher in the untreated controls than in NSO or K-Optimal. Grain yields were about 14% higher in NSO or K-Optimal treated sorghum than in controls. Gross margins were between 16- and 35-fold higher in protected sorghum compared to the untreated ones.

Conclusion: These findings suggest that an effective integrated pest management strategy for sorghum farmers must comprise cultivars that do not have compact heads, and the use of about two sprays of NSO or a synthetic pyrethroid when high numbers of panicle-feeding insects are observed during the growing season. Judicious use of insecticides and the "right" cultivar will improve the profitability of sorghum farmers with gross marginal returns that are at least 15-fold higher than that obtained by farmers who adopt only good agronomic practices without insecticide sprays.

Keywords: Cultivars, Damage, Grain yields, Insecticides, Insect pests, Marginal returns

Background

Sorghum (*Sorghum bicolor* (L.) Moench) is a tropical cereal grass cultivated across the world in areas with warmer climate. It is an important food grain for many of the most food insecure people in the world (Mundia et al. 2019; Taylor 2003). The crop is mainly consumed as grain but can also be prepared into food products such as porridges, breads, lactic and alcoholic beverages, and weaning meals. Globally, sorghum is the fifth largest most important cereal grain, after wheat, maize, rice, and barley (Adebayo and Omodele 2015; Anglani 1998). On continental basis, Africa (41%) is the largest producer of sorghum in the world followed by the Americas (38%) (Mundia et al. 2019). In Africa, sorghum is the third most cultivated cereal with Nigeria (33.8%), Sudan (21.4%), Ethiopia (7.3%) and Burkina Faso (6.6%) accounting for

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almost 70% of total production. This cereal is adapted to arid regions on the continent that are mostly characterized by harsh weather conditions. Sorghum can tolerate extreme conditions such as drought, salinity and high temperatures (Taylor 2003; Anglani 1998). Generally, sorghum cultivation in Africa is largely at a subsistence level. This notwithstanding, it is increasingly becoming the foundation of successful food and beverage industries (Taylor 2003).

In Africa, sorghum grain yields are generally lower (< 1 t/ha) than its potential (> 3.5 t/ha) (Taylor 2003). Poor field and crop management practices (i.e., lack of or minimal use of improved seeds and other inputs) as well as abiotic stresses (i.e., drought, high soil salinity) are major contributors to the low yields on farmers' fields (Adebayo and Omodele 2015; Taylor 2003). Another major challenge is biotic stresses such as parasitic weeds (e.g., striga), birds and infestation of panicle-feeding insect pests (Kiple 2000). Of about 150 insect pest species associated with sorghum worldwide (Harris 1995), over 100 of them occur in Africa. In West, Central and Southern Africa, over 42 insect species are reported to be serious pests that infest and feed on sorghum panicles (Kruger et al. 2008). Some of the important panicle-feeding insects in Africa are sorghum midge [*Stenodiplosis sorghicola* (Coquillett)), earhead bugs (*Calidea dregii* Germar, *Campylomma angustior* (Poppius), *Creontiades pallidus* Ramb, *Eurystylus bellevoyei* Reut., *E. rufocunealis* (Poppius), *Nezara viridula* (L.), *Dysdercus superstitiosus* (F.), *D. volkeri* (Stal.)], earhead beetles (*Cylindrothorax westermanni* Makl., *Psalidolytta fusca*, *P. theresae* Pic, and *Mylabris* spp.), Cetoniid beetles (*Rhabdotis sobrina* Sory and Perch, *Pachnoda cordata* (Drury), *P. interrupta* (Olivier), and *Pseudoprotaeta burmeisteri* Arr.) and earhead caterpillars [*Eublemma brachygonia* Hmps, *E. gayneri* Roths., *Heliothis armigera* Hbn., *Pyroderces hemizopa* (Meyr.), *P. risbeci* (Ghesq.), *P. simplex* (Wism.), *P. tripola* (Meyr.)] (Reddy 1991). Although sorghum is attacked by many different insect pests in Africa, data on yield loss caused by pest are scarce and difficult to obtain (Sharma and Nwanze 1997; Reddy 1988). However, in India, it is estimated that nearly 32% of sorghum crop is lost due to insect pest infestation. Also, up to 84% of this loss are due to panicle-feeding insect pest (Sharma and Nwanze 1997; Leuschner and Sharma 1983).

Mitigating pest damage in sorghum requires greater agricultural inputs, such as insecticides or improved seed cultivars (Mundia et al. 2019). The commonest strategy for managing sorghum insect pests is through breeding insect resistant cultivars. Several quantitative trait loci (QTLs) for insect resistant breeding programmes have been identified and this has led to the availability of cultivars that are resistant to many of the economically important insect pest infesting the crop (Guo et al. 2011; Sharma et al. 2005). Insecticides such as Dimethoate 30 EC at 0.03% and Imidacloprid 17.8 SC at 0.09% have also been found to be among the most effective ones for reducing pest infestations and damage. Crop rotation is another common practice that effectively reduces the build-up of sorghum insects in the same field (Guo et al. 2011; Chilcutt and Matocha 2007). Intercropping sorghum with pigeon pea (red gram, *Cajanus cajan*) or soybean (*Glycine max*) is reported to significantly reduce stem borer (*Chilo partellus* Swinhoe) infestation and increase sorghum yields (Spurthi et al. 2009).

Currently, most smallholder farmers in Ghana and other Sub-Saharan African (SSA) countries do not protect their sorghum from insect pest damages. This negatively affects grain yield and viability of farmer-saved seeds. Hence, this study sought to assess the infestation levels of panicle-feeding insect pest in different sorghum cultivars and the effect of investments in their management on grain yield and profits. The hypotheses tested were: (1) panicle-feeding insect pests infestation levels do not differ among sorghum cultivars; (2) different sorghum cultivars respond in a similar manner to protection from panicle-feeding insects; (3) grain yield of sorghum cultivars protected from panicle-feeding insect pests is the same as that from unprotected ones; (4) grain yield of sorghum protected with synthetic insecticide is not different from those protected with a botanical pesticide; (5) the marginal returns from investing in protecting sorghum from panicle-feeding insects is the same as that from an unprotected sorghum crop.

