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COMPARATIVE EFFECTS OF DIFFERENT MAIZE CROPPING SYSTEMS ON THE MANAGEMENT OF *SPODOPTERA FRUGIPERDA* (LEPIDOPTERA: NOCTUIDAE), IN SMALLHOLDER FARMING SYSTEMS IN BENIN

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ABSTRACT: *The Spodoptera frugiperda (Lepidoptera: Noctuidae), commonly known as the fall armyworm (FAW), is a highly invasive pest that threatens diverse cropping systems worldwide, particularly maize-based systems in sub-Saharan Africa. Intensive reliance on synthetic insecticides has raised concerns regarding human health risks, environmental contamination, and disruption of natural enemies. This study evaluated whether maize intercropping with edible legumes, combined with botanical and biological treatments, could reduce FAW infestation and improve yield under field conditions in five municipalities of Benin during the 2025 rainy season. Nine treatments were tested: (i) maize monoculture with standard agronomic practices (control), (ii) maize–soybean treated with cashew balm, (iii) maize–groundnut treated with BotaniGard 22WP, (iv) maize–cowpea treated with Ricinus communis extract, (v) maize–mucuna treated with Thevetia neriifolia extract, (vi) maize–sorghum treated alternately with cashew balm and BotaniGard 22WP, (vii) maize monoculture treated with TopBio, (viii) maize monoculture treated with salt plus crushed charcoal, and (ix) the Push–Pull technique. Data collected included FAW infestation symptoms, severity scores, larval density, and maize yield. Results indicated that several treatments significantly influenced infestation severity. The untreated control exhibited the strongest effect, increasing by more than fourfold the probability of belonging to a higher severity category (OR = 4.27; 95% CI: 3.25–5.61; p < 0.001). In contrast, the Maize + soybean + cashew balm (MSB) (OR = 1.27; p = 0.092) and Maize + sorghum + cashew balm + BotaniGard (MSBB) (OR = 0.84; p = 0.22) treatments showed no significant effect on severity. All tested treatments significantly reduced mean larval counts compared with the control plus agronomic practices (p < 0.05). The most pronounced reductions were observed with Crushed charcoal + table sal (CS+A) (IRR = 0.27), MSBB+A (IRR = 0.29), and Maize + TopBio + AgroBio (MT+A) (IRR = 0.37), corresponding to larval decreases exceeding 60%. Notably, MT+A significantly increased maize yield by 0.28 t ha^{-1} (p = 0.018). Overall, maize intercropping with edible legumes and the Push–Pull strategy significantly reduced FAW infestation compared with maize monoculture. These approaches represent promising, environmentally sustainable components of integrated FAW management in African smallholder systems.*

KEYWORDS: Biopesticides, FAW, intercropping, legumes, maize, Push-Pull.

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INTRODUCTION

Fall armyworm (FAW), *Spodoptera frugiperda* (Lepidoptera: Noctuidae), is the most important insect pest of economically important crops across tropical and sub-tropical regions (Lestari et al., 2020). It now occurs in Japan, Australia, and New Zealand and is also reported in the Canary Islands, with a few occurrences in Cyprus, Greece, Portugal, and Turkey (FAO, 2023, 2024; EPPO, 2025). Originating from the Americas, FAW has rapidly spread across Africa, Asia, and, more recently, into Europe (Tay et al.,2023; Cean et al., 2024; Lytra et al., 2024). The FAW larvae can feed on more than 350 plant species, including maize, rice, sorghum, millet, sugarcane, vegetable crops, and cotton (Montezano et al. 2018). The female deposits egg masses of a few hundred eggs, usually on the underside of the leaves, and first instar larvae show phototaxis, moving towards the top of the plant, and disperse by ballooning on silk threads (van Huis,1981). FAW larvae are the most destructive stage, feeding on all developmental stages of maize, but especially the whorls of young plants of 45 days old (Cruz *et al.,* 1999). Chemical insecticides are the primary control strategy against FAW; however, these are not affordable to smallholder farmers in Africa. Furthermore, the nocturnal habits of adult moths and the cryptic and burrowing behaviour of larvae into the maize whorl render control difficult (de Groote et al., 2020). In addition to that, FAW has developed resistance to many chemical insecticides. (Carvalho et al.,2018; Gutiérrez et al.,2019). Excessive use of chemical insecticides also raises health and environmental concerns. Although efforts have been made by farmers to apply available insecticides, it was not been effective and economical (Kumela et al., 2018). It is therefore crucial to identify an environmentally friendly and cost-effective strategy for the management of this pest.

