Evaluation of Sustainable Management Options for the Fall Armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in Maize Production in Burkina Faso

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The fall armyworm, *Spodoptera frugiperda*, attacks important cereals, such as corn, millet and sorghum, causing economic damage. It is has been a new biotic constraint to African agriculture since it invaded the African continent in 2016. Reported in Burkina Faso in 2017, it is present in all regions of the country, causing significant damage to cereal crops. Faced with this threat, farmers have opposed several control methods, including mainly synthetic chemical pesticides with all the consequences that this entails. With this in mind, an evaluation of several sustainable management options for this insect pest was initiated in Bama in western Burkina Faso during the consecutive dry and wet seasons of 2023. For this purpose, a completely randomized block design was set up. It consisted of four treatments, T0 = absolute control; T1=combination Push-pull technology-*Jatropha curcas* oil; T2 = combination Push-pull technology-*Azadirachta indica* oil; T3=combination Push-pull technology-Emamectin benzoate. Four replicates were used. Data were collected by random sampling on twenty maize plants in each elementary plot. Results showed that the different *S. frugiperda* management options reduced significantly pest damage rates: T3 (28% dry season, 34.50% wet season), T1 (41.88% dry season, 47.64% wet season) and T2 (37.88% dry season, 45.38% wet season) compared with the control (66.38% dry season, 59.75% wet season). The best yields were also recorded with management options T1 (3.52t/ha), T2 (3.73t/ha), and T3 (3.57t/ha) for the dry season and T1 (2.91t/ha), T2 (3.26t/ha) and T3 (3.34t/ha) for the wet season and were not significantly different.
The Push-Pull-Emamectin option is recommended to Burkina Faso farmers for the control of the Fall Armyworm.

1. INTRODUCTION

Cereal products play a major role in human and animal nutrition worldwide. In 2019, maize represented the world's second most important cereal in terms of production, with 1,148,487,000 tons, or 12.27% of production, ahead of wheat (8.18%) and paddy rice (8.07%) [1]. In Africa, maize maintains its second-place ranking in terms of quantity produced among cereals, with 81,891,000 tons out of a total of 946,111,000 tons, or 8.66% of the continent's cereal production [1]. In 2021, South Africa contributed 1.34% to global maize production, according to a survey by the USDA Foreign Agricultural Service. In Burkina Faso, maize ranked first (19.87%) in cereal production in 2019, ahead of paddy rice (4.38%) [1]. With cereal production estimated at 5,763,232 tons on an area of 4,275,072 ha in 2021, maize ranked second in terms of area (28%) after sorghum (42%) [2]. This production satisfies a significant proportion of the country's maize food requirement, but still needs to be increased to take into account the needs of industry and livestock [3]. Unfortunately, maize production faces enormous difficulties including unfavorable agro-climatic conditions, insecure land tenure, difficulties in accessing finance, insufficient agricultural inputs and some herbivorous pests such as *Spodoptera frugiperda* Smith, which commonly

known as the fall armyworm (FAW). FAW is a polyphagous insect known for its with great capacity to spread, multiply and destroy crops which can feed on over 350 plant species [4].

Of these host plant species listed by Montezano et al. [4], 30% belong to the Poaceae. Despite this broad host range, the most regularly impacted in Africa, Asia and now Australia appears to be maize (*Zea mays* L., 1753) [5,6]. *S. frugiperda* attacks all aerial parts of corn, stems, leaves, flowers and ears [7] (Yaméogo et al., 2024). A strong egg-laying preference of *S. frugiperda* on *Z. mays* has been evidenced in the laboratory [8,9,10]. This oviposition preference correlates with larval performance, as *Z. mays* appears to be highly conducive to the survival and development of *S. frugiperda* larvae compared with other cultivated species [11,8,12]. It threatens the food and nutritional security of thousands of farmers due to the extent of its damage to maize and other cereal crops, resulting in significant yield losses and economic consequences [5,7,6].

To deal with this situation, the Burkina Faso government supported growers as soon as the insect pest appeared, with 6,465 liters of chemical pesticides in addition to the quantities that themselves purchased [2]. Using pesticides on traditional cereals such as maize, sorghum

and millet was not common in Burkina Faso before the arrival of *S. frugiperda* in 2017 [13,14]. Henceforth, chemical control is the most used control method by growers [15,16]. However, the increasing and uncontrolled use of chemical insecticides can destroy the biodiversity of natural enemies and causing the emergence of resistant insect populations [17,18]. For this reason, biological control is likely to become an important part of *S. frugiperda* management in Africa [19,13]. Habitat diversification strategies are attracting much interest as pest control methods [20]. So, as part of one such research initiative, the International Insect Research Center (ICIPE) and its partners have developed a new technology called push-pull technology to control Striga weeds, improving soil fertility and pest management, the most recent of which is FAW [21] (Midega et al., 2018). It's a biological integrated pest control technique using a repellent plant ("Push") and an attractive plant ("Pull") which traps pests. Push-Pull was developed in 1999 by Indian Professor Zeyaur Khan, a scientist at the International Insect Research Center at Mbita station in Kenya, in collaboration with local farmers. Push-Pull technology is therefore an association of crops that increases plant biodiversity [22]. Plant biodiversity plays a major role in balancing insect populations, as it increases the impact of natural enemies in regulating pest populations [23,24]. Push-Pull involves intercropping cereals with a forage legume, *Desmodium*, and planting the poaceous *Brachiaria* as a border crop. *Desmodium* "pushes" stem borers and attracts their natural enemies, while *Brachiaria* "pulls" these insect pests towards itself in order to trap them with substances it secretes that inhibit *S. frugiperda* larval development [25,26]. This technology has been tested in East African countries such as Kenya, Uganda, Ethiopia and Tanzania, and has raised great hopes for the ecological management of stem-boring pests and weeds such as striga [27,28]. By 2014, over 96,000 farmers in East Africa had adopted Push-pull strategy and their maize yields increased by an average of one to 3.5 tons per hectare, without the use of chemical insecticides and with minimal inputs [29]. In addition to improving maize yields, the strategy increased small-scale livestock production, conserved soil quality, controlled weeds, enhanced functional biodiversity and increased the income and empowerment of small-scale farmers [30]. It is in this context that the present study, the first of its kind in Burkina Faso was initiated using Push-Pull technology in combination with insecticides (both chemical and botanicals) aim to find an effective, ecological and sustainable management strategy for *S. frugiperda* in Burkina Faso.

