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Fertilizer-bioinsecticide synergy improves maize resilience to *Spodoptera frugiperda* infestation

Kokou Rodrigue Fiaboe[a,b,c,*], Komi Agboka[a], Agnamto Ossara Agnamba[a,b], Koffi Laurent Teyo[a], Adjo Laurence Amegah[a], Djima Koffi[a], Gbèdéhoué Esaïe Kpadonou[d], Komi Mensah Agboka[c,e], Rehemah Gwokyalya[c], Ken Okwae Fening[b,f], Komi Kouma Mokpokpo Fiaboe[g]

[a] *Ecole Supérieure d'Agronomie (ESA), Université de Lomé, 01 B.P. 1515 Lomé 01, Lomé, Togo*
[b] *African Regional Postgraduate Programme in Insect Science (ARPPIS), University of Ghana, PMB LG 59, Legon, Accra, Ghana*
[c] *International Centre of Insect Physiology and Ecology (icipe), P.O. Box 30772-00100, Nairobi, Kenya*
[d] *Laboratory of Hydraulics and Environmental Modeling (HydroModE Lab), University of Parakou, 03 B.P. 351, Parakou, Benin*
[e] *Pan African University Institute for Basic Science, Technology and Innovation (PAUISTI), Jomo Kenyatta University of Agriculture and Technology (JKUAT), P.O. Box 62000-00200, Nairobi, Kenya*
[f] *Soil and Irrigation Research Centre (SIREC), College of Basic and Applied Sciences, School of Agriculture, University of Ghana, P.O. Box LG 68, Legon, Accra, Ghana*
[g] *International Institute of Tropical Agriculture (IITA), B.P. 2008 (Messa), Nkolbisson, Yaoundé, Cameroon*

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ABSTRACT

Fall armyworm (FAW), *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae), invasion in Africa has threatened food security. Optimization of plant tolerance and post-infestation recovery are among the management tactics that are being promoted for the integrated management of this pest, but these techniques are poorly studied in sub-Saharan Africa. Our study examined the efficacy of enriched compost, split-NPK fertilization, conventional fertilization, and bioinsecticides on FAW infestation rates, maize plant resilience, natural enemy presence, and grain yield. We found that split-NPK fertilization significantly improved maize plant robustness and reduced FAW incidence and leaf damage in a phenology-dependent manner, leading to higher grain yields. A synergistic effect was observed when split-NPK was coupled with bioinsecticides, resulting in increased populations of natural predators, and specifically the egg endoparasitoid, *Telenomus remus* (Nixon) (Hymenoptera: Scelionidae). Multivariate analyses confirmed that factors like split-NPK fertilization, bioinsecticide usage, stem circumference, and overall plant robustness are major determinants of maize grain yield. Our results endorse soil fertility management via split-NPK fertilization as an effective cultural control measure against FAW, providing an alternative to synthetic insecticides. These insights set the stage for future research focused on assessing the economic viability of this integrated approach, exploring the integration of split-NPK with alternative insecticides, evaluating environmental impacts, and examining the underlying resilience mechanisms to FAW, among other avenues.

1. Introduction

In sub-Saharan Africa (SSA), maize *Zea mays* L. is cultivated in almost all eco-zones and constitutes a staple food and a cash crop for millions of smallholder farmers (Badu-Apraku and Fakorede, 2017). Maize provides the major part of the energy required for human and animal nutrition (Ekpa et al., 2018) and its cultivation has been targeted as a priority sector in many SSA countries (Alene et al., 2009; Van Zyl and Nel, 1988). While under intensified maize production in the USA for instance, 11 t/ha are often reached, yet, despite a more than 56% increase in maize yield in SSA between 1980 and 2009 (Alene et al., 2009), maize productivity on the continent remains under 1 t/ha (Alene et al., 2009; Santpoort, 2020). This is partly caused by biotic and abiotic factors, including edaphic parameters (soil fertility and acidity), maize varieties, drought and climate variabilities, diseases, and insect pests (Alene et al., 2009; Badu-Apraku and Fakorede, 2017; Koffi et al., 2020a; Tambo and

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[*] Corresponding author. Ecole Supérieure d'Agronomie (ESA), Université de Lomé, 01 B.P. 1515 Lomé 01, Lomé, Togo.
E-mail address: rfiaboe@yahoo.com (K.R. Fiaboe).

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Abdoulaye, 2012).

Among maize pests, the fall armyworm (FAW), *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae), presents the biggest threat and has thus gathered all attention since its first reports from several SSA countries (Day et al., 2017; Goergen et al., 2016). This invasive pest has not only established itself in Africa but also seems to have displaced other key pests like stemborers species, previously associated with maize production (Abang et al., 2021; Sokame et al., 2021). Its impact is significant, compromising food security by degrading both the quality and yield of maize, leading to substantial economic losses for smallholder farmers (Assefa and Ayalew, 2019; Koffi et al., 2020a; Kuate et al., 2019; Niassy et al., 2021). Beyond maize, FAW also infests sorghum and other crops belonging to Solanum, Ipomoea, Saccharum, Phaseolus and Gossypium genera (Kuate et al., 2019; Montezano et al., 2018), posing a broader agricultural challenge. The pest may reduce the quality and quantity of maize produced up to 5-fold where control measures are overlooked (Sisay et al., 2019).

To counteract FAW infestations, farmers often use chemical pesticides (Agboyi et al., 2023; Babendreier et al., 2020; Koffi et al., 2021). However, these chemicals raise serious environmental and health concerns (Chandler et al., 2011). These studies encompass investigations into novel insecticides, biopesticides, and the implementation of push-pull technology (Agboyi et al., 2020, 2023; Akutse et al., 2019; Babendreier et al., 2020; Deshmukh et al., 2020; Idrees et al., 2022; Midega et al., 2018; Togola et al., 2018). However, the practical adoption of these innovative technologies by smallholder farmers encounters persistent Challenges. The limited availability of financial resources characteristic of these farmers makes it arduous for them to overcome the initial costs associated with embracing environmentally-friendly approaches to pest control. This has led to gaps in the pursuit of ecologically sustainable and economically viable alternatives, particularly in the context of SSA where maize productivity remained low. This brings us to consider the potential of Integrated Pest Management (IPM) strategies, which could offer more sustainable solutions (Agboyi et al., 2023; Akutse et al., 2019; Babendreier et al., 2020; Koffi et al., 2021; Prasanna et al., 2018).

In this context, various researchers have delved into the African ecosystems to study conservation biological control strategies. These focus on fostering environments that attract beneficial organisms, predominantly predators and parasitoids (Agboyi et al., 2020, 2023; Kenis et al., 2019; Koffi et al., 2020b; Sokame et al., 2021). Among these beneficial organisms, the egg parasitoid *Telenomus remus* (Nixon) (Hymenoptera: Scelionidae) has been identified as a promising candidate for the biological control of FAW in Africa (Agboyi et al., 2020; Colmenarez et al., 2022; Kenis et al., 2019; Prasanna et al., 2018). These studies also suggested adoption of cultural practices that offer food, shelter, and favorable conditions for the parasitoid to thrive (Agboyi et al., 2020; Kenis et al., 2019; Prasanna et al., 2018). Indeed, among the IPM facets, cultural practices are usually the cheapest and safest way of managing agricultural pests (Prasanna et al., 2018). Cultural practices only require the manipulation of conventional production practices and rarely affect non-target organisms (Akutse et al., 2020; Midega et al., 2018). They are a cornerstone of every IPM program for managing insect pests, including FAW. These practices include among others, crop rotation, sanitation, crop diversification, and soil health management.

The role of soil quality in IPM for combating FAW remains largely unexamined, especially in SSA, where most maize soils are deficient in nutrients (Tully et al., 2015). Paradoxically, while some studies indicate that proper soil management can enhance plant defenses against pests and diseases and resulting in better crop yield (Schlickmann-Tank et al., 2020; Schmidt-Jeffris et al., 2021), others suggest that enriched soil could inadvertently favor certain pests (Rashid et al., 2017; Veromann et al., 2013). Within this landscape, our research hypothesizes that only optimal soil nutrient management may benefit maize production. This approach could enhance plant resilience and recovery while concurrently mitigating feeding by FAW and the consequent damage. This hypothesis is rooted in observations that excessive soil nutrients could render plants more appealing to certain defoliators, thus introducing complexity to pest management efforts (Altieri and Nicholls, 2003; Jiang and Schulthess, 2005; Rashid et al., 2017; Schmidt-Jeffris et al., 2021; Veromann et al., 2013; Wang et al., 2022). For instance, Rashid et al. (2017) found that high nitrogen levels in soil were shown to enhance the bionomics of brown planthopper, *Nilaparvata lugens* (Stål) (Hemiptera: Delphacidae) in rice. Moreover, high soil nutrient level has shown to modulate the release of volatile organic compounds (VOCs) from both plants and herbivore frass, attracting both herbivores and beneficial parasitoid species (Veromann et al., 2013).

Given this backdrop of conflicting evidence, our research hypothesizes that altering the standard fertilizer application process—by splitting the recommended quantity into smaller, more frequent doses—could influence both the interaction between plants and herbivores and maize productivity. In essence, our research seeks to delve into the intricate relationship between soil nutrient management, plant responses, and the dynamics of the populations of FAW and its associated natural enemies. By establishing a nuanced understanding of how soil quality interplays with the ecological system, we aimed at contributing valuable insights to the development of more effective and sustainable IPM strategies for the control of FAW infestations in maize crops within SSA.

2. Materials and methods

2.1. Experimental site conditions

The research was carried out at agricultural research station of the University of Lomé in Togo (6°22′N, 1°13′E; height 50 m) in Togo. The site is situated in the Coastal Savannah Agro-ecological Zone and experiences a bimodal rainfall pattern. The first rainy season occurs from mid-March to late July, followed by a second rainy season from early September to early mid-November (Nimon et al., 2020). There are two main maize growing seasons (April–July and September–November), with an average annual precipitation of 800-1100 mm and an average annual temperature of 27 °C. However, due to unpredictable climate scenarios and the increasing demand for fresh maize, farmers have been growing the crop throughout the year, deviating from the traditional seasonal patterns (Cairns et al., 2013).

Two on-station experiments covering two cropping seasons were carried out: wet season (April 20 to August 7, 2020) and dry season (October 27, 2020 to February 6, 2021). Supplementary Fig. 1 presents the normalized variations of the climatic information of the experiment periods. During the first trial, the average air temperature was 25.99 ± 0.07 °C, whereas the average earth skin temperature was 26.25 ± 0.07 °C. The total precipitation for the wet season experiment was 3724.6 mm, with the wettest day receiving 145.74 mm. The relative humidity varied from 72.69 to 94.31%. The average air temperature, earth skin temperature, total precipitation, and relative humidity for the dry season experiment were 27.66 ± 0.07 °C, 28.41 ± 0.11 °C, 154.44 mm, and 61.50–89.06%, respectively. After two years of alternating maize and tomato planting, the experimental land was kept fallow a year before this experiment. The soil is ferralsol-characterized. Supplementary Table 1 displays the results of soil physico-chemical analyses conducted on soil samples obtained from the 0–25 cm horizon.

2.2. Planting material and experimentation design

The Togolese Institute of Agronomic Research (ITRA) provided certified maize seeds var. QPM Obatanpa for the study. This maize variety reaches maturity roughly 105 days after seeding (Sallah et al., 2008).