Crop diversification with various temporal and spatial arrangements reduces pest incidence while increasing the population of beneficial arthropods (Altieri et Liebman, 1986; Ogenga-Latigo et al., 1992; Girma et al., 2000; Girma, 2006; Seran and Brintha, 2010), and this has been reported as one management option for FAW (Altieri, 1980a, 1980b).

Recommended cultural methods include timely planting following the main rainfalls, intercropping, crop rotation, and landscape management by clearing major and alternate hosts around maize fields (Assefa, 2018; Kasoma et al., 2020). Unlikely to provide adequate control alone, they help in reducing the fall armyworm populations and damage. Intercropping is the establishment on the same surface of several plant species and varieties simultaneously, which cross during an important part of their growth cycle. The rows of the main crop are intercropped with additional crops in rows or strips. In general, intercropping provides a protective microclimate that increases the richness and abundance of beneficial insects (Matova et al., 2020). Maize planted closer to hedges of Crotalaria *Crotalaria grahamiana* Wight & Arn, Calliandra, Gliricidia *Gliricidia sepium* Jacq., and croton *Croton megalocarpus* Musine registered less stemborer infestation, compared with those planted away from these hedges (Girma et al.,2000). Furthermore, certain crops and their arrangements will help disrupt host location by pests, and act as repellents or deterrents, reducing oviposition on host crops (Nayanya et al., 2000; Khan et al., 2010). In Ethiopia, for instance, Kebede et al. (2018) reported increased abundance of generalist predators as well as the predation rate of stem borer eggs and fall armyworm by associating common bean (*Phaseolus vulgaris* L.) with maize. In Uganda, damages caused by the fall armyworm were significantly reduced in intercropping maize with legumes, such as *P. vulgaris*, *Glycine max*(L.) Merr. and *Vigna unguiculata* L. Walp. (Hailu et al.,2018). In East Africa, the abundance of stem-borer predators (ants, earwigs, and spiders) was increased in fields intercropping maize and *Desmodium*, *D. uncinatum*, with Napier grass (*P. purpureum*) as a trap crop around the field (push-pull) (Kebede et al., 2018).

In an extension of the push-pull approach, it was observed that intercropping maize with the nonhost molasses grass *M. minutiflora* and *Desmodium* spp. significantly decreased levels of infestation by certain stem borer species in the main crop and also increased the parasitism of stem borer larvae by *C. sesamiae* (Khan et al., 2016). Push-pull approach may not only impact some stem borer species, but also other lepidopteran pests of maize and other cereals (Hassanali et al., 2008). Intercrops may also reduce pest oviposition through olfactory camouflage or the release of repellent volatiles. For example, the release of repellent volatiles by *Desmodium* spp. is the main mechanism by which FAW damage is reduced in climate-adapted push-pull (Midega et al. 2018; Hailu et al. 2018; Niassy et al. 2021a).