2. MATERIALS AND METHODS

2.1 Materials

Study site: The study was conducted at the Bama agricultural research station (Fig. 1) during two consecutive agricultural seasons, the 2023 dry season and the 2023 wet season. The climate in the study area is South Sudanian, with a distinct rainy season from May to October and a dry season from November to April. Rainfall frequently exceeds 1000 mm [31].

Plant material:

It consisted of:

- The popularized maize variety Komsaya, medium-cycle, high-yielding and known to be not very susceptible to *Spodoptera frugiperda* attacks according to Yaméogo et al. [32];
- *Desmodium uncinatum* (Jacq.), a perennial legume that covers the soil between the rows of the main crop (maize);
- *Brachiaria mullato* II (L.), a perennial poaceae.

Insecticides: The insecticides used are shown in Table 1.

2.2 Methods

2.2.1 Experimental set-up

The experimental set-up is a Fisher block with 4 treatments and 4 replicates, i.e. 16 elementary plots. Each elementary plot is 8 m long and 5 m wide, i.e. a surface area of 40 m2. Spacing is 5 m between blocks and 5 m between treatments. The dimensions of the trial are 55 m long by 39 m wide, giving a total area of 2145 m². The different treatments were composed as follows:

T0= absolute control with no technology or insecticide application;

T1= combination of Push-pull technology and *Jatropha curcas* (Linnaeus) oil;

T2= Push-pull technology - *Azadirachta indica* (A. Juss.) oil combination;

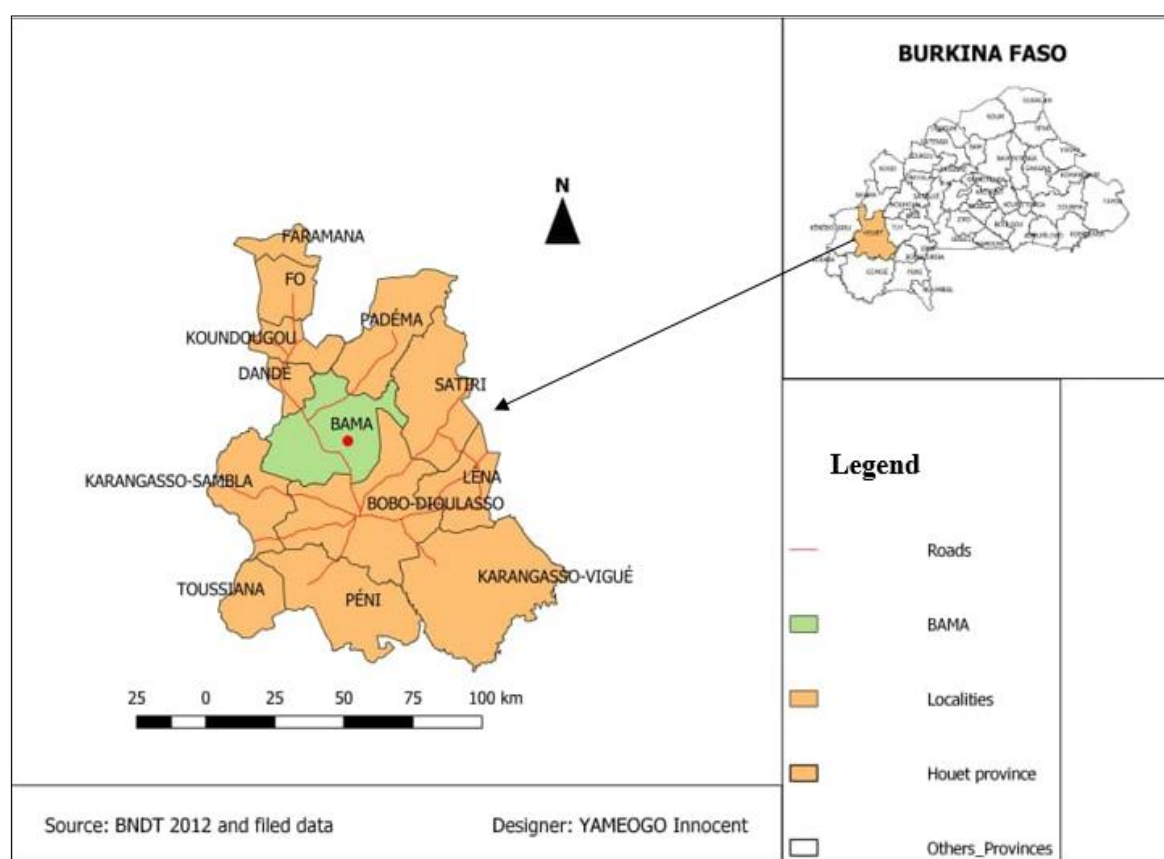T3= Push-pull technology - Emamectin benzoate combination.

Fig. 1. Location of study area

Table 1. Characteristics of insecticides used

Commercial names	Active ingredients	Doses	Crops	Targets
Emacot	Emamectine benzoate	0.5l/ha	Vegetable crops, Subsistence crops, Cotton	*Spodoptera frugiperda* *Helicoverpa armigera* (Hübner)*, Earias* spp (Hübner)*, Diparopsis watersi* (Rothschild)*, Spodoptera littoralis* (Boisduval)*, Sylepta derogata* (Fabricius) *Plutella xylostella* (Linnaeus)
Neem oil	Azadirachtine	5l/ha	Vegetable crops, Subsistence crops, Fruit and flower crops	*Planococcus* spp. (Risso), *Icerya purchasi* (Maskell), *Aonidiella aurantii* (Maskell), *Ceroplaste rusci* (Linnaeus) etc.
Jatropha curcas' oil		5l/ha	Vegetable crops, Subsistence crops, Fruit and flower crops	*Spodoptera. frugiperda, Busseola fusca* (Fuller), *Sesamia calamistis* (Hampson)*, Aphis gossypii* (Glover), *Callosobruchus maculatus* (Linnaeus).

2.2.2 Setting up the experiment

2.2.2.1 Soil preparation and crop establishment

The experiment was conducted in the dry season from January to May 2023 and in the wet season from June to October 2023.

In order to provide the best conditions for the development of the maize plants, a 15 to 25 cm deep ploughing was carried out on wet soil, followed by levelling to ensure a good distribution of inputs in the soil. The system was set up using metric tape, rope and stakes, in accordance with the experimental system, followed by a rack to mark out the sowing lines. Finally, the sub-plots were labelled to facilitate their identification for data collection and processing operations.