The trials were set up using a split-plot design with four replicates. On sub-plots of 4 m × 3 m, equidistant by 2.5 m, a sowing layout of 0.80 × 0.20 m was used, with one plant per hill. The sub-plots included: (i)

Control (CT; without fertilizers); (ii) Compost (EC; 10 t/ha of enriched compost at planting and 100 kg Urea (46% Nitrogen)/ha at 45 DAS); (iii) Split NPK (SN; 100 kg $N_{15}P_{15}K_{15}$/ha at planting, 150 kg $N_{15}P_{15}K_{15}$/ha at 30 DAS, and 100 kg Urea (46% Nitrogen)/ha at 45 DAS); and (iv) Recommendation (RC; 250 kg $N_{15}P_{15}K_{15}$/ha at 15 DAS and 100 kg Urea (46% Nitrogen)/ha at 45 DAS). To apply the fertilizers, two 3–5 cm deep hills were excavated on both sides of each plant and closed after the subsequent amounts were evenly dispersed into the hills. The main plots consisted of two levels of bioinsecticide spray (control vs. bioinsecticide). BYPEL 1® (*Pieris rapae* granulovirus (*Pr*GV) 10,000 PIB/mg + *Bacillus thuringiensis* subsp. *kurstaki* (*Btk*) 16,000 IU/mg) was employed. The choice of BYPEL 1® was based on its proven sublethal efficacy against the bionomics of FAW, substantiated by previous research in Togo and Ghana (Agboyi et al., 2023; Fiaboe et al., 2023). The bioinsecticide was prepared as a water solution at a concentration of 1.33 g/L water solution. The bioinsecticide was sprayed every two weeks on the relevant sub-plots until early tasseling. As needed, uniform irrigation using tap water was administered to the plants on a localized basis.

2.3. Measurement of plant growth parameters and robustness

Data on plant growth were collected from five designated maize plants in each experimental sub-plot, employing a non-invasive sampling strategy. To identify these sample plants, numbered placards from 1 to 5 were positioned at the base of each plant. Data collection began two weeks after initial planting. Measurements were taken during key growth stages, including the third collar leaf (V3), sixth collar leaf (V6), ninth collar leaf (V9), and twelfth collar leaf (V12) stages, in accordance with the Iowa State University scaling system (Infante et al., 2018). Various growth metrics were evaluated at each of these stages: (i) plant height was measured using a measuring tape; (2) leaf count per plant was assessed through visual inspection; (3) circumference of the pseudo-stems was gauged at 20 cm above the soil surface, also using a measuring tape. The robustness of the plant was determined using the following formula adapted from Fournier et al. (2013):

$$Plant\ robustness = \frac{Stem\ circumference \times Total\ leaves\ per\ plant}{Plant\ height}$$

2.4. Measurement of pest larval incidence

As previously outlined for the metrics concerning maize plant growth (see, 2.3), the incidence of FAW was monitored on five predetermined plants in each experimental sub-plot. The FAW incidence was quantified by enumerating the larvae found on various parts of the maize plant—namely, the leaves, whorl, tassels, and cobs. These counts were performed at multiple growth stages of the maize plant: V3, V6, V9, and V12. Further evaluations were conducted during the key phenological phases of tasseling (VT), silking (R1), and the blister stage, which is the beginning of milk kernel development (R2) (Infante et al., 2018).

2.5. Percent damage per plant and plant recovery from FAW infestation

The percentage of damage caused by FAW was calculated by dividing the number of FAW larvae-damaged leaves by the total number of leaves on each sample maize plant. Plant recovery index was calculated using the following formula:

$$PRI = (\text{Percent damage at } T_i - \text{Percent damage at } T_{i+1})$$

PRI is the plant recovery index; T_i is previous data collection date; T_{i+1} is the actual data collection date.

2.6. Evaluation of parasitism by Telenomus remus and predators abundance

The assessment of the abundance of the egg parasitoid *T. remus* and the predators targeting FAW involved a comprehensive approach encompassing visual observation, specimen collection, and subsequent morphological identification. Predators that were observed preying on FAW larvae were directly captured and preserved in a solution of 70% ethanol. Furthermore, a representative sample of colonies of wasps present on the FAW egg masses was similarly collected and preserved in 70% ethanol. Identification of the specimens preserved in ethanol was executed using a Leica EZ4D microscope (Leica microsystems, Wetzlar, Germany). The valuable expertise of Mr. Koffi Djima, stemming from his previous work (Koffi et al., 2020b), proved invaluable in assisting with the identification process.

To determine the rate of parasitism, a tally of the egg masses counted on each maize plant was documented, with a specific distinction made between those that had been parasitized (occupied by parasitic wasps) and those that were free from wasp activity. The following formula was used to calculate the parasitism rate per maize plant (Koffi et al., 2020b):

$$Parasitism\,Rate = \frac{Number\ of\ wasp - colonized\ FAW\ egg\ masses\ per\ plant}{Total\ number\ of\ FAW\ egg\ masses\ per\ plant} \times 100$$

2.7. Measurement of maize grain yield

Cobs were hand-harvested from individual plants as maize matured. The seeds were then sun-dried to 14 percent moisture for 10–15 days before being shelled. The grains were weighed per plant and then extrapolated to hectares using maize density per hectare as a guide.

2.8. Statistics

The growth characteristics of maize plants (plant height, stem circumference, and robustness), FAW larval incidence, rates of parasitization of FAW eggs by *T. remus*, and the abundance of the predators were analyzed using Generalized Linear Model (GLM) of log-linear regression (Poisson distribution). The model was chosen using Likelihood Ratio (LR) at alpha significance level of 0.05. The effects of fertilizer and bioinsecticide on percent maize leaf damage by FAW and maize grain yield were evaluated using One-way ANOVA ($\alpha = 0.05$) with Best Model as the model selection criteria and Mean Squared Error (MSE) as the performance gauge. Tukey (HSD) was used for pairwise comparisons. Multiple Linear Regression analysis was conducted to predict the factors affecting maize grain yield production. All the statistical analyses were conducted in Rstudio (R Core Team, 2022).

3. Results

3.1. Effect of fertilization options and bioinsecticide treatments on maize plant height, stem circumference and plant robustness

3.1.1. Maize plant height

In the wet season, the fertilization models, when not accompanied by bioinsecticide spray, produced significant gains in plant height (LR with GLM, $\chi^2 = 23.84$, df = 3, $p < .0001$; Fig. 1a). Recommended fertilization plots outperformed the control, enriched compost, and split-NPK in terms of plant height (Fig. 1a). Similarly, when bioinsecticide was applied, both recommended and split-NPK fertilization models resulted in significantly greater heights (LR with GLM, $\chi^2 = 36.90$, df = 3, $p < .0001$; Fig. 1a).

During the dry season, in the absence of bioinsecticide application, all maize plants receiving mineral fertilizers and enriched compost exhibited statistically significant increases in plant height compared to the control treatment (LR with GLM, $\chi^2 = 62.83$, df = 3, $p < .0001$; Fig. 1b). Likewise, with the application of bioinsecticide along with

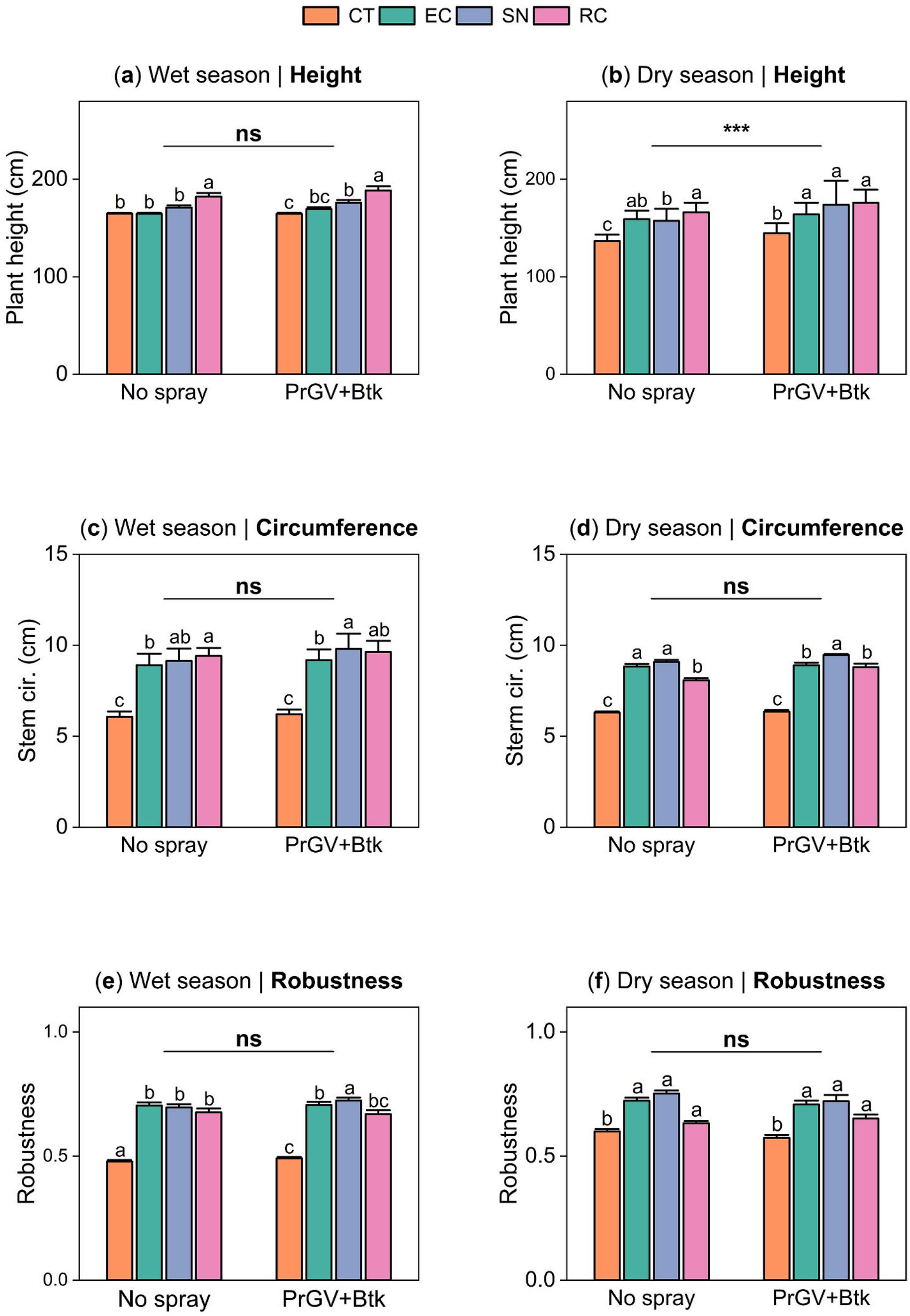

Fig. 1. Effect of fertilization and bioinsecticide on maize plant height, stem circumference and plant robustness. For plant height, measurements were taken at the V12 growth stage by tracing the arch of the topmost leaf down to the soil level (**a, b**). Stem circumference was also gauged at the V12 stage, specifically at a height of 20 cm above the soil surface (**c, d**). Plant robustness was calculated using a formula that multiplies the number of leaves by the stem circumference, and then divides that product by the plant height (**e, f**). The data were subjected to a Likelihood Ratio Test (LR test) within a Generalized Linear Model (GLM) framework. Subsequent pairwise comparisons were carried out with Tukey's Honest Significant Difference (HSD) test. The bars represent the mean values with Standard Error (SE) indicated. Fertilization treatments that led to significantly different results are marked with distinct lowercase letters above the error bars ($p < .05$; sample size = 20). Asterisks are used to denote significant differences between bioinsecticide treatments: ***$p < .001$. "ns" signifies non-significance between bioinsecticide treatments. Treatment abbreviations are as follows: CT refers to the control group with no fertilizers; EC stands for enriched compost; SN represents split-NPK fertilization; and RC is the recommended fertilization. For insecticides, *Pr*GV denotes *Pieris rapae* granulovirus, and Btk signifies *Bacillus thuringiensis* subsp. *kurstaki*.

enriched compost, split-NPK, and recommended fertilization treatments, the highest plant heights were observed compared to the control (LR with GLM, $\chi^2 = 76.08$, df = 3, $p < .0001$; Fig. 1b).