Methods

Experimental site

Field experiments were conducted on the research farm of CSIR – Savanna Agricultural Research Institute (SARI) at Tanina (N 9°53′4.14″, W 2°27′42.72″, 345 m a.s.l.) in the Wa West District of the Upper West Region during the 2017 and 2018 cropping seasons. The experimental site is within the Guinea Savanna zone which is characterized by grassland vegetation interspersed with few trees. The soils of the experimental fields are generally of sandy loam texture with a pH of 4.5–5.5 and organic matter content of 0.89–0.99%. This ecological zone has a unimodal rainfall pattern that falls from May to October of each year followed by a long dry period from November to April (Neumann et al. 2007). Measurements of weather elements during both study seasons were obtained from the Meteorology Unit, CSIR–SARI, Wa in both years. The mean total monthly rainfall, temperature and relative humidity were 116.2 mm, 27.5 °C and 77.7%, respectively, for the 2017 cropping season. In 2018, the mean total

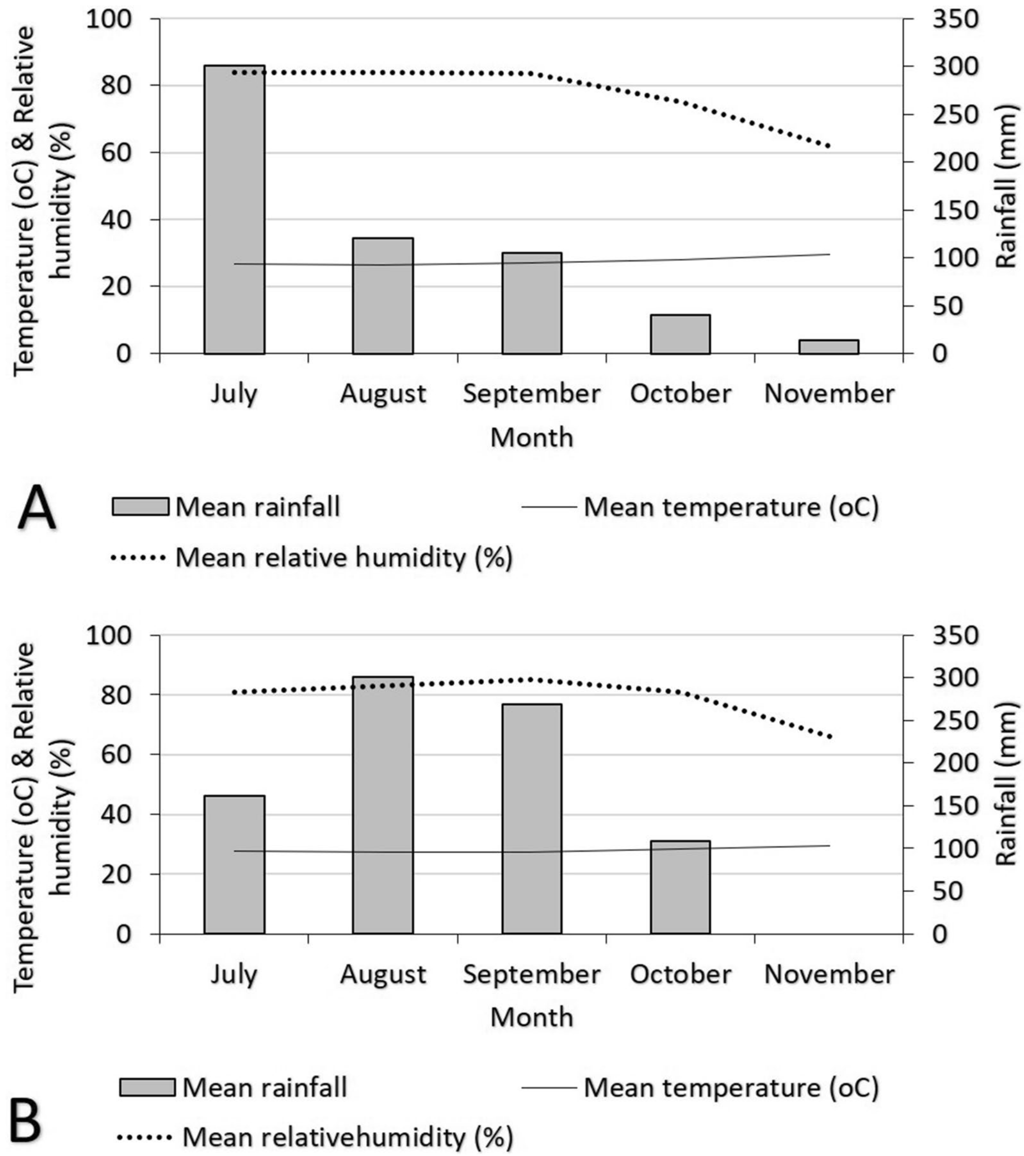

Fig. 1 Mean total monthly rainfall (mm), temperature (°C) and relative humidity (%) recorded at the study site in the 2017 (**A**) and 2018 (**B**) cropping seasons

monthly rainfall, temperature and relative humidity were 168.0 mm, 28.1 °C, 79.2%, respectively (Fig. 1).

Plant materials and land preparation

Seeds of two sorghum genotypes (CSSOR08 V01, CSSOR10 V07) and two commercial cultivars (Kapaala and Dorado) were obtained from the Sorghum Improvement Programme of CSIR—SARI. The genotype, CSSOR 08-V01, is a cross between ICSV 16A and Kapaala. The number of days to physiological maturity for this genotype is 90–95. The grains are mottled red in colour and the head is not compact. However, the genotype, CSSOR 10-V07, is a cross between Grinkan and A12T9. It is photoperiod sensitive, non-compact head with white-coloured grains.

The two commercial cultivars, Kapaala and Dorado, have physiological maturity periods of 100–105 days and 100–110 days, respectively. Both varieties have compact heads and white-coloured grains with high brewery quality. Dorado has an additional quality of being a short cultivar and is suitable for mechanized farming (GVRC 2019). The trial field was disc-ploughed followed by harrowing before planting.

Experimental design and treatments

A 3 × 4 factorial study laid in split-plots design with four replications was used. Insecticide treatments were on the main plots while cultivars/genotypes were on the sub-plots. The insecticide treatments tested were untreated control, neem seed oil (NSO, 3% Azadirachtin) and K-optimal (15 g/l Lambda-cyhalothrin + 20 g/l Acetamiprid) while cultivars/genotypes were CSSOR 08-V01, CSSOR 10-V07, Dorado and Kapaala. The main plots were separated by 3 m alleys to minimize insecticide drift during spray applications. In contrast, the sub-plot treatments consisted of six rows of each cultivar planted on plots of 5 m length (i.e., plot size of 4.5 m × 5 m). The inter- and intra-row spacings in these sub-plots were 0.75 m and 0.40 m, respectively. The sub-plots were separated by 2 m alleys.

Blocks were separated by 3 m unplanted alleys. The application of main plot treatments commenced during the heading stage when pest numbers reached a threshold of 10 insects/head. Two insecticide applications were done at 3-week interval before harvest. The NSO was applied at a rate of 3% v/v a.i. ha^{-1} while K-Optimal was applied at 1 l a.i. ha^{-1}. Spray applications were done using a 15-l capacity knapsack sprayer.