The two species involved in the Push-Pull technology were planted 10 days before maize sowing, on January 09 and July 05, 2023 for the dry and wet seasons respectively. Maize was sown at a rate of 3 to 4 seeds per poquet at a depth of 2 to 6 cm, followed by resowing 9 days after the 1st sowing (JAS). Maize was sown at 80 cm between rows and 40 cm between rows. *Desmodium uncinatum* is sown in continuous rows between two rows of maize and *B. mullato* II is sown in rows of three bunches 20 cm apart.

Weeding was carried out at 2 plants per bunch from the 9th day of the season. The first weeding was carried out at 10 to 15 days. Mineral fertilization at a rate of 300 kg/ha of cotton fertilizer (14-23-14, 6S+1B) was applied on the same date. A second weeding was carried out two weeks later, between DAS 22 and 25, followed by the application of the first fraction of cover fertilizer at a rate of 100 kg/ha of urea (46%), i.e. 6.4 kg for the trial.

Ridging was carried out between the 38th and 40th DAS to reinforce plant vigor and cover the second fraction of urea applied at a rate of 50 kg/ha of urea (46%), i.e. 3.2 kg for the trial.

An irrigation system was set up in the dry season to supply water to the plants every three days during their development cycle. This was gravity irrigation or surface irrigation which consists of circulating water without pressure on the surface of cultivated plots, by channeling it.

Whether it is a flood or a furrow, in this method the water is diverted directly onto the ground surface, without any outfall or component. This technique has a relatively low cost and does not require any technology. Irrigation began at the time of ploughing and ended one week before harvest.

2.2.2.2 Insecticide treatments

Insecticide treatments were carried out once a week from maize emergence to plant maturity, as follows:

- For the neem oil treatment, as for *Jatropha curcas*, we used 650 liters of water + 5 liters of neem or *Jatropha curcas* oil + 65 ml of liquid soap for an area of one hectare. So, to treat the 40 m² of the elementary plot, we used 2.6 liters of water + 20ml of neem or *Jatropha curcas* oil + 0.26 ml of liquid soap.

- The dose of Emamectin benzoate to be applied is 0.5 liters of commercial product/ha, i.e. 2 ml and 1.28 liters of Emamectin benzoate water for 40 m² of elementary plot.

- Control plot: no insecticide or Push-Pull treatment.

2.2.2.3 Data collection

In each of the elementary plots, 20 maize plants were randomly sampled each week, from JAS 13 to maize maturity. The following parameters were collected using a data collection sheet:

- Plant size;
- Number of leaves/plant ;
- Number of whorls/plant;
- Number of whorls attacked/plant;
- Number of attacked leaves/plant;
- Number of attacked spikes/plant;
- Presence or absence of larvae on observed plants.

The damage caused by *S. frugiperda* larvae in the whorls and on the leaves of each plant was recorded. Damage was scored using the *S. frugiperda* damage assessment scale developed by Davis and Williams [33].

The infestation rate was determined, according to the formula proposed by FAO [34]:

Infestation rate = (Σ of infested plants) x 100 / Σ total of targeted plants.

At maturity, a 20 m² yield square was laid out in each elementary plot, taking care to leave at

least one border line on each side of the plot. The ears harvested from the various yield squares were dried, shelled and their kernels weighed. The weight of the weighed samples was corrected after adjusting for a moisture content of 14%. The biomass of the yield squares was also harvested and weighed.

- RDT (t/ha) = grain dry weight (kg) x 10000 (m2) / CR area (m2) x 1000
- RDT (14%) (t/ha) = (RDT at X% x (100-X)) / (100-14)

RDT = yield
X = grain moisture content.
CR= yield square

2.2.3 Data analysis

The data collected were entered and processed on a Microsoft Excel 2010 spreadsheet, then imported into R software version 4. 2. 1. The data were subjected to a Shapiro-Wilk normality test. Data following a normal distribution were subjected to an analysis of variance. Means were separated using Tukey's test at the 5% threshold. Those that did not follow a normal distribution were subjected to the Kruskal Wallis test, and means were separated by pgirmess at the 5% threshold.

3. RESULTS AND DISCUSSION

3.1 Results

Variation in parameters associated with *S. frugiperda* as a function of factors: Table 2 presents the results of statistical analysis of mean infestation rates, mean *S. frugiperda* attack scores, and mean grain and haulm yields. Production season, treatment and phenological stages and their interaction significantly affected mean infestation rates, mean attack scores and mean grain and haulm yields (P<0.0001).

In contrast, season and treatment interaction had no significant impact (P> 0.05) on mean grain attack scores and mean grain and haulm yields over the course of the study.

Average *S. frugiperda* infestation rates in maize according to treatments: During the two growing seasons of 2023, the push-pull-Emamectin benzoate treatments showed the lowest average infestation rates, i.e. 28±20.07%

for the dry season and 34.50±16.17% for the wet season. The control treatments in both growing seasons had the highest average infestation rates (66.38±15.30%; 59.75±17.37% in the dry and wet seasons respectively). The Push-pull technology - *Jatropha curcas'* oil combination treatment (T1) showed average plant infestation rates of 41.88±16.43% for the 2023 dry season and 47.64 ±21.10% for the 2023 wet season. The Push-pull technology - neem oil combination treatment (T2) recorded a mean infestation rate of 37.88±13.97% for the 2023 dry season and 45.38 ±15.84%, for the 2023 wet season (Fig. 2). Production seasons ($X2 = 1311.9$, df = 3, p-value < 0.0001 in dry season; $X2 = 635.33$, df = 3, p-value < 0.0001 in wet season) had a highly significant impact on the average *S. frugiperda* maize infestation rates of the treatments.

Average *S. frugiperda* infestation rates in maize as a function of plant phenological stages : The curve illustrating average *S. frugiperda* infestation rates on maize in the dry season was decreasing from emergence to plant maturity, while that for the wet season was increasing from emergence to bolting and then decreasing from bolting to maize heading. The highest average infestation rate in the dry season was recorded at emergence with 59.90 ± 16.92%, while in the wet season it was recorded at bolting with 58.46 ± 19.46%. The lowest average infestation rates were recorded at heading with 34.21 ± 16.15% in the dry season and 41.56 ± 19.64% in the wet season (Fig. 3). A significant difference was observed between development stages ($X2= 457.35$; df = 3; p-value < 0.0001 in the dry season and $X2= 412.71$; df = 3; p-value < 0.0001 in the wet season) with regard to average infestation rates.