Overall, during the wet season, there were no significant differences among the treatment plots in terms of plant height (LR with GLM, $\chi^2 = 3.77$, df = 1, $p > .05$; Fig. 1a). However, in the dry season, the use of bioinsecticide resulted in significant height gains compared to maize plants that were not sprayed (LR with GLM, $\chi^2 = 24.03$, df = 1, $p < .0001$; Fig. 1b).

3.1.2. *Maize stem circumference*

During the wet season, maize stem circumference demonstrated significant variations due to all the fertilization models when compared to the control, whether the bioinsecticide was sprayed (LR with GLM, $\chi^2 = 18.57$, df = 3, $p < .001$; Fig. 1c) or not (LR with GLM, $\chi^2 = 20.90$, df = 3, $p < .001$; Fig. 1c).

In the dry season, without the spray, enriched compost and split-NPK treatments notably resulted in significantly larger stem circumferences, outperforming the control and recommended fertilization models (LR with GLM, $\chi^2 = 12.28$, df = 3, $p < .01$; Fig. 1d). Conversely, with the bioinsecticide spray, the split-NPK treatment displayed a significantly greater maize stem circumference compared to other treatments, including enriched compost and recommended fertilization models (LR with GLM, $\chi^2 = 14.42$, df = 3, $p < .05$; Fig. 1d).

Overall, the application of bioinsecticide did not significantly impact the variance in maize plant stem circumference during both the wet season (LR with GLM, $\chi^2 = 0.50$, df = 1, $p > .05$; Fig. 1c) and the dry season (LR with GLM, $\chi^2 = 0.45$, df = 1, $p > .05$; Fig. 1d).

3.1.3. Maize plant robustness

During the wet season, the various fertilization models significantly improved the robustness of maize plants when no bioinsecticide spray was used, as compared to the control treatment (LR with GLM, $\chi^2 = 88.75$, df = 3, $p < .01$; Fig. 1e). Similarly, when bioinsecticide sprays were applied, the fertilization-amended plots produced significantly more robust maize plants (LR with GLM, $\chi^2 = 99.42$, df = 3, $p < .0001$; Fig. 1e).

In the dry season, without bioinsecticide spray, there was a significant difference in plant robustness between the fertilization models and the control treatment (LR with GLM, $\chi^2 = 71.30$, df = 3, $p < .0001$; Fig. 1f). Likewise, under bioinsecticide applications, the fertilization models significantly and positively impacted the robustness of maize plants compared to the control treatments (LR with GLM, $\chi^2 = 55.09$, df = 3, $p < .0001$; Fig. 1f), with the highest values observed in the split-NPK and enriched compost treatments.

Overall, there was a significant increase in robustness in bioinsecticide-treated maize plants compared to untreated plants during the wet season (LR with GLM, $\chi^2 = 4.83$, df = 1, $p < .05$; Fig. 1e). However, there was no significant difference between the bioinsecticide and control treatments regarding the robustness of maize plants during the dry season (LR with GLM, $\chi^2 = 0.14$, df = 1, $p > .05$; Fig. 1f).

3.2. Effect of fertilization, and bioinsecticide on FAW larval incidence

Overall, during the wet season without bioinsecticide spray, the influence of fertilization options on FAW larval incidence was not statistically significant (LR with GLM, $\chi^2 = 5.61$, df = 3, $p > .05$; Fig. 2a; Supplementary Table 2). However, when considering specific growth stages, a significant difference between the fertilization models emerged at both the V12 (LR with GLM, $\chi^2 = 8.89$, df = 3, $p < .05$; Fig. 2a; Supplementary Table 2) and R1 stages (LR with GLM, $\chi^2 = 11.23$, df = 3, $p < .05$; Fig. 2a; Supplementary Table 2). This resulted in fewer FAW larvae on split-NPK plots compared to the control treatment (Fig. 2a; Supplementary Table 2). Conversely, when bioinsecticide was applied during the wet season, there was a generally significant effect of the fertilization models on the incidence of FAW larvae (LR with GLM, $\chi^2 =$

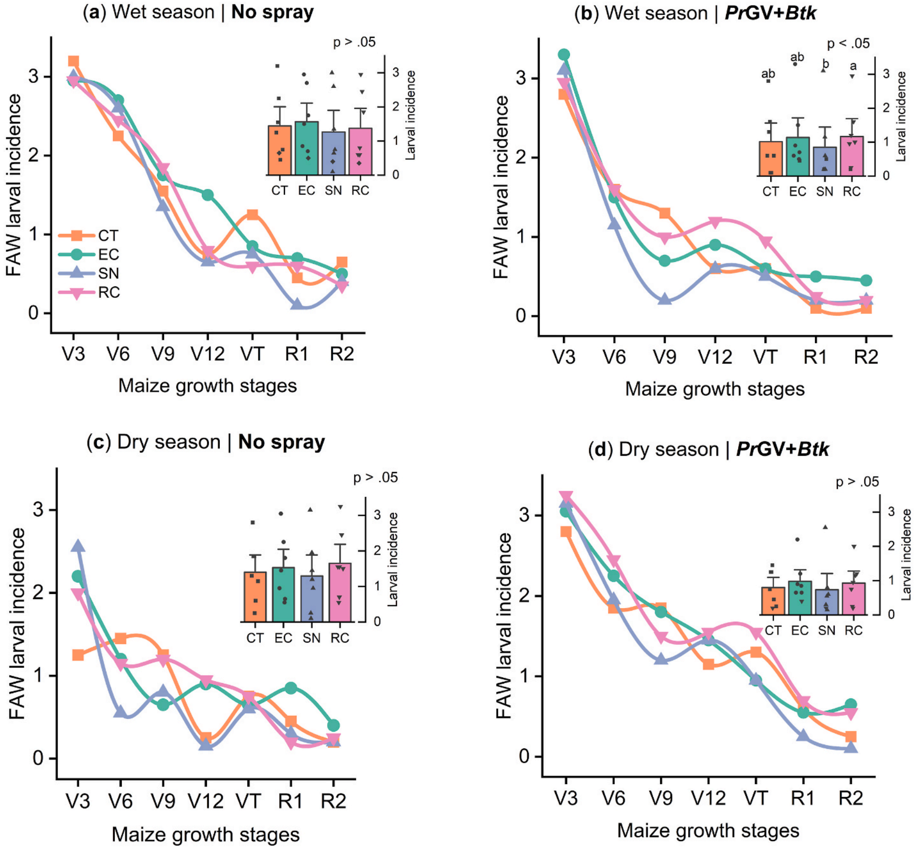

Fig. 2. Effect of fertilization and insecticide on FAW larval incidence on maize plant. The graph lines represent the average incidence of FAW larvae for each treatment across different growth stages of the maize plant, expressed as the number of FAW larvae per individual maize plant. The bar graphs represent the overall mean ± SE of larval incidence per treatment. Statistical analysis was performed using the Likelihood Ratio Test (LR test) within a Generalized Linear Model (GLM), with a significance level set at $p < .05$ and a sample size of 20. Subsequent pairwise comparisons were carried out with Tukey's HSD test. The fertilization treatments that led to significantly different results are marked with distinct lowercase letters above the error bars. "ns" signifies non-significance between treatments. Treatment abbreviations are as follows: CT refers to the control group with no fertilizers; EC stands for enriched compost; SN represents split-NPK fertilization; and RC is the recommended fertilization. For insecticides, *Pr*GV denotes *Pieris rapae* granulovirus, and *Btk* signifies *Bacillus thuringiensis* subsp. *kurstaki*. Growth phases are indicated as V3, V6, V9, and V12 for three-, six-, nine-, and twelve-collar leaves, respectively. Moreover, VT, R1, and R2 are used to mark the tasseling, silking, and blister phases of maize growth, respectively.

8.47, df = 3, $p < .05$; Fig. 2b; Supplementary Table 2). When examining specific growth stages of the maize plants, the significant difference was only recorded at the V9 stage (LR with GLM, $\chi^2 = 19.343$, df = 3, $p < .001$; Fig. 2b; Supplementary Table 2).

In the dry season, without the application of bioinsecticide, there were no significant differences in the incidence of FAW larvae, regardless of the growth stages of the maize plants as well as fertilization models (LR with GLM, $\chi^2 = 6.88$, df = 3, $p > .05$; Fig. 2c; Supplementary