The compound fertilizer NPK (23-10-10) was applied at 2 weeks after emergence at a rate of 250 kg ha^{-1} and this was followed by top dressing with urea at 125 kg ha^{-1} 5 weeks after emergence. The pre-emergence herbicide, Pendimethalin (Stomp 440 Herbicide, BASF Corp., Victoria, Australia), was applied immediately after planting at 1.0 kg a.i. ha^{-1}. This was followed by hand weeding of fields at 3 and 6 weeks after planting or before canopy closure.

Sampling

Data were collected on the abundance of panicle-feeding insect pest, their damage to sorghum heads and grain yield. Data collection commenced from the booting stage. Insect pest infestations were recorded at approximately 2 weeks intervals on 10 randomly selected plants from the 4 inner rows. In all, the fields were sampled thrice before maturity in both seasons.

At maturity, the sorghum heads from the 4 inner rows were used to score for the proportion of insect damage ones. This was undertaken by randomly selecting 20 heads, sorting the damaged from the undamaged ones and then computing the proportion of damaged heads. Damaged heads were those that had shriveled and punctured/damaged grains due to insect feeding and were sometimes mouldy in appearance.

Grain yield was determined by threshing all the heads from the four inner rows, winnowing to remove debris, and then recording the dry weight at 12% moisture content. These were then converted to grain yield on per ha basis.

Data analysis

Data on panicle-feeding insect pest infestations for each year were subjected to repeated measures analysis of variance (ANOVA) in GenStat® statistical programme (12th edition). This was because the variances of the data from the fortnightly pest assessments could not be independent. The treatment structure for this analysis was Insecticide treatments × Cultivar/Genotype and Blocking structure was the replications. Prior to undertaking these analyses, the data were subjected to Box's tests for symmetry of their covariance matrix and whenever the data lacked sphericity, they were adjusted using the Greenhouse–Geisser epsilon estimate. Means that were significant were separated at the 5% probability level using their least significant differences (LSD).

Data on damage and yield for each year were subjected to ANOVA using the split-plot design. In these analyses, the insecticide treatments were the main-plot factor and cultivars/genotypes were the sub-plots factor. Replications was the blocking factor. Afterwards, the means of data from the two seasons were subjected to a combined ANOVA with year as the blocking factor. Whenever year effect was significant, the results for each year were presented separately. Means that were significant at 5% probability level were separated using Fisher's protected LSD.

Assessment of gross margin

To measure the monetary returns from the treatments tested, gross margins were computed for each treatment. The gross margin measures the gross income to the farmer per treatment and per hectare. It is a function of the total variable cost per hectare (TVC_p) and total revenue per hectare (TR_p). The gross margin per hectare is expressed as follows;

$$GM_t = f\left(TR_p, TVC_p\right) = f\left[\left(Q_{output}, P_{output}\right), \left(q_{inp}, p_{inp}\right)\right]$$

where GM_t is the gross margin [Ghana cedi (GHC)] per treatment per hectare. TVC_t is the total variable cost [Ghana cedi (GHC)] of production per treatment per hectare. TR_t is the total revenue [Ghana cedi (GHC)] per treatment per hectare. Q_{output} represents the total quantity of sorghum kg per treatment per hectare. P_{output} represents the price [Ghana cedi (GHC)] per kilogram. q_{inp} represents the quantities of input used per treatment per hectare. p_{inp} represents the price [Ghana cedi (GHC)] per unit of the inputs per treatment per hectare.

Returns to protection of sorghum was also calculated based on the gross margin per hectare divided by the cost of insecticides and cost of application as in the equation below;

$$\text{Returns to protection} = GM_t / [\text{Cost}_t(\text{insecticide}) + \text{Cost}_t(\text{insecticide application})].$$

Results

Insect pest abundance

Insect pest recorded over the two seasons comprised *Stenodiplosis sorghicola, Clavigralla tomentosicollis* Ställion*, Dysdercus fasciantus* Signoret*, Nezara viridula, Riptortus dentipes* (Fabricius)*, Pachnoda interrupta, Anoplocnemis curvipes* (Fabricius) and *Poophilus costalis* Walker*.* The number of *P. costalis* recorded in the two seasons were very low; data on this pest were therefore not subjected to statistical analysis.

Pest infestations in 2017 cropping season

The results showed significant Insecticide treatments ($F_{2,33}=239.99$; $p<0.001$), Cultivars/Genotypes ($F_{3,33}=15.08$; $p<0.001$) and Insecticide × Cultivars/Genotypes ($F_{6,33}=6.21$; $p<0.001$) interaction effects for the abundance of *S. sorghicola*. Date of sampling also had a significant effect on the abundance of this insect ($F_{2,72}=11.35$; $p=0.002$). The genotype, CSSOR 10-V07, sprayed with K-Optimal recorded the lowest infestation by this pest while untreated Kapaala was highest. There were no significant differences among cultivars/genotypes sprayed with K-Optimal, in terms of *S. sorghicola* infestation*.* In contrast, infestation levels in CSSOR 08-V01 and CSSOR 10-V07 were significantly lower than that in Dorado and Kapaala in the untreated control plots. Among cultivars/genotypes protected with NSO, infestations in CSSOR 08-V01 and CSSOR 10-V07 were lower than that in Kapaala. There were no differences between infestations in the latter and Dorado (Fig. 2a). The numbers of this pest decreased significantly over time after the first sampling (Table 1).

The abundance of *C. tomentosicollis* was significantly affected by Insecticide treatments ($F_{2,33}=67.30$; $p<0.001$), Cultivar/Genotypes ($F_{3,33}=10.92$; $p<0.001$) and Insecticide treatments × Cultivar/Genotypes interaction ($F_{6,33}=5.09$; $p=0.002$). Date of sampling also had a significant effect on this variable ($F_{2,72}=9.41$; $p=0.002$).