Severity of *S. frugiperda* damage on maize leaves and kernels according to treatments : The average severity of *S. frugiperda* attacks on maize leaves and kernels according to treatment is presented in Table 3. During the vegetative phase of maize, the highest average infestation scores observed were 2.59 ± 1.36 and 1.89 ± 0.97 in the dry and wet seasons respectively. These mean scores were recorded in the control treatment (T0). The lowest mean infestation scores (1.50 ± 0.83 and 1.55 ± 0.74) recorded in the dry and wet seasons respectively were observed with treatment T3 (Push-pull technology - Emamectin benzoate combination) and T2 (1.63 ± 0.80) in the wet season.

Table 2. Variation in parameters associated with *S. frugiperda*

Sources of variation	Average infestations rates			Average foliar damage scores			Average grain damage scores			Average grain yield			Average haulm yield		
	df	F	P	df	F	P	df	F	P	df	F	P	df	F	P
Season	1	52.31	< 0.0001 ***	1	8.58	0.0034 **	1	20.99	0.0001 ***	1	15.90	0.0005***	1	59.61	0.0001 ***
Treatment (T)	3	457.35	< 0.0001 ***	3	38.00	< 0.0001 ***	3	9.62	0.0001 ***	3	14.63	0.0001***	3	5.95	0.0035 **
Stag	3	1741.30	< 0.0001 ***	3	197.12	< 0.0001 ***									
Season:stag	3	763.81	< 0.0001 ***	3	57.29	< 0.0001 ***									
Season: T	3	105.50	< 0.0001 ***	3	33.78	< 0.0001 ***	3	2.39	0.0690 ns	3	0.57	0.6431ns	3	0.69ns	0.5680ns
Stag: T	9	116.16	< 0.0001 ***	9	7.06	0.0001 ***									
Season:Stag:T	9	68.61	< 0.0001 ***	9	27.70	< 0.0001 ***									

*Df: degree of freedom; F: variance P: probability; ns: not significant; *: significant; **: highly significant; ***: very highly significant; Stag: stage*
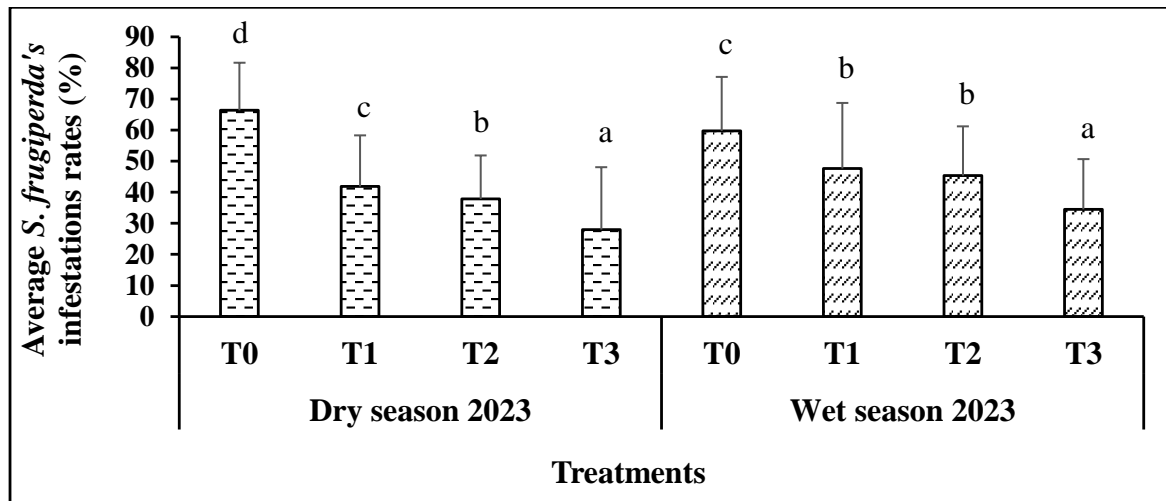
Fig. 2. Average rates of *S. frugiperda* infestation in maize as a function of treatment, Bama, Burkina Faso
Means assigned the same letters are not significantly different according to the Kruskall-Wallis (K-W) test at the 5% threshold.
T0= control, T1= combination of Push-pull technology and Jatropha curcas oil
T2= Push-pull technology/neem oil combination
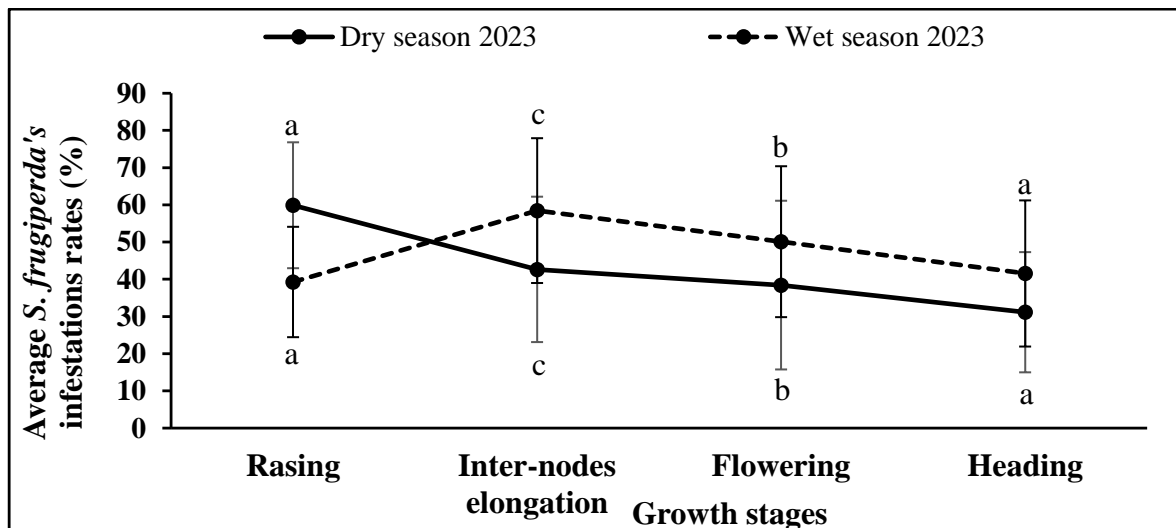*T3= Push-pull technology - Emamectin benzoate combination*

Fig. 3. Average rates of *S. frugiperda* infestation in maize according to phenological stage, Bama, Burkina Faso
Means affected by the same letters are not significantly different according to the Kruskall-Wallis (K-W) test at the 5% threshold

A significant difference was observed between the mean infestation scores on the vegetative apparatus during the dry season ($X2= 197.12$; df = 3; p-value <0.0001) and also during the wet season ($X2= 137.75$; df = 3; p-value <0.0001) depending on the treatments.