Several pesticidal plants have been tested against FAW (Rioba & Stevenson 2020), including commercial products (Forim *et al.*, 2010) and extracts which can be prepared by farmers from plants growing in the surroundings of their farms (Pavela 2016; Marchand 2017; Assefa & Ayalew 2019; Sisay et al. 2019a; Silvie *et al.* 2021). Compared to chemical insecticides, they are expected to be more environmentally friendly due to their short persistence, lower requested concentrations of a more diverse range of active substances, and anti-feeding/repellent modes of action (Bhusal & Chapagain, 2020). Entomopathogenic fungi are already widespread

in maize fields and naturally contribute to the suppression of many crop pests (Vega, 2018). After the introduction of the fall armyworm, larvae infected with entomopathogenic fungi were found in African maize fields according to early reports (Chinwada, 2018; Cokola, 2019). *Beauveria bassiana* is one of the most commonly used biological control agents worldwide (James et al., 2010), and has been identified in maize fields in West Africa (Cherry et al., 1999; Cherry et al., 2004). Recently, *B. bassiana* was demonstrated to be efficient against eggs and second instar larvae of fall armyworm (Akutse et al., 2019). Some commercially available products, based on *M. anisopliae* or *B. bassiana,* are available on the West African market (Bateman et al., 2018; CSP, 2019). This study therefore, focused on comparing the effects of certain intercropping systems combining maize and edible legumes that received plant extracts and the Push-Pull technique on the abundance and severity of fall armyworm infestation in maize in Benin.

MATERIALS AND METHODS

Study area

The study was conducted in five municipalities located in the central and northern regions of Benin: Bassila, Djidja, Glazoué, N'Dali, and Ouèssè. These areas were selected because of their importance in maize production and their agroecological diversity, which is a common approach used to ensure the representativeness of results in agronomic studies on *Spodoptera frugiperda* in West Africa (Zanzana et al., 2025).

All the municipalities included in the study fall within a climatic continuum ranging from tropical subequatorial to Sudano-Guinean climates, with bimodal or unimodal rainfall regimes and variable annual precipitation levels, which are characteristic of the country's intensive maize-growing zones. The variability of climatic and edaphic conditions among these municipalities made it possible to account for the diversity of cropping systems under real farming conditions. This approach is consistent with the methodological frameworks described in previous studies on fall armyworm (FAW) in Benin, which emphasize the importance of accurately describing survey sites in order to interpret differences in the spatial and seasonal distribution of pest populations (Zanzana *et al.*, 2025).

Figure 1. Map of the study area showing the municipalities of Bassila, Djidja, Glazoué, N'Dali, and Ouèssè in Benin.