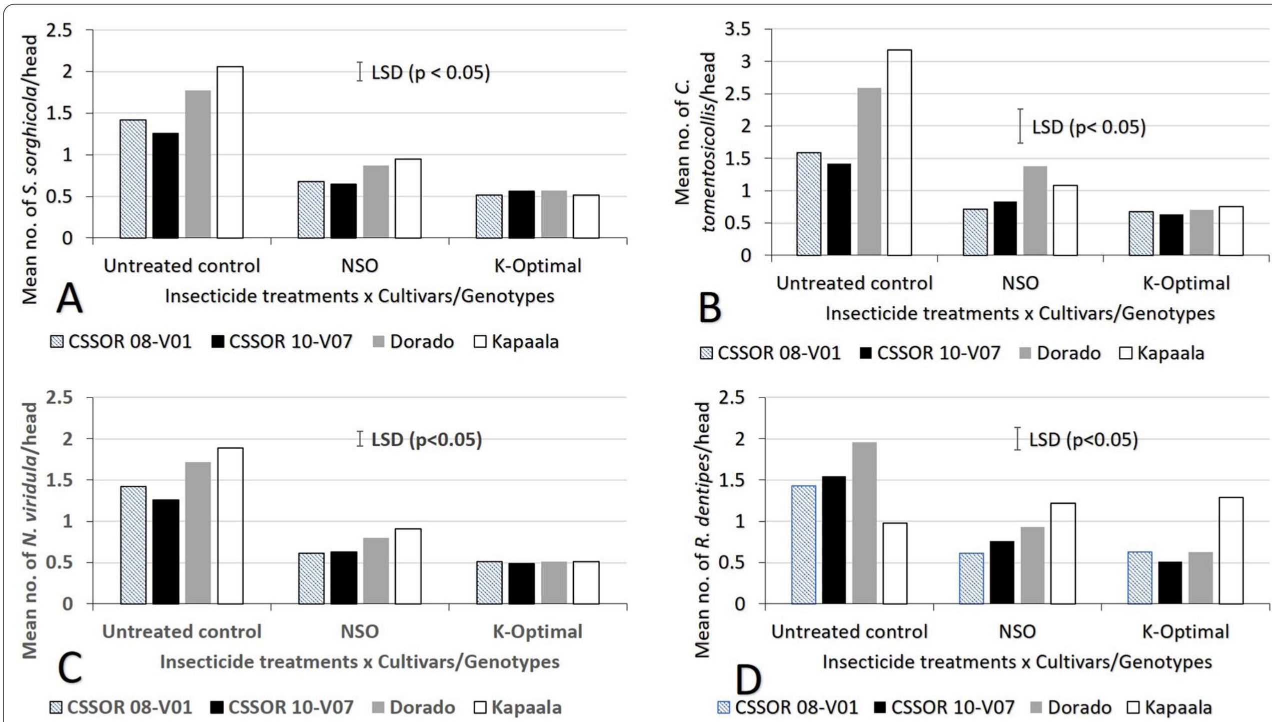

Fig. 2 Insecticide treatments × Cultivars/Genotypes interaction effect on the mean number of **A** *Stenodiplosis sorghicola,* **B** *Clavigralla tomentosicollis,* **C** *Nezara viridula* and **D** *Riptortus dentipes* in the 2017 cropping season. Note: NSO = Neem seed oil; LSD ($p<0.05$) = Least significant difference at 5% probability threshold

Table 1 Panicle-feeding insect pest mean infestations on sorghum heads at different dates of sampling in the 2017 cropping season

Date of sampling	*Stenodiplosis sorghicola*/head	*Clavigralla tomentosicollis*/head	*Dysdercus fasciantus*/head	*Nezara viridula*/head	*Riptortus dentipes*/head
27/09/2017	1.15	0.88	1.29	0.90	0.88
09/10/2017	0.93	1.71	3.52	1.03	1.41
25/10/2017	0.88	1.23	6.42	0.88	1.10
p value	0.002	0.002	< 0.001	0.026	0.042
LSD ($p < 0.05$)	0.14	0.42	1.31	0.12	0.22

LSD = least significant difference at 5% probability threshold

Table 2 Effect of Insecticide treatments and sorghum Genotypes/Cultivars on *Dysdercus fasciantus* infestations/head in 2017 cropping season

Variable	*Dysdercus fasciantus*/head
Insecticide treatments	
NSO	4.14
K Optimal	2.44
p value	< 0.001
LSD ($p < 0.05$)	0.88
Genotypes/cultivars	
CSSOR 08-V01	2.75
CSSOR 10-V07	4.51
Dorado	4.42
Kapaala	3.30
p value	0.003
LSD ($p < 0.05$)	1.01

LSD = least significant difference at 5% probability threshold

In general, there were no significant differences in *C. tomentosicollis* infestations among cultivars/genotypes sprayed with K-Optimal; infestations in this treatment were low. In contrast, infestations were significantly high in all cultivars/genotypes in the untreated control; however, the genotypes, CSSOR 08-V01 and CSSOR 10-V07, had significantly lower infestations than the cultivars, Dorado and Kapaala in that treatment. Except Dorado, infestation by this insect were not significantly different among the cultivars/genotypes sprayed with NSO or K-Optimal (Fig. 2b). The numbers of this insect declined after the second sampling (Table 1).

For *D. fasciantus*, its abundance was significantly affected by Insecticide treatments ($F_{2,33} = 14.88$; $p < 0.001$) and Cultivar/Genotypes ($F_{3,33} = 6.21$; $p = 0.003$), but there were no significant Insecticide treatments × Cultivar/Genotypes interactions ($p > 0.05$). Date of sampling had significant effect on this pest ($F_{2,72} = 38.08$; $p < 0.001$). Among the insecticide treatments, sorghum protected with K-Optimal had the lowest *D. fasciantus* infestation while those in the untreated control were highest. The genotype, CSSOR 08-V01, recorded the lowest infestation while Dorado was highest (Table 2). The abundance of this pest generally increased with time (Table 1).

Infestation by *N. viridula* was significantly affected by Insecticide treatments ($F_{2,33} = 319.44$; $p < 0.001$), Cultivar/Genotypes ($F_{3,33} = 15.07$; $p < 0.001$), and Insecticide treatments × Cultivar/Genotypes interactions ($F_{6,33} = 4.98$; $p = 0.002$). There was a significant Date of sampling effect for the abundance of this pest ($F_{2,72} = 5.30$; $p = 0.026$). Again, there were no significant differences among the different cultivars/genotypes sprayed with K-Optimal and infestations by this pest was lowest in this treatment. The highest infestations were in the untreated control with numbers in CSSOR 08-V01 and CSSOR 10-V07 being lower while that in Dorado and Kapaala were higher. Similarly, infestations in CSSOR 08-V01 and CSSOR 10-V07 were lower in NSO sprayed plots while Dorado and Kapaala had higher infestations (Fig. 2c). The abundance of this insect decreased after the second sampling (Table 1).

For *R. dentipes*, its abundance was significantly affected by Insecticide treatments ($F_{2,33} = 185.76$; $p < 0.001$), Cultivars/Genotypes ($F_{3,33} = 7.32$; $p = 0.001$), Insecticide treatments × Cultivars/Genotypes ($F_{6,33} = 4.01$; $p = 0.007$) and Dates of sampling ($F_{2,72} = 4.21$; $p = 0.042$). The genotype, CSSOR 10-V01, sprayed with K-Optimal had the lowest infestation while untreated Dorado was highest. Except Kapaala, the numbers of this pest were lower in CSSOR 08-V01, CSSOR 10-V07 and Dorado sprayed with K-Optimal. Infestations by this pest were high in all cultivars/genotypes in the untreated control, apart from Kapaala. In NSO sprayed plots, *R. dentipes* infestations were lower in the genotypes than in the released Cultivars (Fig. 2d). After the second sampling, infestations of this insect declined (Table 1).