Similarly, statistical analysis of mean grain scores revealed a significant difference

($X2=21.86$; df = 3; p-value <0.0001 in the dry season and $X2=9.46$; df = 3; p-value = 0.0237 in the wet season) between treatments at the 5% threshold according to the Kruskal-Wallis test. The highest average infestation scores on grains were recorded in the control (1.69 ± 1.09 in the dry season and 1.89 ± 0.97 in the wet season), while the lowest average attack scores on grains were recorded in treatments T1 (1, 26 ± 0.65)

(Push-pull-*Jatropha curcas* technology combination) and T2 (1.19 ± 0.51) (Push-pull - neem oil technology combination) during the dry season, T2 (1.56 ± 0.69) and T3 (1.43 ± 0.59) during the wet season.

Average severity of *S. frugiperda* damage as a function of the phenological stage of the maize plant : The average severity of *S. frugipera* damage to maize plants as a function of phenological stage over the two growing seasons of 2023 is shown in Fig. 4.

The mean score of maize leaves damaged by *S. frugiperda* was highest at emergence (2.27 ± 1.09) in the 2023 dry season and at bolting (2.10 ± 1.03) in the 2023 wet season. The lowest mean scores were recorded at heading (1.60 ± 0.93) and emergence (1.72 ± 0.86) in the dry and wet seasons respectively. The effect of seasons had a significant impact ($X2 = 194.5$; $df = 3$; p-value < 0.0001 in the dry season and $X2 = 58.47$; $df = 3$; p-value < 0.0001 in the wet season) on the mean vegetative scores according to the phenological stages of the maize plant.

Table 3. Average severity of *S. frugiperda* damage on maize plants

Treatments	Dry season 2023		Wet season 2023	
	Average vegetative scores	Average grains scores	Average vegetative scores	Average grains scores
T0	2.59 ± 1.36c	1.69 ± 1.09b	2.12 ± 0.98c	1.89 ± 0.97b
T1	1.82 ± 1.01b	1.26 ± 0.65a	1.92 ± 1.03b	1.63 ± 0.80ab
T2	1.78 ± 1.03b	1.19 ± 0.51a	1.90 ± 1.04b	1.56 ± 0.69a
T3	1.50 ± 0.83a	1.11 ± 0.36a	1.55 ± 0.74a	1.43 ± 0.59a
df	3	3	3	3
X²	336.89	21.866	137.75	9.4669
P	< 0.0000	0.0001	< 0.0000	0.0237

Means assigned the same letters are not significantly different from each other according to the Kruskall-Wallis (K-W) test at the 5% threshold.
T0= control, T1= Push-pull technology - Jatropha curcas oil combination
T2= Push-pull technology/neem oil combination
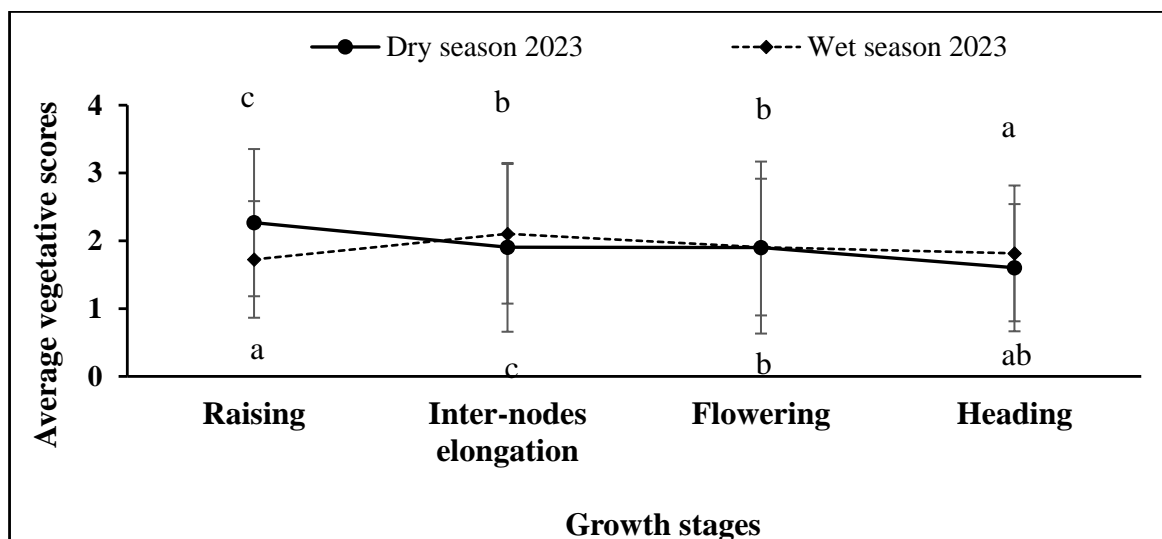*T3= Push-pull technology - Emamectin benzoate combination*

Fig. 4. Mean vegetative scores for damage inflicted on maize by *S. frugiperda* as a function of plant phenological stages, Bama, Burkina Faso
Means affected by the same letters are not significantly different according to the Kruskall-Wallis (K-W) test at the 5% threshold

Larval presence of *S. frugiperda* : Generally speaking, treatments that received insecticide applications combined with Push-Pull technology showed lower average larval presence rates than control plots. The highest average larval presence rate (31.88 ± 0.47% for the 2023 dry season and 38.63 ± 0.49% for the 2023 wet season) was observed in treatment T0 (control), while the lowest average larval presence rate (4.25 ± 0.20% for the dry season and 8.13 ± 0.27% for the wet season) was recorded in treatment T3 (Push-Pull technology - Emamectin benzoate combination) (Table 4). Treatments had a significant effect ($X2$= 298.87; df = 3; p-value < 0.0001 in the dry season and $X2$= 314.39; df = 3; p-value < 0.0001 in the wet season) on the presence rate of the FAW larvae.

Average *S. frugiperda* larval presence rates according to maize phenological stages: The presence rate of *S. frugiperda* larvae during the two 2023 growing seasons ranged from 3.54 ± 0.18% to 25.94 ± 0.44%, depending on maize development stage (Fig. 5).