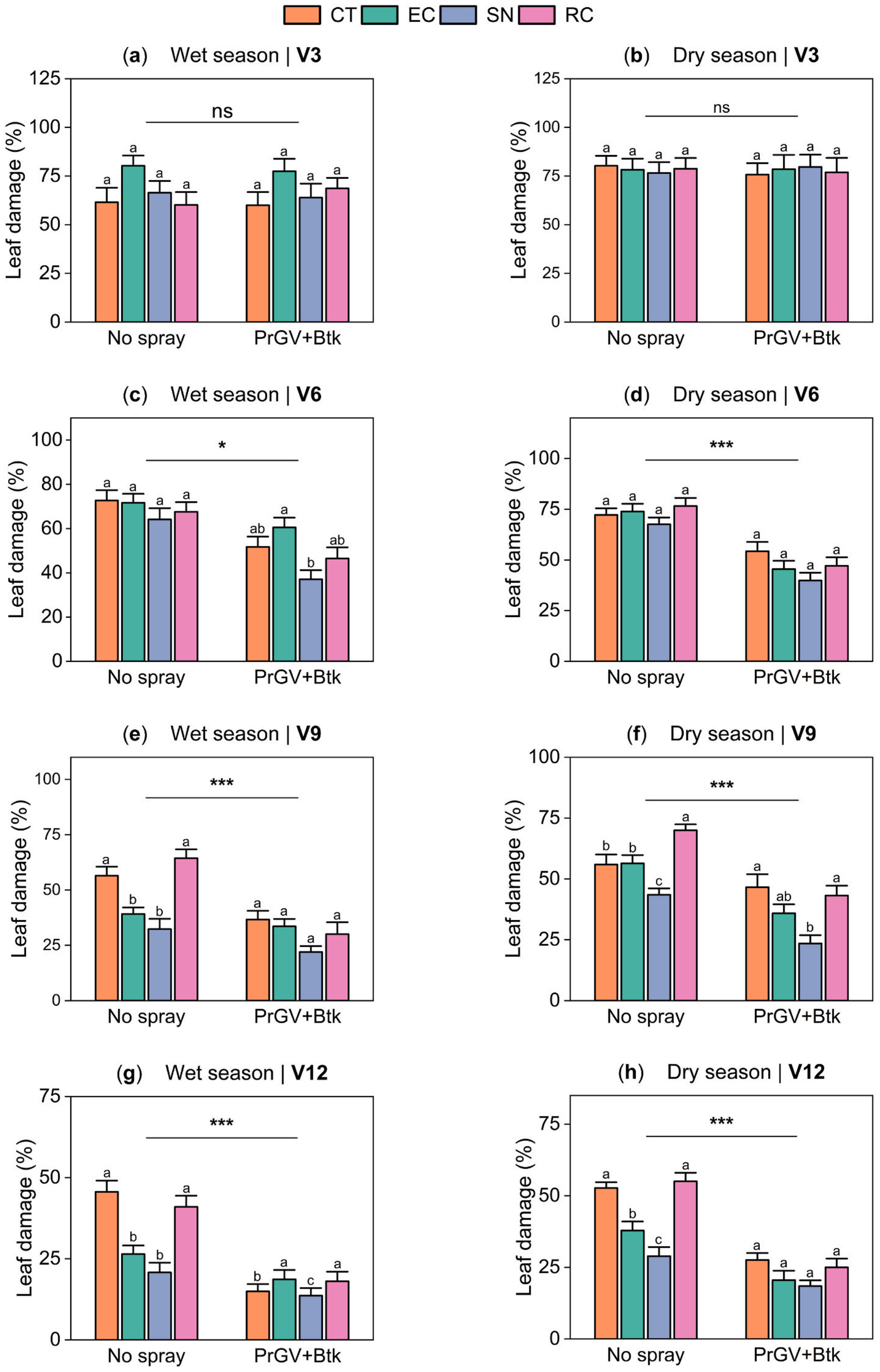

Fig. 3. Effects of fertilization and bioinsecticide on the percent damage caused by FAW to maize plant during the maize vegetative phases. Bars depict the average percentage of leaf damage, accompanied by Standard Error (SE). This percentage is computed by dividing the number of leaves damaged by FAW larvae by the total number of leaves on each maize plant. The data underwent one-way Analysis of Variance (ANOVA) based on the best model selection criteria, using Mean Squared Error (MSE) as the performance gauge. Subsequent pairwise comparisons were carried out with Tukey's HSD test. Different alphabetic characters above the bars signify statistically significant variations between fertilization treatments ($p < .05$; $n = 20$). Asterisks indicate significant disparities between bioinsecticide treatments (*$p < .05$, ***$p < .001$). The label "ns" denotes non-significant differences between bioinsecticide treatments. Treatment abbreviations are as follows: CT refers to the control group with no fertilizers; EC stands for enriched compost; SN represents split-NPK fertilization; and RC is the recommended fertilization. For bioinsecticides, *Pr*GV denotes *Pieris rapae* granulovirus, and *Btk* signifies *Bacillus thuringiensis* subsp. *kurstaki*. Growth phases are indicated as V3, V6, V9, and V12 for three-, six-, nine-, and twelve-collar leaves, respectively.

Table 3). However, with the application the bioinsecticide, significant effects of fertilization models on FAW larvae incidence were recorded especially at the V3 (LR with GLM, $\chi^2 = 9.67$, df = 3, $p < .05$; Fig. 2d; Supplementary Table 3), V6 (LR with GLM, $\chi^2 = 8.98$, df = 3, $p < .05$; Fig. 2d; Supplementary Table 3), V12 (LR with GLM, $\chi^2 = 20.79$, df = 3, $p < .0001$; Fig. 2d; Supplementary Table 3), and R1 growth stages (LR with GLM, $\chi^2 = 10.27$, df = 3, $p < .05$; Fig. 2d; Supplementary Table 3). Nonetheless, when considering the overall dry season, including the bioinsecticide spray, there was no significant difference in the incidence of FAW larvae across all fertilization models (LR with GLM, $\chi^2 = 6.18$, df = 3, $p > .05$; Fig. 2d; Supplementary Table 3).

3.3. Impact of fertilization and bioinsecticide on maize plant damaged by FAW across growth stages

At the V3 growth stage of maize plants, without bioinsecticide, there were no significant differences among the fertilization models, during both the wet season (One-way ANOVA, df = 3, F = 2.08, $p > .05$; Fig. 3a), and the dry seasons (One-way ANOVA, df = 3, F = 0.08, $p > .05$; Fig. 3b). Similarly, when bioinsecticide was applied during both the wet and dry seasons, no significant differences in damage were observed across fertilization models at V3 (One-way ANOVA, df = 3, F = 0.78, $p > .05$; Fig. 3a and b). Consequently, there was no significant difference between bioinsecticide-treated and untreated plots at the V3 stage (One-way ANOVA, df = 3, F = 0.003, $p > .05$; Fig. 3a and b).

Transitioning to the V6 stage, fertilization had no significant impact on leaf damage without bioinsecticide, in both wet (One-way ANOVA, df = 3, F = 0.75, $p > .05$; Fig. 3c) and dry seasons (One-way ANOVA, df = 3, F = 1.09, $p > .05$; Fig. 3d). However, at V6, the influence of fertilization models on maize leaf damage by FAW in bioinsecticide-treated plots was significant during the wet season (One-way ANOVA, df = 3, F = 4.64, $p < .05$; Fig. 3c). Notably, split-NPK showed lower maize leaf damage by FAW in bioinsecticide-treated plots in both seasons (Fig. 3c and d). Furthermore, in the dry season at V6, the application of bioinsecticide spray significantly reduced leaf damage caused by FAW when compared to untreated plots (One-way ANOVA, F = 86.91, df = 1, $p < .0001$; Fig. 3d).

Advancing to the V9 stage, a significant difference in the impact of fertilization models on damage caused by FAW larvae was observed, both in the absence of bioinsecticide spray, during both the wet (One-way ANOVA, F = 13.96, df = 3, $p < .0001$; Fig. 3e), and dry seasons (One-way ANOVA, F = 11.29, df = 3, $p < .0001$; Fig. 3f). Notably, split-NPK and enriched compost resulted in less damage (Fig. 3e and f). Furthermore, this reduction corresponded to a statistically significant increase in the recovery of maize plants from damage caused by FAW larvae on split-NPK and enriched compost plots between the V6 and V9 stages (One-way ANOVA, F = 5.38, df = 3, $p < .01$; Supplementary Table 4; Supplementary Fig. 2). During the dry season, significantly less leaf damage by FAW was recorded on split-NPK compared to other fertilization models when the bioinsecticide was used (One-way ANOVA, F = 5.95, df = 3, $p < .01$; Fig. 3f). However, during the wet season, there was no significant effect of the fertilization models on leaf damage (One-way ANOVA, F = 2.58, df = 3, $p > .05$; Fig. 3e). Overall, the application of bioinsecticide consistently reduced damage by FAW larvae compared to untreated plots, regardless of the fertilization models, during both the wet (One-way ANOVA, F = 37.76, df = 1, $p < .0001$; Fig. 3e), and dry seasons (One-way ANOVA, F = 51.73, df = 1, $p < .0001$; Fig. 3f).

Finally, at the V12 growth stage, significant differences in the impact of fertilization models on FAW larval damage were evident, both without bioinsecticide spray, in both the wet (One-way ANOVA, F = 13.91, df = 3, $p < .0001$; Fig. 3g), and dry seasons (One-way ANOVA, F = 18.81, df = 3, $p < .0001$; Fig. 3h). Notably, split-NPK and enriched compost resulted in reduced damage in both scenarios (Fig. 3g and h). However, when bioinsecticide was applied, there were no significant differences between fertilization models regarding FAW larval damage, neither in the wet season (One-way ANOVA, F = 0.85, df = 3, $p > .05$; Fig. 3g), nor in the dry season (One-way ANOVA, F = 2.29, df = 3, $p > .05$; Fig. 3h). Overall, the use of bioinsecticide consistently reduced FAW larval damage compared to untreated plots, regardless of the fertilization models, during both the wet (One-way ANOVA, F = 70.37, df = 1, $p < .0001$; Fig. 3g), and dry seasons (One-way ANOVA, F = 107.19, df = 1, $p < .0001$; Fig. 3h).

3.4. Effect of fertilization and bioinsecticide on the parasitism by *Telenomus remus* and predators' abundance

3.4.1. Parasitization of FAW eggs by *Telenomus remus*

During the rainy season, the choice of fertilization methods had a significant impact on the parasitization of FAW eggs by *T. remus*, both in the absence of bioinsecticide application (LR with GLM, $\chi^2 = 151.84$, df = 3, $p < .0001$; Fig. 4a) and when bioinsecticides were utilized (LR with GLM, $\chi^2 = 122.86$, df = 3, $p < .0001$; Fig. 4a). In both scenarios, the highest rates of parasitization were observed in plots treated with enriched compost and split-NPK fertilization (Fig. 4a). However, there was no statistically significant distinction between the use and non-use of bioinsecticides (LR with GLM, $\chi^2 = 3.52$, df = 1, $p > .05$; Fig. 4a).

During the dry season, the choice of fertilization methods had a significant impact on the parasitization of FAW eggs by *T. remus*, both in the absence of bioinsecticide application (LR with GLM, $\chi^2 = 79.12$, df = 3, $p < .0001$; Fig. 4b) and when bioinsecticides were applied (LR with GLM, $\chi^2 = 58.07$, df = 3, $p < .0001$; Fig. 4b). In general, plots treated with enriched compost and split-NPK demonstrated significantly higher rates of parasitization compared to those using the recommended fertilization model and the control (LR with GLM, $\chi^2 = 129.10$, df = 3, $p < .0001$; Fig. 4b). Furthermore, overall, there was a significantly lower level of parasitization observed on plots treated with bioinsecticides compared to untreated ones (LR with GLM, $\chi^2 = 18.83$, df = 1, $p < .0001$; Fig. 4b).

3.4.2. Abundance of predators

In terms of predator abundance, the data showed a significantly greater abundance of such predators in plots that received fertilization treatments compared to the untreated control plots. This pattern was evident in both the wet season (LR with GLM, $\chi^2 = 19.65$, df = 3, $p < .001$; Fig. 4c) and the dry season (LR with GLM, $\chi^2 = 129.10$, df = 3, $p < .0001$; Fig. 4d; Supplementary Table 5). The types of predators included were Araneae (Thomisidae), Coleoptera (Carabidae and Coccinellidae), Dermaptera (Forficulidae), Hemiptera (Pentatomidae), Hymenoptera (Formicidae and Vespidae), and Mantodea (Mantidae) as detailed in Supplementary Table 5. However, as a general pattern, there was no statistically significant difference in the abundance of predators between the bioinsecticide-treated and untreated plots (LR with GLM, $\chi^2 = 2.35$, df = 3, $p > .05$; Fig. 4c and d; Supplementary Table 5). Yet, the highest predator abundance was observed on bioinsecticide-treated split-NPK plots during the dry season (LR with GLM, $\chi^2 = 28.64$, df = 3, $p < .0001$; Fig. 4d; Supplementary Table 5).