Infestations of *P. interrupta* and *A. curvipes* were not significantly affected by Insecticide treatments ($p > 0.05$), Cultivar/Genotypes ($p > 0.05$) or their interactions

($p>0.05$). The mean numbers of these pests were 1.36/head and 1.22/head for *P. interupta* and *A. curvipes*, respectively.

Pest infestations in 2018 cropping season

Infestations of *S. sorghicola* was significantly affected by Insecticide treatments ($F_{2,33}=521.61$; $p<0.001$), Cultivar/Genotypes ($F_{3,33}=4.59$; $p=0.009$), Insecticide treatments × Cultivar/Genotypes ($F_{6,33}=7.34$; $p<0.001$) as well as Dates of sampling ($F_{2,72}=4.15$; $p=0.025$). Infestations by this pest were low in all cultivars/genotypes protected with K-Optimal or NSO but high in the untreated control. There were no significant differences between infestation level of this pest in cultivars/genotypes protected with NSO and K-Optimal. Among the cultivars or genotypes in the untreated control, infestations were lower in CSSOR 08-V01 and CSSOR 10-V07 but higher in Dorado and Kapaala (Fig. 3a). Infestations of this insect declined after the second sampling (Table 3).

The infestations of *C. tomentosicollis* was significantly affected by Insecticide treatments ($F_{2,33}=7.19$; $p=0.003$) only, with no Cultivars/Genotypes ($p>0.05$)

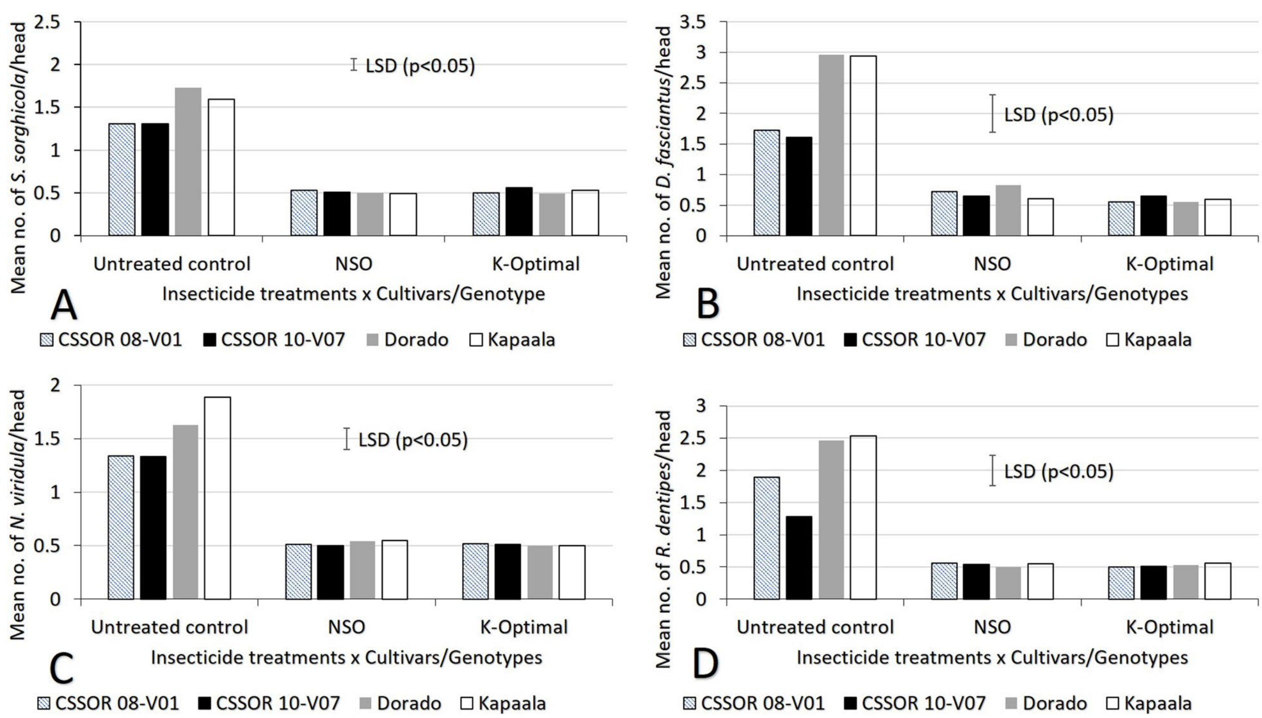

Fig. 3 Insecticide treatments × Cultivars/Genotypes interaction effect on the mean number of **A** *Stenodiplosis sorghicola*, **B** *Dysdercus fasciantus*, **C** *Nezara viridula* and **D** *Riptortus dentipes* in the 2018 cropping season. *Note* NSO = Neem seed oil; LSD ($p<0.05$) = Least significant difference at 5% probability threshold

Table 3 Panicle-feeding insect pest mean infestations on sorghum head at different dates of sampling in the 2018 cropping season

Date of sampling	*Clavigralla tomentosicollis*/head	*Dysdercus fasciantus*/head	*Stenodiplosis sorghicola*/head	*Nezara viridula*/head	*Riptortus dentipes*/head	*Pachnoda interrupta*/head
04/10/2018	1.23	0.87	0.87	0.81	0.92	1.07
17/10/2018	1.29	1.43	0.85	0.95	0.89	1.42
30/10/2018	2.88	1.29	0.80	0.81	1.29	1.03
p value	< 0.001	0.022	0.025	0.032	0.003	< 0.001
LSD ($p<0.05$)	0.44	0.40	0.05	0.12	0.23	0.12

LSD = least significant difference at 5% probability threshold

Table 4 Effect of Insecticide treatments on mean infestations of *Clavigralla tomentosicollis* and *Pachnoda interrupta* in 2018 season

Insecticide treatments	*Clavigralla tomentosicollis*/head	*Pachnoda interrupta*/head
Untreated control	2.17	1.55
NSO	1.86	1.03
K-Optimal	1.38	0.95
p value	0.003	< 0.001
LSD ($p<0.05$)	0.42	0.24

LSD = least significant difference at 5% probability threshold

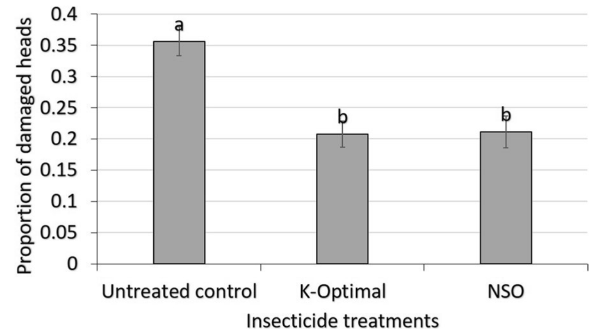

Fig. 4 Mean proportion of sorghum heads damaged by insect pests under different insecticide treatments. Note: Data are means ± standard error of means (S.E.M); NSO = Neem seed oil; Bars with different letters are significantly different at 5% probability threshold

or Insecticide treatments × Cultivars/Genotypes interactions ($p>0.05$). There was a significant date of sampling effect ($F_{2,72}=45.74$; $p<0.001$). Among the insecticide treatments, sorghum sprayed with K-Optimal had the lowest infestations while the untreated control was highest (Table 4). The abundance of this pest increased over time (Table 3).