The highest average larval presence rate was observed at the bolting stage (23.75 ± 0.43% for the dry season and 25.94 ± 0.44% for the wet season), followed by the emergence stage (18.65 ± 0.39% for the dry season 21.77 ± 0.41% for the wet season). The average larval presence rate was 12.81 ± 0.33% for the dry season and 13.54 ± 0.34% for the wet season at the flowering stage. The lowest average larval presence rates (3.54 ± 0.18% for the dry season and 11.41 ± 0.32% for the wet season) were recorded at heading (Fig. 5). Phenological stages had a significant influence ($X2$= 155.94;

df = 3; p-value < 0.0001 in the dry season and $X2$= 68.13; df = 3; p-value < 0.0001 in the wet season) on the larval presence rate of the pest.

Average maize plant height by treatment : The analysis of variance of mean maize plant heights according to the different treatments during the two growing seasons revealed a significant difference (F =13.63; df = 3; p < 0.0001 in the dry season and F =9.05; df = 3; p < 0.0001 in the wet season) between treatments at the 5% threshold according to Tukey's test. Treatment T1 recorded the maize plants with the highest mean heights whatever the growing season (203.11 ± 17.46 for the dry season and 201.49 ± 23.20 for the wet season). The lowest mean heights (186.74 ± 17.36 and 183.41 ± 20.11 for the dry and wet seasons respectively) were observed with treatment T0 (control) (Fig. 6).

Average maize grain yields by treatment: An analysis of variance of the average maize grain yields obtained during the two consecutive growing seasons revealed a significant difference (F=7.82; df = 3, p= 0.0037 in the dry season and F = 7.40; df = 3; p = 0.0046 in the wet season) between treatments at the 5% threshold according to Tukey's test. The lowest average yields were obtained with the T0 treatments, at 2.81 t/ha for the 2023 dry season and 2.43 t/ha for the 2023 wet season (Fig. 7). The mean yields recorded in treatments T1 (3.52 ± 0.30), T2 (3.73 ± 0.32), and T3 (3.57 ± 0.24) during the dry season and T2 (3.26 ± 0.18) and T3 (3.34 ± 0.43) during the wet season, were not significantly different from each other (Fig. 7).

Table 4. Average rates of larval presence of *S. frugiperda* on maize plants

	Average *S. frugiperda*'s larval presence rate (%)	
	Dry season 2023	**Wet season 2023**
T0	31.88 ± 0.47c	38.63 ± 0.49c
T1	10.38 ± 0.31b	14.13 ± 0.35b
T2	9.38 ± 0.29b	11.32 ± 0.32ab
T3	4.25 ± 0.20a	8.13 ± 0.27a
df	3	3
X^2	298.87	314.39
P	< 0.0001	<0.0001

Means assigned the same letters are not significantly different from each other according to the Kruskall-Wallis (K-W) test at the 5% threshold.
T0= control, T1= Push-pull technology - Jatropha curcas oil combination
T2= Push-pull technology/neem oil combination
T3= Push-pull technology - Emamectin benzoate combination
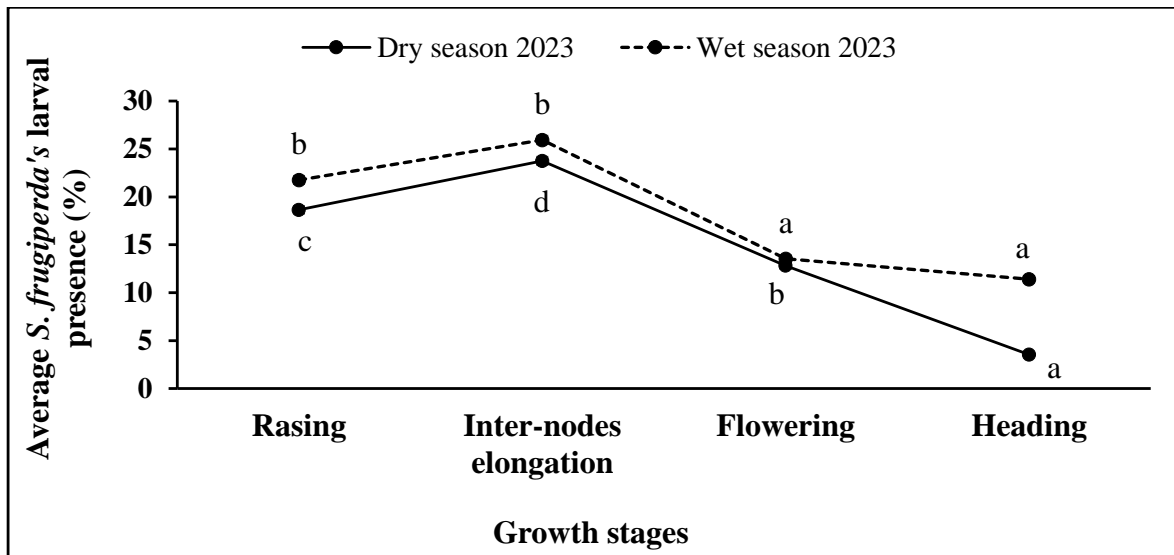
Fig. 5. Mean larval presence rates of *S. frugiperda* as a function of phenological stages of the maize plant, Bama, Burkina Faso
Means assigned the same letters are not significantly different from each other according to the Kruskall-Wallis (K-W) test at the 5% threshold
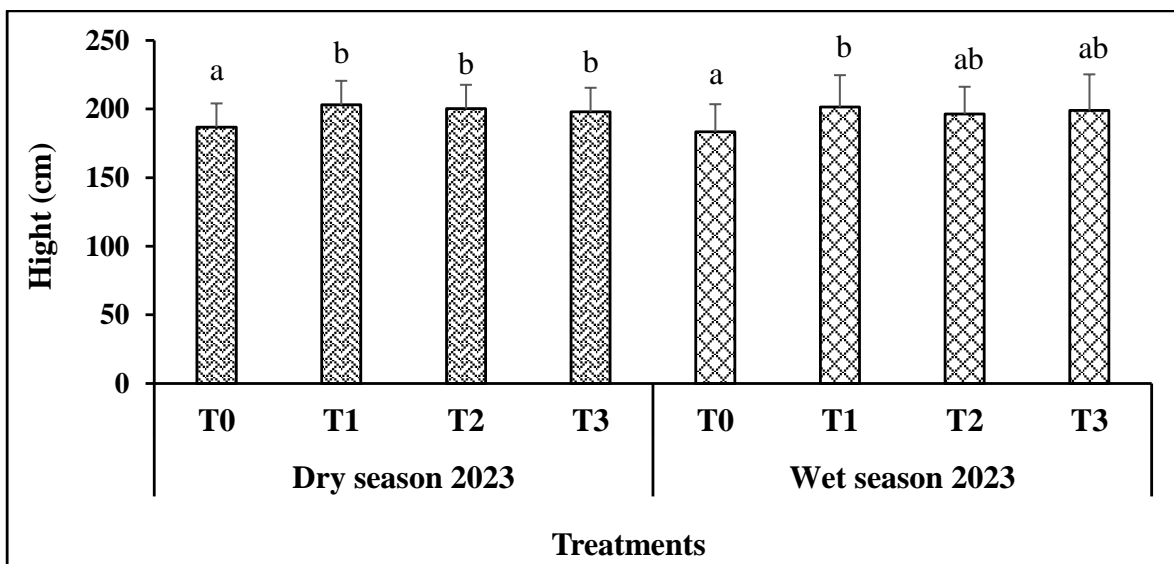