3.5. Maize grain yield responses to fertilization and bioinsecticide

In the wet season, all fertilization models resulted in higher maize grain yields compared to the control (One-way ANOVA, F = 142.04, df = 3, $p < .0001$; Fig. 5a). The highest maize grain yield, at 5.67 t/ha, was significantly associated with split-NPK when no bioinsecticide was applied (One-way ANOVA, F = 326.26, df = 3, $p < .0001$; Fig. 5a). Additionally, with the use of the bioinsecticide spray, the yield reached 6.03 t/ha (One-way ANOVA, F = 356.87, df = 3, $p < .0001$; Fig. 5a), which was statistically equivalent to the yield of 6.19 t/ha observed on plots following the recommended fertilization model. Moving to the dry season, in the absence of bioinsecticide spray, the highest maize grain yield of 5.60 t/ha was recorded on split-NPK plots (One-way ANOVA, F = 265.21, df = 3, $p < .0001$; Fig. 5b). However, when the bioinsecticide

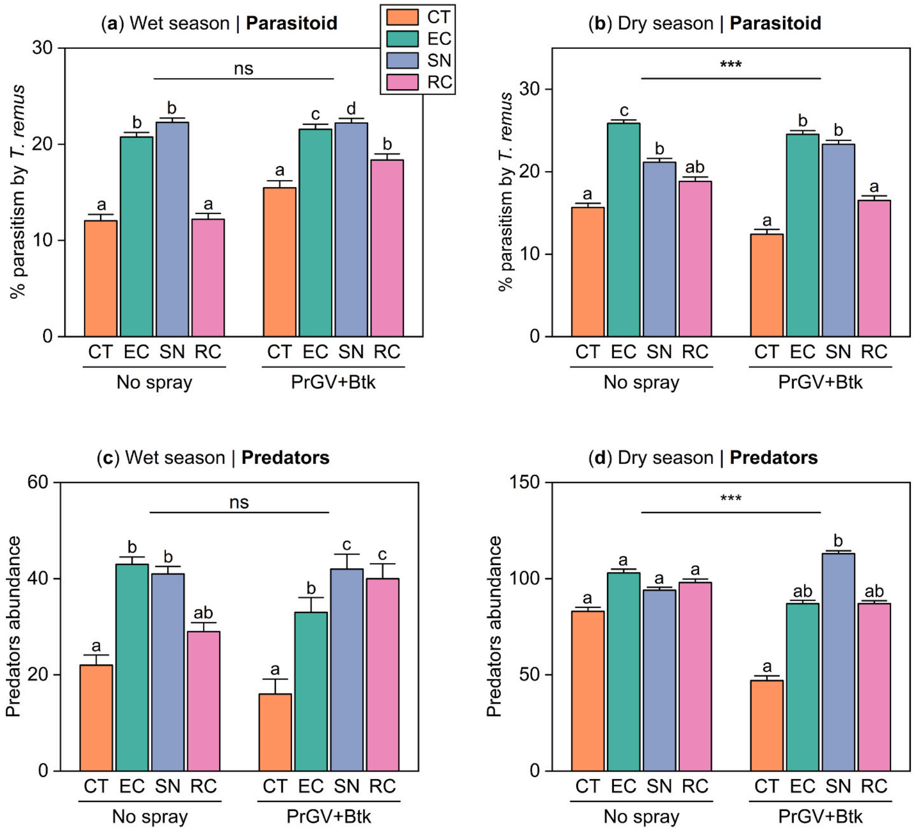

Fig. 4. Parasitism of FAW eggs by *Telenomus remus* and FAW predator abundance on maize plants. The parasitism rate was quantified as the ratio of parasitized FAW egg batches to the total number of egg batches found per maize plant. Additionally, predator abundance refers to the total number of predator species preying on immature FAWs, with the specific species listed in Supplementary Table 5. The bar graphs represent the overall mean ± SE of parasitism rate of *T. remus* during the wet season (**a**) and the dry season (**b**), and the predator abundance during the wet season (**c**) and dry season (**d**). Statistical analysis was performed using the Likelihood Ratio Test (LR test) within a Generalized Linear Model (GLM), with a significance level set at $p < .05$ and a sample size of 20. Subsequent pairwise comparisons were carried out with Tukey's HSD test. The fertilization treatments that led to significantly different results are marked with distinct lowercase letters above the error bars. The asterisks (*) indicate significant difference between treatments (***$p < .001$). "ns" signifies non-significance between treatments. Treatment abbreviations are as follows: CT refers to the control group with no fertilizers; EC stands for enriched compost; SN represents split-NPK fertilization; and RC is the recommended fertilization. For bioinsecticides, *Pr*GV denotes *Pieris rapae* granulovirus, and *Btk* signifies *Bacillus thuringiensis* subsp. *kurstaki*.

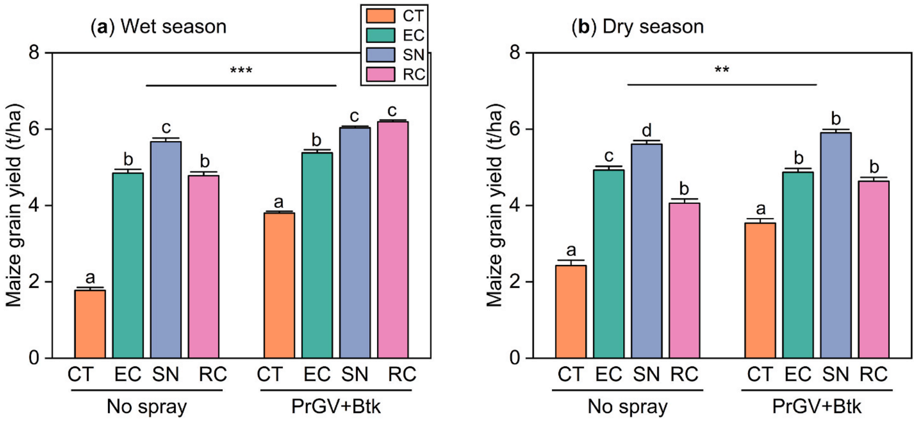

Fig. 5. Maize grain yield responses to fertilization and bioinsecticide options during the wet season (a) and the dry season (b). Maize grain yield was determined by extrapolating grain yield per plant to hectare (t/ha). Bar represent mean ± SE. The data underwent one-way ANOVA based on the best model selection, using MSE as the performance criteria. Subsequent pairwise comparisons were carried out with Tukey's HSD test. Different alphabetic characters above the bars signify statistically significant variations between fertilization treatments ($p < .05$; $n = 20$). Asterisks indicate significant disparities between bioinsecticide treatments (***$p < .001$). The label "ns" denotes non-significant differences between bioinsecticide treatments. Treatment abbreviations are as follows: CT refers to the control group with no fertilizers; EC stands for enriched compost; SN represents split-NPK fertilization; and RC is the recommended fertilization. For bioinsecticide, *Pr*GV denotes *Pieris rapae* granulovirus, and *Btk* signifies *Bacillus thuringiensis* subsp. *kurstaki*.

was applied, all fertilization treatments equally yielded significantly higher maize grain yields compared to the control treatment (One-way ANOVA, F = 134.04, df = 3, $p < .0001$; Fig. 5b), resulting in yields of 5.90 t/ha, 4.87 t/ha, and 4.63 t/ha on split-NPK, enriched compost, and recommended fertilization model plots, respectively. Overall, the use of the bioinsecticide had a significant impact on maize grain yield compared to untreated plots in both the wet and dry seasons (One-way ANOVA, F = 32.94, df = 1, $p < .0001$; Fig. 5a and b).

3.6. Principal factors affecting maize grain yield

The standardized coefficients of the multiple linear regression analysis showed that maize grain yield was positively influence by the wet season, maize plant circumference, plant robustness, split-NPK fertilization model, and bioinsecticide spray (Fig. 6, Supplementary Table 6). However, control fertilization model and plant height negatively influence maize grain production (Fig. 6, Supplementary Table 6).

4. Discussion

Our study explored the impact of different soil fertilization approaches, including both mineral and compost-based models, along with bioinsecticide application, on maize growth and resistance to Fall Armyworm (FAW). We specifically looked at how the timing of nitrogen (N), phosphorus (P), and potassium (K) fertilization affected various aspects of maize development, tolerance to FAW herbivory, and grain yield. Our results emphasized the critical role of fertilization strategies in enhancing maize plant resilience against FAW infestations.

Our study identified key benefits in two different fertilization approaches for maize growth. The first approach, aligning with traditional recommendations, applied maximum NPK levels all at once, 15 DAS, and resulted in notably taller plants. The second, a split-NPK method, divided the NPK application into two phases—at sowing and at 30 days—leading to more robust plants with thicker stems. This stem robustness was likely influenced by the early availability of key nutrients such as phosphorus and potassium, which are crucial for root and shoot development (Ciampitti et al., 2013; Lopez et al., 2023). Moreover, thicker stems may reduce risks like lodging while enhancing nutrient and water uptake, contributing to overall plant health and productivity (Hou et al., 2022; Zhou et al., 2019). Split-NPK fertilization model also enabled an additional nitrogen boost during the pre-tasseling stage, which is critical for plant health and productivity (Ciampitti et al., 2013; De Oliveira et al., 2018). Conversely, our study found a negative correlation between plant height resulting from recommended fertilization, and grain yield, reinforcing the issue of lodging (Xue et al., 2020), but also reduced productivity. These findings align with earlier studies, emphasizing the importance of optimized fertilization timing for sustainable and efficient maize cultivation (Davies et al., 2020).

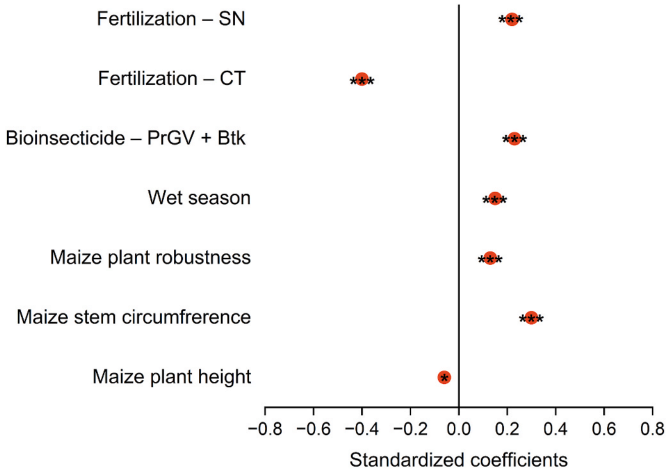

Fig. 6. Principal drivers of maize grain yield production. The red data points represent standardized regression coefficients derived from a multiple regression analysis, correlating various factors with maize grain yield. Points positioned to the left indicate negative correlations, while those on the right signify positive correlations. Significance levels for these variables are indicated by asterisks: *$p < .05$; ***$p < .001$. For more detailed information and exact P-values, refer to Supplementary Table 6. Treatment abbreviations are as follows: CT refers to the control group with no fertilizers; EC stands for enriched compost; SN represents split-NPK fertilization; and RC is the recommended fertilization. For bioinsecticide, *Pr*GV denotes *Pieris rapae* granulovirus, and *Btk* signifies *Bacillus thuringiensis* subsp. *kurstaki*.

On the other hand, regardless of the season, the effectiveness of various fertilization models on FAW larval incidence was inconsistent. However, during the advanced growth stages (V9, V12, and R1), a significant reduction in FAW larvae was observed in plots that used the split-NPK fertilization compared to recommended fertilization model plots. Meanwhile, the lack of significant difference in early vegetative stages might be because maize plants do not fully switch to autotrophy until approximately the V3 stage (Infante et al., 2018). Until that point, the plants mainly rely on stored nutrients in the kernel, making them less influenced by different fertilization models in terms of FAW infestation during these early stages. In contrast, the reduced FAW incidence in the split-NPK treated plots during advanced growth stages could be linked to the more synchronized supply of nutrients with plant demand. Unlike the recommended fertilization treatment, which applied 250 kg/ha of NPK all at once and 100 kg/ha of urea after 30 days, the split-NPK model applied nutrients in smaller, divided amounts. This approach is assumed to temper the excessive nitrogen that could otherwise oversupply the plants and make them more attractive to pests (Altieri and Nicholls, 2003; Li et al., 2021); yet, enough to ensure plant growth and development. Supporting this notion, research suggested that moderate applications of mineral fertilizers can influence plant defense mechanisms against pests and diseases (Bala et al., 2018; Hu et al., 2021; Lambers, 2022; Lopez et al., 2023; Neher and Barbercheck, 2019). This influence can be either direct—by stimulating enzymes that produce defensive metabolites like callose, glucosinolates, lignin, phenols, and phytoalexins—or indirect—by improving the agrochemical and microbiological properties of soils (Gautam et al., 2020; Geisseler and Scow, 2014; Hu et al., 2021; Jacoby et al., 2017; Tatsumi et al., 2020; Widdig et al., 2020). For example, such fertilization encourages the proliferation of soil microbes responsible for ammonification and nitrification, as well as spore-forming bacteria (Tatsumi et al., 2020). These microbes aid in the mineralization of soil organic matter and eventually release nutrients upon their death, further supporting plant growth and tolerance to pests (Gautam et al., 2020; Jacoby et al., 2017; Kaiser et al., 2010; Tatsumi et al., 2020).