For *D. fasciantus*, its infestations were significantly affected by Insecticide treatments ($F_{2,33}=73.26$; $p<0.001$), Cultivars/Genotypes ($F_{3,33}=4.07$; $p=0.014$), Insecticide treatments × Cultivars/Genotypes interactions ($F_{6,33}=4.12$; $p=0.003$) and Dates of sampling ($F_{2,72}=5.85$; $p=0.022$). Infestation by this insect was lowest in CSSOR 08-V01 sprayed with K-Optimal but highest in untreated Dorado. Generally, the numbers of this pests were low in all cultivars/genotypes sprayed with NSO or K-Optimal but high in those in the untreated control. Among the untreated control, CSSOR 08-V01 and CSSOR 10-V07 had lower infestations while Dorado and Kapaala were higher. (Fig. 3b). There was a decline in infestations of this pest after the second sampling (Table 3).

There were significant Insecticide treatments ($F_{2,33}=296.66$; $p<0.001$), Cultivars/Genotypes ($F_{3,33}=5.46$; $p=0.004$), Insecticide treatments × Cultivars/Genotypes interactions ($F_{6,33}=4.88$; $p=0.001$) and Dates of sampling ($F_{2,72}=4.83$; $p=0.032$) effects for infestations of *N. viridula*. Here, infestations by this stink bug were lowest in Dorado or Kapaala sprayed with K-Optimal or NSO, respectively, and highest in untreated Kapaala. There were generally no significant differences in infestations among cultivars or genotypes sprayed with NSO or K-Optimal. For cultivars or genotypes in the untreated control, CSSOR 08-V01 and CSSOR 10-V07 had lower infestations than Dorado and Kapaala (Fig. 3c). The numbers of this pest declined significantly after the second sampling (Table 3).

There were significant Insecticide treatments ($F_{2,33}=111.68$; $p<0.001$), Cultivars/Genotypes ($F_{3,33}=4.32$; $p=0.011$), Insecticide treatments × Cultivars/Genotypes interaction ($F_{6,33}=4.05$; $p=0.004$) and dates of sampling ($F_{2,72}=9.98$; $p=0.003$) for *R. dentipes*. Spraying CSSOR 08-V01 with K-Optimal resulted in the lowest infestations while untreated Kapaala was highest. There were no significant differences among the cultivars/genotypes in their infestation levels when they were treated with NSO or K-Optimal. However, infestations were significantly lower in CSSOR 08-V01 and CSSOR 10-V01 in the untreated control plots (Fig. 3d). The numbers of this insect decreased after the first sampling but increased by the third sampling date (Table 3).

The abundance of *A. curvipes* was not significant for Insecticide treatments, Cultivars/Genotypes, Insecticide treatments × Cultivars/Genotypes and Dates of sampling. The mean numbers of this pest were 1.28/head. In contrast, infestations of *P. interrupta* were significantly affected by Insecticide treatments ($F_{2,33}=15.78$; $p<0.01$) and dates of sampling ($F_{2,72}=29.22$; $p<0.001$) only. Among insecticide treatments tested, infestation was lowest in K-Optimal and highest in untreated control (Table 4). The numbers of this pest increased after the first sampling date but declined afterwards (Table 3).

Head damage and grain yield

The proportion of insect damaged heads was not significantly affected by year ($F_{1,11}=1.13$; $p=0.310$) when the two season's data were combined and analyzed. However, it was significantly affected by insecticide treatments only ($F_{2,11}=4.34$; $p=0.041$). The untreated control recorded the highest proportion of damaged heads while plots sprayed with K-Optimal were lowest. Damage levels in

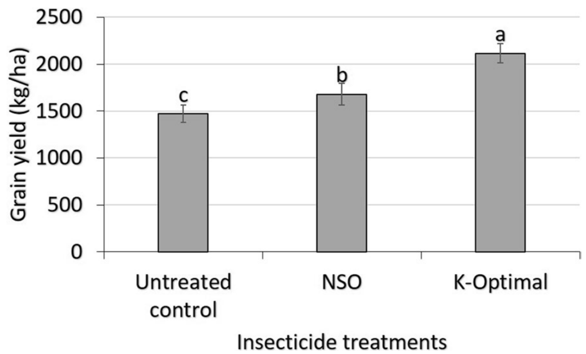

Fig. 5 Effect of insecticide treatments on grain yield of sorghum (kg/ha) in the 2017 cropping season. Data are means ± standard error of means (S.E.M.). NSO = Neem seed oil; Bars with different letters are significantly different at 5% probability threshold

NSO treated sorghum were not different from those sprayed with K-Optimal (Fig. 4).

Grain yield was significantly affected by year ($F_{1,11} = 8.88$; $p = 0.013$). Yield in the 2018 season (2145 kg/ha) was higher than that in 2017 (1755 kg/ha). In 2017, yield was significantly affected by insecticide treatments ($F_{3,27} = 4.44$; $p = 0.009$) only. Mean yields in sorghum protected with K-Optimal was highest while those in the untreated control were lowest. The yield in K-Optimal treated sorghum was 44% higher than that in the untreated control, while for NSO, yield was 14% higher than that in the untreated control (Fig. 5).

In 2018, yield was significantly affected by insecticide treatment ($F_{2,27} = 146.74$; $p < 0.001$) and cultivars/genotypes ($F_{3,27} = 4.79$; $p = 0.008$); there were no significant interactions effect in that year. Among the insecticide treatments, mean yield was highest in K-Optimal protected sorghum and lowest in the untreated control. Generally, spraying sorghum with K-Optimal resulted in almost 92% yield increment over the untreated control. Also, the use of NSO resulted in approximately 75% yield increment over the untreated control (Fig. 6a). Among the cultivars, Kapaala had the highest yield while CSSOR 10-V07 was lowest (Fig. 6b).