Fig. 6. Average maize plant heights, Bama, Burkina Faso
Means assigned the same letters are not significantly different from each other according to the Kruskall-Wallis (K-W) test at the 5% threshold.
T0= control, T1= combination of Push-pull technology and Jatropha curcas' oil
T2= Push-pull technology/neem oil combination
T3= Push-pull technology combination - Emamectin benzoate

Average haulm yields (t/ha) by treatment: The effect of the different treatments significantly influenced average maize haulm yields (F= 4.51; df = 3; p = 0.0243 in the dry season and F= 4.31; df = 3; p = 0.0279 in the wet season) at the 5% threshold according to Tukey's test, as shown in Fig. 8. The lowest average maize biomass yields

(4.26 ± 0.37 obtained in the dry season and 2.94 ± 0.39 recorded in the wet season) were observed in plot T0 (control). Next came treatment T3 (Push-Pull technology - Emamectin benzoate combination) with 5.28 ± 0.52 (dry season) and 3.37 ± 0.69 (wet season) of maize biomass. Then T2 (Push-Pull technology - neem

oil combination) with 5.60 ± 0.55 (dry season) and 3.80 ± 0.66 (wet season) and finally T1 (Push-Pull technology - *Jatropha curcas* combination) which records the highest biomass with 5.73 ± 0.93 (dry season) and 4.25 ± 0.35 (wet season).
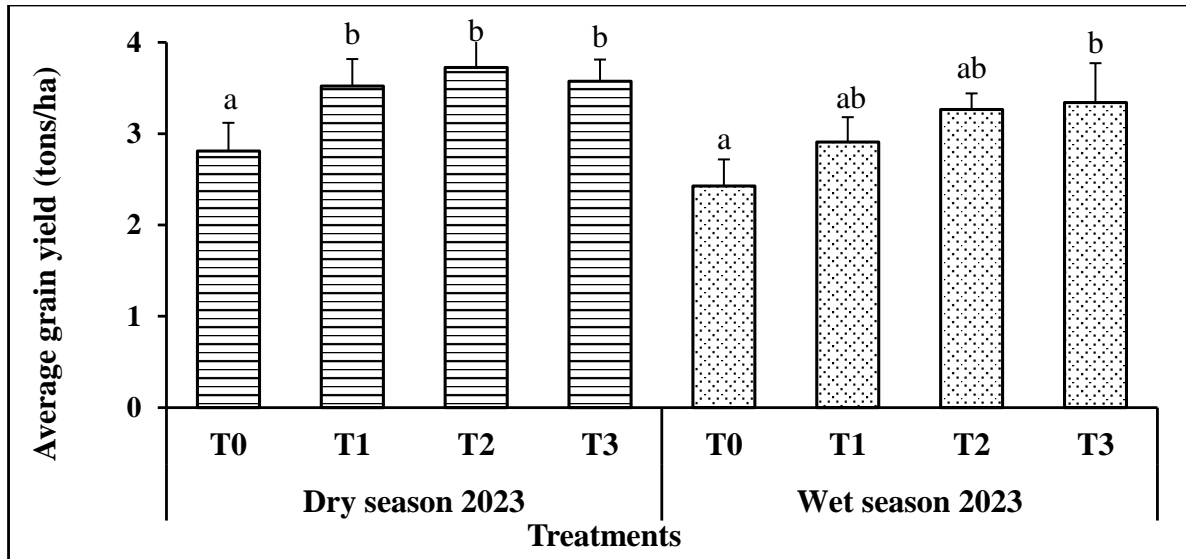

Fig. 7. Average grain yield (t/ha), Bama, Burkina Faso
Means assigned the same letters are not significantly different from each other according to the Kruskall-Wallis (K-W) test at the 5% threshold
T0= control, T1= Push-pull technology - Jatropha curcas oil combination
T2= Push-pull technology/neem oil combination
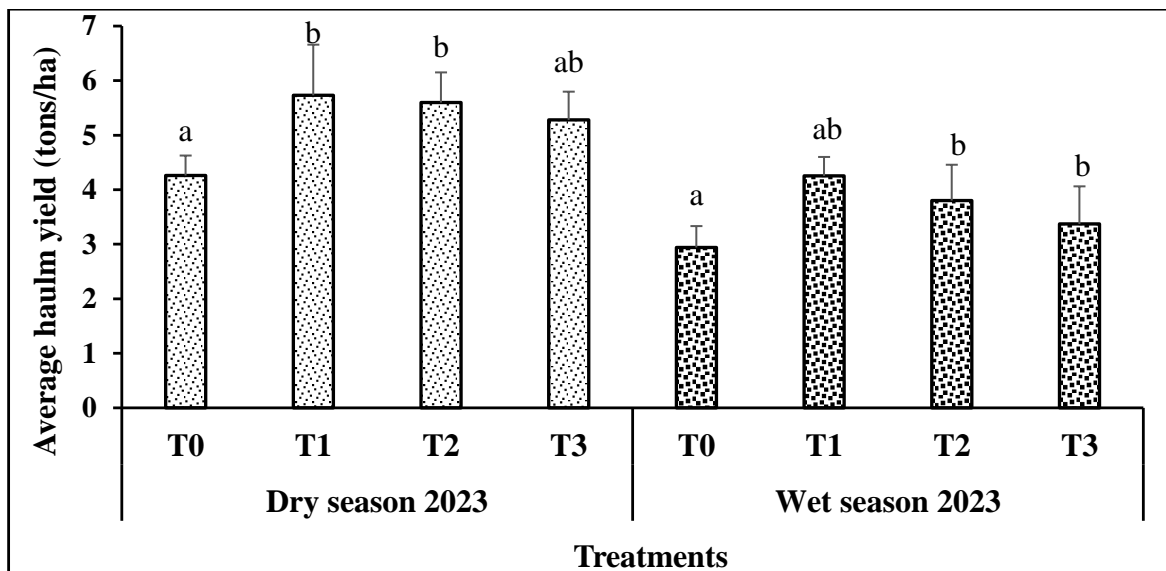*T3= Push-pull technology combination - Emamectin benzoate*

Fig. 8. Average maize haulm yield by treatment
Means marked with the same letters are not significantly different from each other according to the Kruskall-Wallis (K-W) test at the 5% threshold.
T0= control,
T1= Push-Pull-oil and Jatropha curcas technology combination
T2= Push-Pull technology -neem oil combination
T3= Push-Pull technology - Emamectin benzoate combination

3.2 Discussion

The results of the present study, carried out during the two consecutive growing seasons of 2023, showed that average infestation rates, average attack severity and average presence rates of *S. frugiperda* larvae on maize plants varied according to treatments and plant phenological stages.