The early application of NPK in split-NPK plots might enhance maize tolerance towards FAW, notably due to the roles phosphorus and potassium might play in boosting plant defenses against biotic stressors (Amtmann et al., 2008; Bala et al., 2018; Wang et al., 2013; Zhang et al., 2014). Specifically, potassium strengthens plant tissues and maintains cellular water balance, making plants less attractive to herbivorous pests like FAW (Amtmann et al., 2008; Sardans and Peñuelas, 2021; Wang et al., 2013). These tougher tissues might also discourage female FAW from laying eggs, as emerging larvae could struggle to feed on such surfaces (Pannuti et al., 2016; Sadek, 2011). Moreover, plants in plots fertilized according to recommendations may develop softer tissues due to relatively cumulative amendment of nitrogen in the advanced vegetative growth stages of the maize plants (Marschner, 2012). These softer tissues could be more appealing for FAW egg-laying (Pannuti et al., 2016; Wyckhuys and O'Neil, 2006). Moreover, FAW larval incidence tended to naturally decrease across maize growth stages, likely due to both the hardening of plant tissues as the plant matures (Durocher-Granger et al., 2021) and increased cannibalistic behavior among FAW larvae when food is scarce (Chapman et al., 1999). On the other hand, the early provision of phosphorus may not only lead to larger plant stems and more robust, as previously discussed, but it may also indirectly play a role in reducing FAW infestations in the split-NPK plots. A robust maize plant may allow the plant to absorb more nutrients and water, enhancing its overall resilience against FAW. Moreover, phosphorus is vital for cellular energy processes, potentially enabling the plant to activate its defense mechanisms against pest infestations (Lambers, 2022).

Our study found that FAW larvae significantly damaged early-stage maize plants, in line with previous research linking high larval incidence to this stage (Pannuti et al., 2016; Wyckhuys and O'Neil, 2006). Interestingly, the effectiveness of fertilization became prominent at the V6 stage when the bioinsecticide was applied. Specifically, split-NPK performed markedly better in reducing damage than enriched compost, contrary to a study Hu et al. (2022) suggesting high nitrogen might enhance insecticide tolerance in *Spodoptera litura*. Our data suggest a potential synergistic interaction between NPK fertilization and bioinsecticides, highlighting the importance of considering the specific fertilizer type, quantity used, and the splitting approach used in the present study. Moreover, we hypothesize that phosphorus in our fertilizer blend could heighten FAW vulnerability to bioinsecticides, signaling a research avenue for exploring such synergies. Our data also showed that by the V9 stage, enriched compost started to show protective effects comparable to split-NPK, both in damage reduction and in aiding plant recovery between the V6 and V9 stages. This delayed effectiveness of enriched compost might be attributed to the time required for the compost to mineralize and release beneficial minerals (Guo et al., 2020; Ho et al., 2022; Neher and Barbercheck, 2019; Palm et al., 2001; Tatsumi et al., 2020). Interestingly, even in the absence of biopesticides, both fertilization methods—split-NPK and enriched compost—offered some level of protection against FAW, especially during the rainy season. This suggests that environmental variables such as soil moisture and temperature could enhance the effectiveness of fertilization models like split-NPK and enriched compost (Guo et al., 2020; Ho et al., 2022). This insight is particularly relevant for regenerative and conservation agriculture approaches that could incorporate augmentative biological controls within an Integrated Pest Management (IPM) framework.

On another note, our study indicated that the choice of fertilization methods significantly impacts the rate at which *Telenomus remus* parasitized FAW eggs. Specifically, plots fertilized with enriched compost or split-NPK fertilizers exhibited the highest levels of egg parasitization, across both the wet and dry seasons. Similarly, predator abundance was positively influenced by the fertilization models, constantly, split-NPK. Studies have shown that soil fertilization to improve the occurrence and performance of natural enemies (Jiang and Schulthess, 2005; Veromann et al., 2013). Nitrogen amendment, for example, has been shown to improve *Cotesia flavipes* (Hymenoptera: Braconidae) parasitism on *Chilo partellus* (Lepidoptera: Crambidae) (Jiang and Schulthess, 2005). This impact of fertilization may be attributed to quantitative and qualitative difference in the release of volatile organic compounds by plants that can repel or attract insect pests and their natural enemies, or secondary metabolites that can act as antifeedant or phagostimulants released by fertilized plants compared to control plants, as well as chemical signals of frass and exuviae from insect that fed on fertilized plants (Ayelo et al., 2021; Garratt et al., 2010, 2011; Jiang and Schulthess, 2005; Wang et al., 2022). The results of our study carry significant implications for biological control of FAW. Specifically, the use of enriched compost or split-NPK fertilizers could serve as a cornerstone strategy for enhancing natural biological controls. By opting for these fertilization methods, farmers could potentially increase the rates of FAW egg parasitization by *T. remus* and boost the abundance of other natural predators. This would not only help in controlling FAW more effectively but also promote an eco-friendly approach to pest management. Interestingly, the bioinsecticide formulation had no adverse effects on *T. remus* parasitization rates or predator abundance. This suggests they could be included in IPM strategies without negative consequences on natural enemies. Additionally, our data point to a synergistic relationship between the bioinsecticide and split-NPK fertilization in enhancing natural enemy occurrence. This observed synergy warrants further in-depth investigation to uncover the underlying mechanisms that allow these two seemingly disparate strategies to function more effectively in synergy.

Finally, our study found that all fertilization methods improved maize grain yields compared to the control group. The split-NPK fertilization treatment was especially notable, achieving the highest yields in both the wet and dry seasons without bioinsecticide. When bioinsecticide was used in the dry season, split-NPK plots exhibited the peak yield of 5.90 t/ha. Similarly, in the wet season, the use of bioinsecticide on the split-NPK model boosted yields to the peak, which was statistically equivalent the grain yield observed in the recommended fertilization plots. These findings suggest that, unlike recommended fertilization and enriched compost models, split-NPK exceled in constantly delivering maximum yields across both seasons, irrespective of whether bioinsecticide is used. Split-NPK fertilizer applications have been highlighted for improving nutrient absorption efficiency, plant phenological growth parameters, and crop productivity (Davies et al., 2020). In the present study, we can explain the performance of split-NPK model over other fertilization models by the fact that this model positively affect the plant stem circumference and overall robustness which are key driving factors of maize grain yield (Mousavi and Nagy, 2021; Munyiri et al., 2013). In addition to these factors, our multi-regression analysis also pointed to the wet season as a significant positive driver for maize grain productivity. These findings strongly suggest an IPM strategy that combines robust plant varieties with split-NPK fertilization and judicious use of bioinsecticides, ideally tailored to the specific conditions of each growing season.

5. Conclusion

This study examined the impact of soil amendments, including mineral and compost fertilizers, on maize yields and FAW activity. We found that conventional fertilization increased FAW larvae, likely due to elevated nitrogen in the maize, whereas split-NPK fertilization reduced FAW incidence and leaf damage, leading to higher grain yields. Our data suggest a synergy between bioinsecticides and split-NPK in both enhancing natural enemy populations and reducing leaf damages. These insights hold substantial implications, extending into regenerative and conservation agricultural practices. These findings pave the way for future research, which should assess the cost-effectiveness of combining split-NPK and bioinsecticides, explore the efficacy of different insecticides, evaluate the environmental impacts, understand the underlying mechanisms of resilience to FAW, and examine scalability and applicability to other crops and climates.

Author contributions

Conceptualization and project administration: KRF, KA, OAA.
Data collection: KLT, ALA, KRF.
Data analysis: KRF, KMA, GEK, RG.
Resources: KA, KRF, DK, OAA.
Supervision: KA, KOF, KKMF.
Writing - original draft: KRF.
Writing - review & editing: KKMF, RG, KA, DK, KRF.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cropro.2023.106548.

References

Abang, A.F., Fotso Kuate, A., Nanga Nanga, S., Okomo Esi, R.M., Ndemah, R., Masso, C., Fiaboe, K.K.M., Hanna, R., 2021. Spatio-temporal partitioning and sharing of parasitoids by fall armyworm and maize stemborers in Cameroon. J. Appl. Entomol. 145, 55–64. https://doi.org/10.1111/JEN.12827.

Agboyi, L.K., Goergen, G., Beseh, P., Mensah, S.A., Clottey, V.A., Glikpo, R., Buddie, A., Cafà, G., Offord, L., Day, R., Rwomushana, I., Kenis, M., 2020. Parasitoid complex of fall armyworm, *Spodoptera frugiperda*. In: Ghana and Benin. https://doi.org/10.3390/insects11020068. Insects 11.

Agboyi, L.K., Nboyine, J.A., Asamani, E., Beseh, P., Badii, B.K., Kenis, M., Babendreier, D., 2023. Comparative effects of biopesticides on fall armyworm management and larval parasitism rates in Northern Ghana. J. Pest. Sci. 2004 https://doi.org/10.1007/s10340-023-01590-z.

Akutse, K.S., Kimemia, J.W., Ekesi, S., Khamis, F.M., Ombura, O.L., Subramanian, S., 2019. Ovicidal effects of entomopathogenic fungal isolates on the invasive Fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae). J. Appl. Entomol. 143, 626–634. https://doi.org/10.1111/jen.12634.

Akutse, K.S., Subramanian, S., Maniania, N.K., Dubois, T., Ekesi, S., 2020. Biopesticide research and product development in Africa for sustainable agriculture and food security – experiences from the International Centre of Insect Physiology and Ecology (*icipe*). Front. Sustain. Food Syst. 4, 1–14. https://doi.org/10.3389/fsufs.2020.563016.

Alene, A.D., Menkir, A., Ajala, S.O., Badu-Apraku, B., Olanrewaju, A.S., Manyong, V.M., Ndiaye, A., 2009. The economic and poverty impacts of maize research in West and Central Africa. Agric. Econ. 40, 535–550. https://doi.org/10.1111/j.1574-0862.2009.00396.x.

Altieri, M.A., Nicholls, C.I., 2003. Soil fertility management and insect pests: harmonizing soil and plant health in agroecosystems. Soil Tillage Res. 72, 203–211. https://doi.org/10.1016/S0167-1987(03)00089-8.

Amtmann, A., Troufflard, S., Armengaud, P., 2008. The effect of potassium nutrition on pest and disease resistance in plants. Physiol. Plantarum 133, 682–691. https://doi.org/10.1111/j.1399-3054.2008.01075.x.

Assefa, F., Ayalew, D., 2019. Status and control measures of Fall Armyworm (*Spodoptera frugiperda*) infestations in maize fields in Ethiopia: a review. Cogent Food Agric. 5 https://doi.org/10.1080/23311932.2019.1641902.