Partial budget measures (returns to sorghum protection)

The gross margins for CSSOR 08-V01, CSSOR 10-V07 and Dorado cultivated without protection from insect pests (i.e., untreated control) were positive. In contrast, Kapaala cultivated without insecticide treatment had a negative gross margin. The returns on investment in pest management when the genotype, CSSOR 08-V01, was protected from insect pests using K-Optimal or NSO were 32- and 33-folds, respectively, compared to the untreated controls. Similarly, the returns on investing in sorghum protection in CSSOR 10-V07 was 35- and 16-fold higher compared to the untreated control for K-Optimal and NSO treatments, respectively. Investing in insect pest management for the cultivars, Dorado and Kapaala, resulted in 31- and 33-fold returns, respectively, over the untreated control. Using NSO to protect Dorado or Kapaala also resulted in 26- and 31-fold higher returns on protection of sorghum, respectively (Table 5).

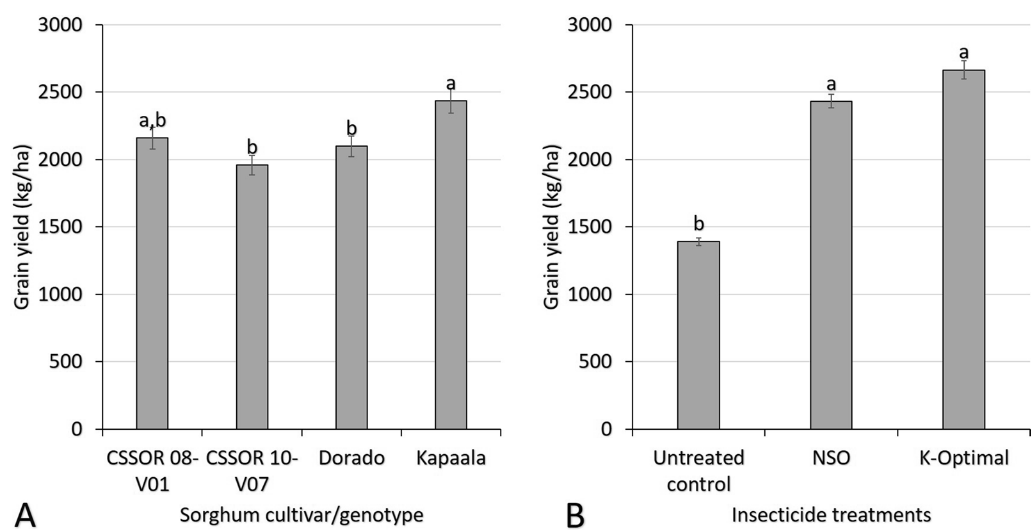

Fig. 6 Effect of insecticide treatments (**A**) and cultivars/genotypes (**B**) on grain yield (kg/ha) of sorghum in 2018 cropping season. Data are means ± standard error of means (S.E.M.). NSO = Neem seed oil; Bars with different letters are significantly different at 5% probability level

Table 5 Gross margins from investing in protecting sorghum from panicle-feeding insect in the savanna zone of Ghana

Cultivar	CSSOR 08-V01			CSSOR 10-V07			Dorado			Kapaala		
Treatment	**Control**	**K-Optimal**	**NSO**	**Control**	**K-Optimal**	**NSO**	**Control**	**K-Optimal**	**NSO**	**Control**	**K-Optimal**	**NSO**
Revenue items												
Grain yield (kg/ha)	2004.02	2275.46	2398.49	1537.4	1902.62	1445.71	1339.33	2289.83	2127.78	146.95	2367.67	2252.38
Gross revenue (GHC/ha)	3967.96	4505.41	4749.01	3044.05	3767.19	2862.51	2651.87	4533.86	4213.00	290.96	4687.99	4459.71
Cost items												
Land preparation cost (GHC/ha)	100	100	100	100	100	100	100	100	100	100	100	100
Cost of seed (GHS/ha)	72	72	72	72	72	72	72	72	72	72	72	72
Labour cost for planting (GHC/ha)	120	120	120	120	120	120	120	120	120	120	120	120
Cost of herbicides (GHS/ha)	60	60	60	60	60	60	60	60	60	60	60	60
Labour cost for herbicides (GHC/ha)	50	50	50	50	50	50	50	50	50	50	50	50
Cost of fertilizer (NPK) (GHC/ha)	210	210	210	210	210	210	210	210	210	210	210	210
Cost of fertilizer (UREA) (GHC/ha)	200	200	200	200	200	200	200	200	200	200	200	200
Labour for fertilizer app. (GHC/ha)	120	120	120	120	120	120	120	120	120	120	120	120
Cost of insecticide (GHC/L/ha)	0	30	32	0	30	32	0	30	32	0	30	32
Cost of labour (GHC/ha)	0	75	75	0	75	75	0	75	75	0	75	75
Labour for harvesting (GHC/ha)	150	150	150	150	150	150	150	150	150	150	150	150
Total cost (GHC/ha)	1082	1187	1189	1082	1187	1189	1082	1187	1189	1082	1187	1189
Gross margin (GHC/ha)	2885.96	3318.41	3560.01	1962.05	2580.19	1673.51	1569.87	3346.86	3024.00	-791.04	3500.99	3270.71
Benefit cost ratio	2.67	2.80	2.99	1.81	2.17	1.41	1.45	2.82	2.54	0.73	2.95	2.75
Returns to insect control	NA	31.60	33.27	NA	24.57	15.64	NA	31.28	28.26	NA	33.34	30.57

NSO Neemseed oil

Discussion

In general, different locations and environments vary in the species of key pests of sorghum present. However, one or a few key insects such as *S. sorghicola*, *Atherigona soccata* Rondani and *Schizaphis graminum* (Rondani) may occur perennially and dominate the pest control practices depending on the sorghum agro-ecology (Huang et al. 2013). Additionally, head bugs (e.g., *Calocoris angustatus* and *Eurystylus oldi* etc.) are usually present and co-dominate in infesting sorghum heads (Aheto et al. 2017). In this study, *S. sorghicola, C. tomentosicollis, D. fasciantus, N. viridula, R. dentipes, P. interrupta, P. costalis* and *A. curvipes* were identified as major insect pests of sorghum that required control in the interior dry savannah regions of northern Ghana.