Attacks by *S. frugiperda* were greatest at maize emergence in the dry season of 2023 and at bolting in the wet season of 2023. These attacks were associated with a high average larval presence rate. The lowest attacks were observed at heading, with a low average larval presence rate in both 2023 growing seasons. In fact, at the emergence and bolting stages, maize leaves are tender and therefore ideal for feeding armyworm larvae [35]. After bolting, maize plants stop producing new leaves and make do with the activity of acquired leaves for the rest of their life cycle. They lengthen through the internodes to reach their final size. Thus, leaf spacing coupled with leaf aging without renewal contribute to a scarcity of food for larvae, exposing them to predators and other climatic hazards (winds, storms, extreme heat, etc.). This explains the high foliar attack rates of the pest observed during the early developmental stages of maize plants, particularly at bolting, and the low foliar attack rates recorded during the later developmental stages of the plant, particularly at apiaison. These results corroborate those of Tindo et al. [36], who reported that the early stages of maize plant development are the most attacked by the armyworm. Also, in the case of treatments designed to control the pest, such a result could be explained by the fact that when Brachiaria mullato II and *D. uncinatum* plants are still small, they would not have enough influence on the pest to reduce its infestations, and therefore its damage. As these two plants develop, they produce more volatile chemical compounds that attract, or repel, S. frugiperda, thus reducing the pest's infestation rate [37]. Pest damage was greater in the control plots than in the other treatments during the two consecutive seasons of 2023. The relatively low level of pest attacks in treatments aimed at controlling *S. frugiperda* could be explained by the combined action of push-pull and insecticide applications. According to Lofinda et al. [37], stimuli emitted by intercropping or marginal plants certainly modify the behavior of insects and plants in the field. As a result, trap plants are not adapted to the survival of pest larval stages, leading to high mortality rates and delayed larval development [21,38].

Among IPM combinations, the Push-pull - Emamectin benzoate technology combination recorded the lowest average rates of larval presence, infestations and average attack severity during the two 2023 growing seasons. These results are in line with those of Koffi et al. (2020), who showed that the application of chemical insecticides is effective in protecting maize and cotton against the armyworm. According to Fandrìàka [39], Emamectin benzoate produces immediate action thanks to anti-appetant toxic substances against *S. frugiperda* larvae. Indeed, the active ingredient, Emamectin benzoate causes paralysis of lepidopteran larvae due to activation of the chloride channel in the nerves [39]. The biological pesticides used in the present study, namely Azadirachta indica oil and Jatropha curcas oil, also considerably reduced *S. frugiperda* damage. In fact, Azadirachtin, the active ingredient in A. indica oil, acts by slowing down the insect's feeding rate, causing paralysis and dieback of target organisms [40,41]. Gnago et al. [42] have also reported that *A. indica* oil reduces the fecundity of FAW females, which is justified by the considerable reduction in the number of egg clusters of this caterpillar and its damage. Habou et al. [43] have also shown that *J. curcas* oil is effective in regulating Lepidoptera populations. Our results also corroborate those of Adebowale and Adedire [44], who showed that *J. curcas* oil caused the total death of eggs and larvae of the bruchid beetle, *Callosobruchus maculatus* (Fabricius). During the 2023 growing season, maize plants developed better in plots that had received a push-pull combination with pesticides than in control plots. Similarly, average grain and haulm yields were higher in the push-pull plots than in the control plots. This result could be explained by the presence of *D. uncinatum* in the push-pull plot, which would have contributed to the increase in biomass available in the maize plot. Legumes harbor symbiotic nitrogen-fixing bacteria in their root nodules [45]. Most plants need available nitrogen for vegetative growth. Leguminous plants in association with seedlings provide them with the nitrogen they need for growth and improve their productivity [25,46]. *Desmodium uncinatum* is a legume that improves soil fertility and moisture [47].

Indeed, foliar damage inflicted by *S. frugiperda* on maize results in a reduction in the plant's photosynthetic activity, which in turn can lead to a reduction in maize growth. Our results do not agree with those of Tiendrébéogo [48], who observed normal maize plant growth despite *S. furgiperda* infestations. Soil fertilization with *D. uncinatum* could help provide the nutrients needed for good grain and cob formation. As a result, average grain yields were higher than those obtained with the control. Our results corroborate those reported by Balde et al. [49], who showed that the greater vegetative development and number of ears observed in the push-pull plot can be explained by a combination of factors: increased soil fertility and moisture preservation due to the presence of *D. uncinatum*. Similarly, ICIPE [50] showed that some farmers using Push-Pull technology were harvesting five tons of maize per ha in fields where yields had previously been below one ton. These results demonstrate the effectiveness of push-pull technology in combination with certain pesticides in managing *S. frugiperda* in Burkina Faso [51].

4. CONCLUSION

The FAW is a serious threat to maize production in Burkina Faso. The aim of this study, carried out in western Burkina Faso, specifically in Bama, was to evaluate some management options for *S. frugiperda* in Burkina Faso. The activities carried out within the framework of this study enabled us to estimate the average rates of infestation of maize plants by *S. frugiperda* as a function of treatments and phenological stages of the plant, and to assign average vegetative scores for the same parameters. The results of this study showed that the Push-Pull technology - Emamectin benzoate combination provided a better protection of maize plants against *S. frugiperda* larvae than the other two IPM combinations, which were however more effective than the control.

The combination of Push-Pull technology and Emamectin benzoate therefore appears to be the best combination for managing *S. frugiperda*. However, combinations of Push-Pull technology and biological pesticides showed some effectiveness in reducing damage caused by the FAW larvae. Push-Pull technology may therefore be an interesting avenue for managing *S. frugiperda*, while providing other benefits to growers.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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