Ayelo, P.M., Yusuf, A.A., Pirk, C.W.W., Chailleux, A., Mohamed, S.A., Deletre, E., 2021. Terpenes from herbivore-induced tomato plant volatiles attract *Nesidiocoris tenuis* (Hemiptera: Miridae), a predator of major tomato pests. Pest Manag. Sci. 77, 5255–5267. https://doi.org/10.1002/ps.6568.

Babendreier, D., Agboyi, K.L., Beseh, P., Osae, M., Nboyine, J., Ofori, S.E.K., Frimpong, J. O., Attuquaye, C.V., Kenis, M., 2020. The efficacy of alternative, environmentally friendly plant protection measures for control of Fall armyworm, Spodoptera frugiperda, in maize. Insects. https://doi.org/10.3390/insects11040240.

Badu-Apraku, B., Fakorede, M.A.B., 2017. Maize in sub-Saharan Africa: importance and production constraints. In: Advances in Genetic Enhancement of Early and Extra-early Maize for Sub-saharan Africa. Springer International Publishing AG, p. 632. https://doi.org/10.1007/978-3-319-64852-1, 2017.

Bala, K., Sood, A., Pathania, V., Thakur, S., 2018. Effect of plant nutrition in insect pest management: a review. J. Pharmacogn. Phytochem. 7, 2737–2742.

Cairns, J.E., Hellin, J., Sonder, K., Araus, J.L., MacRobert, J.F., Thierfelder, C., Prasanna, B.M., 2013. Adapting maize production to climate change in sub-Saharan Africa. Food Secur. 5, 345–360. https://doi.org/10.1007/s12571-013-0256-x.

Chandler, D., Bailey, A.S., Mark Tatchell, G., Davidson, G., Greaves, J., Grant, W.P., 2011. The development, regulation and use of biopesticides for integrated pest management. Philos. Trans. R. Soc. B Biol. Sci. 366, 1987–1998. https://doi.org/10.1098/rstb.2010.0390.

Chapman, J.W., Williams, T., Escribano, A., Caballero, P., Cave, R.D., Goulson, D., 1999. Fitness consequences of cannibalism in the fall armyworm, *Spodoptera frugiperda*. Behav. Ecol. 10, 298–303. https://doi.org/10.1093/beheco/10.3.298.

Ciampitti, I.A., Camberato, J.J., Murrell, S.T., Vyn, T.J., 2013. Maize nutrient accumulation and partitioning in response to plant density and nitrogen rate: I. macronutrients. Agron. J. 105, 727–734. https://doi.org/10.2134/agronj2012.0467.

Colmenarez, Y.C., Babendreier, D., Ferrer Wurst, F.R., Vásquez-Freytez, C.L., de Freitas Bueno, A., 2022. The use of *Telenomus remus* (Nixon, 1937) (Hymenoptera: Scelionidae) in the management of *Spodoptera* spp.: potential, challenges and major benefits. CABI Agric. Biosci. 3, 1–13. https://doi.org/10.1186/s43170-021-00071-6.

Davies, B., Coulter, J.A., Pagliari, P.H., 2020. Timing and rate of nitrogen fertilization influence maize yield and nitrogen use efficiency. PLoS One 15, 19. https://doi.org/10.1371/journal.pone.0233674.

Day, R., Abrahams, P., Bateman, M., Beale, T., Clottey, V., Colmenarez, Y., Corniani, N., Early, R., Godwin, J., Gomez, J., Moreno, P.G., Murphy, S.T., Oppong-Mensah, B., Phiri, N., Pratt, C., Silvestri, S., Witt, A., 2017. Fall armyworm: impacts and implications for Africa. Outlooks Pest Manag. 28, 196–201. https://doi.org/10.1564/v28_oct_02.

De Oliveira, S.M., De Almeida, R.E.M., Ciampitti, I.A., Junior, C.P., Lago, B.C., Trivelin, P.C.O., Favarin, J.L., 2018. Understanding N timing in corn yield and fertilizer N recovery: an insight from an isotopic labeled-N determination. PLoS One 13, 14. https://doi.org/10.1371/journal.pone.0192776.

Deshmukh, S., Pavithra, H.B., Kalleshwaraswamy, C.M., Shivanna, B.K., Maruthi, M.S., Mota-Sanchez, D., 2020. Field efficacy of insecticides for management of invasive fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) on maize in India. Fla. Entomol. 103, 221–227. https://doi.org/10.1653/024.103.0211.

Durocher-Granger, L., Mfune, T., Musesha, M., Lowry, A., Reynolds, K., Buddie, A., Cafà, G., Offord, L., Chipabika, G., Dicke, M., Kenis, M., 2021. Factors influencing the occurrence of fall armyworm parasitoids in Zambia. J. Pest. Sci. 94, 1133–1146. https://doi.org/10.1007/s10340-020-01320-9, 2004.

Ekpa, O., Palacios-Rojas, N., Kruseman, G., Fogliano, V., Linnemann, A.R., 2018. Sub-Saharan African maize-based foods: technological perspectives to increase the food and nutrition security impacts of maize breeding programmes. Global Food Secur. 17, 48–56. https://doi.org/10.1016/j.gfs.2018.03.007.

Fiaboe, K.R., Fening, K.O., Gbewonyo, W.S.K., Deshmukh, S., 2023. Bionomic responses of *Spodoptera frugiperda* (J. E. Smith) to lethal and sublethal concentrations of selected insecticides. PLoS One 18, e0290390. https://doi.org/10.1371/journal.pone.0290390.

Fournier, M., Dlouhá, J., Jaouen, G., Almeras, T., 2013. Integrative biomechanics for tree ecology: beyond wood density and strength. J. Exp. Bot. 64, 4793–4815. https://doi.org/10.1093/jxb/ert279.

Garratt, M.P.D., Wright, D.J., Leather, S.R., 2011. The effects of farming system and fertilisers on pests and natural enemies: a synthesis of current research. Agric. Ecosyst. Environ. 141, 261–270. https://doi.org/10.1016/j.agee.2011.03.014.

Garratt, M.P.D., Wright, D.J., Leather, S.R., 2010. The effects of organic and conventional fertilizers on cereal aphids and their natural enemies. Agric. For. Entomol. 12, 307–318. https://doi.org/10.1111/j.1461-9563.2010.00480.x.

Gautam, A., Sekaran, U., Guzman, J., Kovács, P., Hernandez, J.L.G., Kumar, S., 2020. Responses of soil microbial community structure and enzymatic activities to long-term application of mineral fertilizer and beef manure. Environ. Sustain. Indic. 8 https://doi.org/10.1016/j.indic.2020.100073.

Geisseler, D., Scow, K.M., 2014. Long-term effects of mineral fertilizers on soil microorganisms - a review. Soil Biol. Biochem. 75, 54–63. https://doi.org/10.1016/j.soilbio.2014.03.023.

Goergen, G., Kumar, P.L., Sankung, S.B., Togola, A., Tamò, M., 2016. First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (J E Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in West and Central Africa. PLoS One 11, 1–9. https://doi.org/10.1371/journal.pone.0165632.

Guo, X. xia, Liu, H. tao, Zhang, J., 2020. The role of biochar in organic waste composting and soil improvement: a review. Waste Manag. 102, 884–899. https://doi.org/10.1016/j.wasman.2019.12.003.

Ho, T.T.K., Tra, V.T., Le, T.H., Nguyen, N.K.Q., Tran, C.S., Nguyen, P.T., Vo, T.D.H., Thai, V.N., Bui, X.T., 2022. Compost to improve sustainable soil cultivation and crop productivity. Case Stud. Chem. Environ. Eng. 6, 100211 https://doi.org/10.1016/j.cscee.2022.100211.

Hou, Y., Xu, X., Kong, L., Zhang, L., Zhang, Y., Liu, Z., 2022. Improving nitrogen contribution in maize post-tasseling using optimum management under mulch drip irrigation in the semiarid region of Northeast China. Front. Plant Sci. 13, 1–12. https://doi.org/10.3389/fpls.2022.1095314.

Hu, L., Sun, Z., Xu, C., Wang, J., Mallik, A.U., Gu, C., Chen, D., Lu, L., Zeng, R., Song, Y., 2022. High nitrogen in maize enriches gut microbiota conferring insecticide tolerance in lepidopteran pest *Spodoptera litura*. iScience 25, 103726. https://doi.org/10.1016/j.isci.2021.103726.

Hu, L., Wu, Z., Robert, C.A.M., Ouyang, X., Züst, T., Mestrot, A., Xu, J., Erb, M., 2021. Soil chemistry determines whether defensive plant secondary metabolites promote or suppress herbivore growth. Proc. Natl. Acad. Sci. U.S.A. 118 https://doi.org/10.1073/pnas.2109602118.

Idrees, A., Qadir, Z.A., Afzal, A., Ranran, Q., Li, J., 2022. Laboratory efficacy of selected synthetic insecticides against second instar invasive fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae) larvae. PLoS One 17, 1–14. https://doi.org/10.1371/journal.pone.0265265.

Infante, P.A., Moore, K.J., Lenssen, A.W., Archontoulis, S.V., Scott, P., Fei, S.-Z., 2018. Phenology and biomass production of adapted and non-adapted tropical corn populations in central Iowa. Agron. J. 110, 171–182. https://doi.org/10.2134/agronj2016.11.0666.

Jacoby, R., Peukert, M., Succurro, A., Koprivova, A., Kopriva, S., 2017. The role of soil microorganisms in plant mineral nutrition—current knowledge and future directions. Front. Plant Sci. 8, 1–19. https://doi.org/10.3389/fpls.2017.01617.

Jiang, N., Schulthess, F., 2005. The effect of nitrogen fertilizer application to maize and sorghum on the bionomics of *Chilo partellus* (Lepidoptera: Crambidae) and the performance of its larval parasitoid *Cotesia flavipes* (Hymenoptera: Braconidae). Bull. Entomol. Res. 95, 495–504. https://doi.org/10.1079/ber2005381.

Kaiser, C., Koranda, M., Kitzler, B., Fuchslueger, L., Schnecker, J., Schweiger, P., Rasche, F., Zechmeister-Boltenstern, S., Sessitsch, A., Richter, A., 2010. Belowground carbon allocation by trees drives seasonal patterns of extracellular enzyme activities by altering microbial community composition in a beech forest soil. New Phytol. 187, 843–858. https://doi.org/10.1111/j.1469-8137.2010.03321.x.

Kenis, M., du Plessis, H., Van den Berg, J., Ba, M.N., Goergen, G., Kwadjo, K.E., Baoua, I., Tefera, T., Buddie, A., Cafà, G., Offord, L., Rwomushana, I., Polaszek, A., 2019.

Telenomus remus, a candidate parasitoid for the biological control of *Spodoptera frugiperda* in Africa, is already present on the continent. Insects 10, 1–10. https://doi.org/10.3390/insects10040092.

Koffi, D., Agboka, K., Adenka, D.K., Osae, M., Tounou, A.K., Anani Adjevi, M.K., Fening, K.O., Fening, K.O., Meagher, R.L., 2020a. Maize infestation of fall armyworm (Lepidoptera: Noctuidae) within agro-ecological zones of Togo and Ghana in west Africa 3 Yr after its invasion. Environ. Entomol. 49, 645–650. https://doi.org/10.1093/ee/nvaa048.

Koffi, D., Kyerematen, R., Eziah, V.Y., Agboka, K., Adom, M., Goergen, G., Meagher, R.L., 2020b. Natural enemies of the fall armyworm, Spodoptera frugiperda (J.E. Smith) (Lepidoptera: Noctuidae) in Ghana. Fla. Entomol. 103, 85. https://doi.org/10.1653/024.103.0414.