In sorghum cultivation, the flowering stage is the most critical period for managing insect pests' damages (Guo et al. 2011). Effective pest control is attained when insecticides with active ingredients such as Chlorantraniliprole, Flupyradifurone, Spinosad, Esfenvalerate and pyrethroids (especially Deltametrin) are applied as dusts, granules or sprays (Malgwi and Dunuwel 2011; Okosun et al. 2021). In this study, spraying sorghum plants with K-Optimal resulted in low numbers of all panicle-feeding insect pests. The Lambda-cyhalothrin in K-Optimal is a pyrethroid which kills by penetrating the insect's cuticle and disrupting nerve conduction within minutes; this leads to cessation of feeding, loss of muscular control, paralysis, and eventual death. This ingredient also protects the crop through its strong repellent effect toward insects (He et al. 2008; Burr and Ray, 2004). In contrast, Acetamiprid acts on the central nervous system of insects by quickly knocking them down. Symptoms of intoxication, such as excitation, convulsion, and paralysis followed by death, are typical of acetamiprid-treated insects (Yamada et al. 1999). Hence, the combined action of a contact and systemic active ingredient in K-Optimal contributed to the effective control of insect pests infesting sorghum heads.

Also, panicle-feeding insect pests were effectively controlled when NSO was sprayed on sorghum heads; albeit pest abundance in synthetic insecticide treatments were lower compared to that of NSO treatments. This observation is corroborated by studies which show that neem extracts (i.e., NSO, aqueous neem leaf extract, neem leaf powder, aqueous neem seed kernel extract, neem seed granules) are effective alternatives to synthetic insecticides in controlling panicle-feeding insect in sorghum and other crops (Anaso 2010; Montes-Molina et al. 2008; Zongo et al. 1993). The most important active ingredient in these extracts is Azadirachtin which has deterrent, anti-ovipositional, antifeedant, growth-disrupting (growth-regulating), fecundity- and fitness-reducing properties on insects (Badii et al. 2008; Schmutterer 1990). Thus, the environmentally benign NSO offers an effective alternative to resource-poor farmers who may not be able to afford synthetic insecticides for pest control since the tree (*Azadirachta indica* A. Juss.) abounds in large numbers in areas with dry ecologies in Africa. Extracts from this tree can therefore be used for pest management in sorghum.

Irrespective of insecticide treatments and cultivars/genotypes used, pest numbers were high during the soft dough stages but decreased as grain filling was completed and the grains began hardening. Probably, the inability of the pest to feed on the hardened or dry grain resulted in their declined abundance over time.

Over the past decades, large-scale screening of sorghum germplasm for resistance to insect pests has resulted in the identification of several lines that are resistant to shoot fly (*A. soccata*), stem borer (*C. partellus*), midge (*S. sorghicola*) and head bugs (*C. angustatus* and *E. oldi*). However, land areas dedicated to the cultivation of insect resistant sorghum cultivars are limited due to overemphasis on grain yield as a criterion for release of cultivars by national crop improvement programmes (Sharma et al. 2005, 1997; Chandrashekar and Satyanarayana 2006). In this work, the abundance of sap-sucking bugs (*C. tomentosicollis, D. fasciantus, N. viridula, R. dentipes,* and *A. curvipes*) on the open-headed genotypes, CSSOR 10-v07 and CSSOR 08-V01, were generally low compared to the compact headed cultivars, Dorado and Kapaala. Studies show that bug infestations are usually higher in compact headed sorghum cultivars or genotypes because the compact nature of their panicles create a relatively stable and humid micro-climate which favours their continued survival and multiplication (Aheto et al., 2017; Sharma et al. 1994; Ratnadass and Ajayi 1995; Kudadjie-Freeman et al. 2008). For *S. sorghicola,* the physical grain structure (e.g., pericarp thickness and composition) of the genotypes studied might have been antagonistic to this pest (Chandrashekar and Satyanarayana 2006), thus, contributing to the observed resistance of those genotypes compared to Dorado and Kapaala. Further work is however, required to elucidate the factors mediating the low infestation of sorghum heads by *S. sorghicola* in the genotypes studied. Also, the low numbers of *P. interrupta* and *P. costalis* in both years makes the relative susceptibility of the genotypes/cultivars used to these pests inconclusive.

Managing panicle-feeding insect pests infestation impacted positively on grain yield by reducing the proportion of damaged heads and increasing yields by up to 92%, depending on the type of insecticide used. Generally, data on the impact of insect pests on sorghum yields are very scarce (Sharma et al. 2005). However, the findings of the current study are higher than the 10–40% yield reductions due to pest attacks reported by Repellin et al. (2001). In Africa, grain yield is a major criterion for release of sorghum cultivars (Sharma et al. 2005); this criterion resulted in the commercial release of Kapaala and Dorado in Ghana (GVRC 2019; Aheto et al. 2017). However, their susceptibility to panicle-feeding insect pests has always resulted in lower yields on farmers' fields (Aheto et al. 2017). In this work, protecting Kapaala from insect pests resulted in higher yields comparable to the genotypes, CSSOR 10-V07 and CSSOR 08-V01, which appeared to be resistant to head bugs and *S. sorghicola*. Hence, a need for sorghum breeding programmes on the African continent to seriously consider selecting for pest resistance since the high yielding cultivars always succumb to pest infestation and damage, consequently affecting yields. Grain yields were lower in 2017 season compared to 2018 and this was probably due to the poor rainfall distribution in the former season which negatively affected grain filling.

Investments in panicle-feeding insect management strategies resulted in 15- to 34-fold returns to farmers compared to the sole adoption of good agronomic practices without protection from pests. These returns are similar or much higher than that recorded for pest control in cereals such as maize (e.g., Babendreier et al. 2020; Nboyine et al. 2020) by researchers that used NSO or synthetic insecticides. This suggests that smallholder resource-poor sorghum farmers in SSA must be encouraged to invest in managing pests associated with the flowering, grain formation and filling stages of sorghum so as to increase their yields and profits. It was interesting to note that farmers who cultivate Kapaala without investing in any form of pest management may end up incurring losses.

Conclusions

In Africa, the emphasis on grain yield as a major factor for the release of sorghum cultivars has resulted in farmers having access to improved but pest-susceptible cultivars that respond positively to investments in pest managements. The findings of this study therefore indicates that an effective integrated pest management strategy for sorghum must comprise non-compact headed cultivars and the use of about two sprays of NSO or a synthetic pyrethroid when high numbers of panicle-feeding insects are observed during the growing season. These will improve the profits of sorghum farmers by resulting in gross marginal returns that are at least 15-fold higher than that obtained by farmers who adopt only good agronomic practices without insecticide sprays.

Abbreviations

NSO: Neem seed oil; CSIR: Council for Scientific and Industrial Research; SARI: Savanna Agricultural Research Institute.

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Authors' contributions

JAN, KO-O, BKB and FK conceived and designed the experiment. JAN, KO-O, AY, 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, KO-O, BKB, IY and FK wrote the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The authors are willing to share all data used in this study upon a written request to the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

The authors declare that they have no competing interests.

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