Koffi, D., Kyerematen, R., Eziah, V.Y., Osei-Mensah, Y.O., Afreh-Nuamah, K., Aboagye, E., Osae, M., Meagher, R.L., 2021. Assessment of impacts of fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae) on maize production in Ghana. J. Integr. Pest Manag. 11 https://doi.org/10.1093/jipm/pmaa015.

Kuate, A.F., Hanna, R., Doumtsop Fotio, A.R.P., Abang, A.F., Nanga, S.N., Ngatat, S., Tindo, M., Masso, C., Ndemah, R., Suh, C., Fiaboe, K.K.M., 2019. *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) in Cameroon: case study on its distribution, damage, pesticide use, genetic differentiation and host plants. PLoS One 14, 1–18. https://doi.org/10.1371/journal.pone.0217653.

Lambers, H., 2022. Phosphorus acquisition and utilization in plants. Annu. Rev. Plant Biol. 73, 17–42. https://doi.org/10.1146/annurev-arplant-102720-125738.

Li, Z., Xu, B., Du, T., Ma, Y., Tian, X., Wang, F., Wang, W., 2021. Excessive Nitrogen fertilization favors the colonization, survival, and development of *Sogatella furcifera* via bottom-up effects. Plant 10, 875. https://doi.org/10.3390/plants10050875.

Lopez, G., Ahmadi, S.H., Amelung, W., Athmann, M., Ewert, F., Gaiser, T., Gocke, M.I., Kautz, T., Postma, J., Rachmilevitch, S., Schaaf, G., Schnepf, A., Stoschus, A., Watt, M., Yu, P., Seidel, S.J., 2023. Nutrient deficiency effects on root architecture and root-to-shoot ratio in arable crops. Front. Plant Sci. 13, 1–18. https://doi.org/10.3389/fpls.2022.1067498.

Marschner, P., 2012. Marschner's Mineral Nutrition of Higher Plants, third ed. Academic Press. https://doi.org/10.1016/C2009-0-63043-9.

Midega, C.A.O., Pittchar, J.O., Pickett, J.A., Hailu, G.W., Khan, Z.R., 2018. A climate-adapted push-pull system effectively controls Fall armyworm, *Spodoptera frugiperda* (J E Smith), in maize in East Africa. Crop Protect. 105, 10–15. https://doi.org/10.1016/j.cropro.2017.11.003.

Montezano, D.G., Specht, A., Sosa-Gómez, D.R., Roque-Specht, V.F., Sousa-Silva, J.C., Paula-Moraes, S.V., Peterson, J.A., Hunt, T.E., 2018. Host plants of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the americas. Afr. Entomol. 26, 286–300. https://doi.org/10.4001/003.026.0286.

Mousavi, S.M.N., Nagy, J., 2021. Evaluation of plant characteristics related to grain yield of FAO410 and FAO340 hybrids using regression models. Cereal Res. Commun. 49, 161–169. https://doi.org/10.1007/s42976-020-00076-3.

Munyiri, S.W., Mugo, S.N., Otim, M., Tefera, T., Beyene, Y., Mwololo, J.K., Okori, P., 2013. Responses of tropical maize landraces to damage by *Chilo partellus* stem borer. Afr. J. Biotechnol. 12, 1229–1235. https://doi.org/10.5897/AJB12.1802.

Neher, D.A., Barbercheck, M.E., 2019. Soil microarthropods and soil health: intersection of decomposition and pest suppression in agroecosystems. Insects 10, 1–13. https://doi.org/10.3390/insects10120414.

Niassy, S., Agbodzavu, M.K., Kimathi, E., Mutune, B., Abdel-Rahman, E.F.M., Salifu, D., Hailu, G., Belayneh, Y.T., Felege, E., Tonnang, H.E.Z., Ekesi, S., Subramanian, S., 2021. Bioecology of fall armyworm *Spodoptera frugiperda* (J. E. Smith), its management and potential patterns of seasonal spread in Africa. PLoS One 16, 1–24. https://doi.org/10.1371/journal.pone.0249042.

Nimon, P., Issaou, L., Konko, Y., Kokou, K., 2020. Spatio-temporal patterns of rainfall variability for wet season over Togo in West Africa. OALib 7, 1–11. https://doi.org/10.4236/oalib.1106044.

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric. Ecosyst. Environ. 83, 27–42. https://doi.org/10.1016/S0167-8809(00)00267-X.

Pannuti, L.E.R., Baldin, E.L.L., Hunt, T.E., Paula-Moraes, S.V., 2016. On-plant larval movement and feeding behavior of fall armyworm (Lepidoptera: Noctuidae) on reproductive corn stages. Environ. Entomol. 45, 192–200. https://doi.org/10.1093/ee/nvv159.

Prasanna, B.M., Huesing, J.E., Eddy, R., Peschke, V.M. (Eds.), 2018. Fall Armyworm in Africa: A Guide for Intergrated Pest Management, first ed. CIMMYT, Mexico, CDMX.

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Found. Stat. Comput., Vienna, Austria.

Rashid, M.M., Ahmed, N., Jahan, M., Islam, K.S., Nansen, C., Willers, J.L., Ali, M.P., 2017. Higher fertilizer inputs increase fitness traits of brown planthopper in rice. Sci. Rep. 7, 1–16. https://doi.org/10.1038/s41598-017-05023-7.

Sadek, M.M., 2011. Complementary behaviors of maternal and offspring *Spodoptera littoralis*: oviposition site selection and larval movement together maximize performance. J. Insect Behav. 24, 67–82. https://doi.org/10.1007/s10905-010-9238-4.

Sallah, P.Y., Twumasi-Afriyie, S., Ahenkora, K., Asiedu, E.A., Obeng-Antwi, E., Osei-Yeboah, S., Frimpong-Manso, P.P., Ankomah, A., Dzah, B.D., 2008. Agronomic potentials of quality protein maize hybrids developed in Ghana. Ghana J. Agric. Sci. 40, 81–89. https://doi.org/10.4314/gjas.v40i1.2157.

Santpoort, R., 2020. The drivers of maize area expansion in sub-Saharan Africa. How policies to boost maize production overlook the interests of smallholder farmers. Land 9. https://doi.org/10.3390/land9030068.

Sardans, J., Peñuelas, J., 2021. Potassium Control of Plant Functions: Ecological and Agricultural Implications. Plants. https://doi.org/10.3390/plants10020419.

Schlickmann-Tank, J.A., Morales-Galván, O., Pineda-Pineda, J., Espinosa-Vázquez, G., Colinas-León, M.T., Vargas-Hernández, M., 2020. Relationship between chemical fertilization in sorghum and *Melanaphis sacchari/sorghi* (Hemiptera: aphididae) populations. Agron. Colomb. 38, 369–378. https://doi.org/10.15446/agron.colomb.v38n3.87308.

Schmidt-Jeffris, R.A., Moretti, E.A., Wickings, K., Wolfin, M.S., Northfield, T.D., Linn, C. E., Nault, B.A., 2021. Conventional soil management may promote nutrients that lure an insect pest to a toxic crop. Environ. Entomol. 50, 433–443. https://doi.org/10.1093/ee/nvaa167.

Sisay, B., Simiyu, J., Mendesil, E., Likhayo, P., Ayalew, G., Mohamed, S., Subramanian, S., Tefera, T., 2019. Fall armyworm, *Spodoptera frugiperda* infestations in East Africa: assessment of damage and parasitism. Insects 10, 1–10. https://doi.org/10.3390/insects10070195.

Sokame, B.M., Obonyo, J., Sammy, E.M., Mohamed, S.A., Subramanian, S., Kilalo, D.C., Juma, G., Calatayud, P.A., 2021. Impact of the exotic fall armyworm on larval parasitoids associated with the lepidopteran maize stemborers in Kenya. BioControl 66, 193–204. https://doi.org/10.1007/s10526-020-10059-2.

Tambo, J.A., Abdoulaye, T., 2012. Climate change and agricultural technology adoption: the case of drought tolerant maize in rural Nigeria. Mitig. Adapt. Strategies Glob. Change 17, 277–292. https://doi.org/10.1007/s11027-011-9325-7.

Tatsumi, C., Taniguchi, T., Du, S., Yamanaka, N., Tateno, R., 2020. Soil nitrogen cycling is determined by the competition between mycorrhiza and ammonia-oxidizing prokaryotes. Ecology 101. https://doi.org/10.1002/ecy.2963.

Togola, A., Meseka, S., Menkir, A., Badu-Apraku, B., Boukar, O., Tamò, M., Djouaka, R., 2018. Measurement of pesticide residues from chemical control of the invasive *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in a maize experimental field in Mokwa, Nigeria. Int. J. Environ. Res. Publ. Health 15, 11. https://doi.org/10.3390/ijerph15050849.

Tully, K., Sullivan, C., Weil, R., Sanchez, P., 2015. The state of soil degradation in sub-Saharan Africa: baselines, trajectories, and solutions. Sustain. Times 7, 6523–6552. https://doi.org/10.3390/su7066523.

Van Zyl, J., Nel, H.J.G., 1988. The role of the maize industry in the South African economy. Agrekon 27, 10–16. https://doi.org/10.1080/03031853.1988.9524125.

Veromann, E., Toome, M., Kännaste, A., Kaasik, R., Copolovici, L., Flink, J., Kovács, G., Narits, L., Luik, A., Niinemets, Ü., 2013. Effects of nitrogen fertilization on insect pests, their parasitoids, plant diseases and volatile organic compounds in Brassica napus. Crop Protect. 43, 79–88. https://doi.org/10.1016/j.cropro.2012.09.001.

Wang, M., Zheng, Q., Shen, Q., Guo, S., 2013. The critical role of potassium in plant stress response. Int. J. Mol. Sci. 14, 7370–7390. https://doi.org/10.3390/ijms14047370.

Wang, W., Wang, X., Liao, H., Feng, Y., Guo, Y., Shu, Y., Wang, J., 2022. Effects of Nitrogen supply on induced defense in maize (*Zea mays*) against Fall Armyworm (*Spodoptera frugiperda*). Int. J. Mol. Sci. 23 https://doi.org/10.3390/ijms231810457.

Widdig, M., Heintz-Buschart, A., Schleuss, P.M., Guhr, A., Borer, E.T., Seabloom, E.W., Spohn, M., 2020. Effects of nitrogen and phosphorus addition on microbial community composition and element cycling in a grassland soil. Soil Biol. Biochem. 151 https://doi.org/10.1016/j.soilbio.2020.108041.

Wyckhuys, K.A.G., O'Neil, R.J., 2006. Population dynamics of *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) and associated arthropod natural enemies in Honduran subsistence maize. Crop Protect. 25, 1180–1190. https://doi.org/10.1016/j.cropro.2006.03.003.

Xue, J., Ming, B., Xie, R., Wang, K., Hou, P., Li, S., 2020. Evaluation of maize lodging resistance based on the critical wind speed of stalk breaking during the late growth stage. Plant Methods 16, 1–12. https://doi.org/10.1186/s13007-020-00689-z.

Zhang, K., Liu, H., Tao, P., Chen, H., 2014. Comparative proteomic analyses provide new insights into low phosphorus stress responses in maize leaves. PLoS One 9. https://doi.org/10.1371/journal.pone.0098215.

Zhou, Y., Li, Y., Liu, X., Wang, K., Muhammad, T., 2019. Synergistic improvement in spring maize yield and quality with micro/nanobubbles water oxygation. Sci. Rep. 9, 1–10. https://doi.org/10.1038/s41598-019-41617-z.