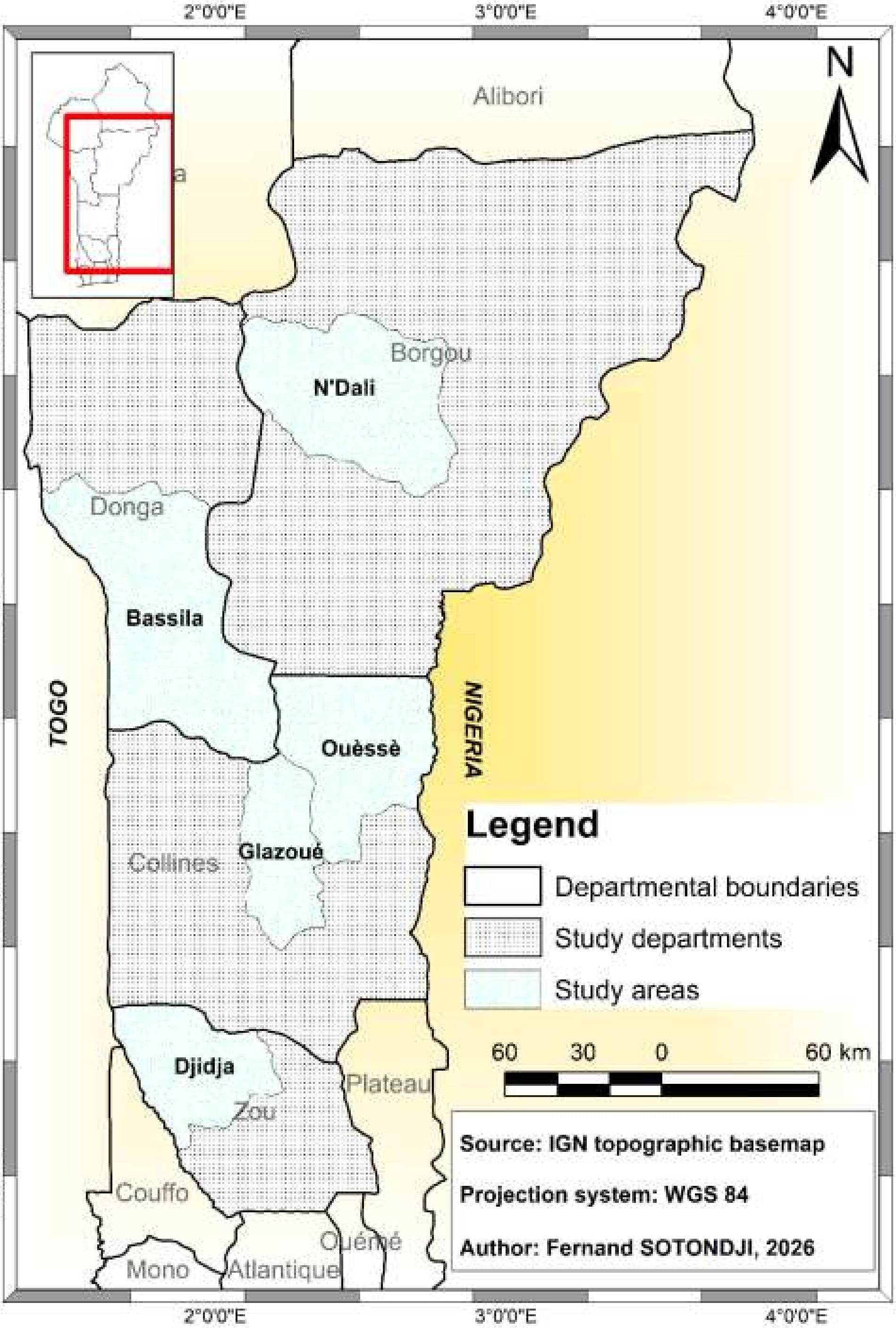

Table 1: **Number of maize cropping systems compared under real farmer field conditions**

Number of treatments	Treatments (Substances)	Doses	Observations
Control + A	Control + A: Agricultural practices only (control plot) + AgroBio	0	No treatment
MSB + A	Maize + soybean + cashew balm + AgroBio	5% formulation	Normal dose
MAB + A	Maize + groundnut + BotaniGard + AgroBio	125 mg/L	Reference control
MNR + A	Maize + cowpea + *Ricinus communis* + AgroBio	10% formulation	Normal dose
MMT + A	Maize + mucuna + *Thevetia neriifolia* + AgroBio	10% formulation	Normal dose
MSBB + A	Maize + sorghum + cashew balm + BotaniGard + AgroBio	125 mg/L+2% CNSL	Reference control
MT + A	Maize + TopBio + AgroBio	125 ml / 16 L of water/ha	Reference control
CS + A	Crushed charcoal + table salt + AgroBio	5% formulation	Normal dose
TPP + A	Climate-adapted push–pull technology + AgroBio	*Pennisetum purpureum* + maize + *Helianthus annuus*	Reference control

Note: A = AgroBio Organic fertilizer applied in combination with the different cropping systems.

Experimental Design and Crop Management

The early-maturing maize variety EVDT 99 W STR was used in the field trials and sown at a spacing of 80 cm between rows and 40 cm between plants. The biological fertilizer AgroBio was applied in all experimental plots at a rate of 100 kg/ ha, three weeks after maize emergence and immediately following the first weeding operation. Two manual weedings were carried out during the cropping cycle at 4-week intervals to maintain optimal field conditions.

Field experiments were conducted from 5 June to 5 August 2025 in the five municipalities previously described. Each experimental site covered 1 ha, and sites were separated by approximately 25 m of natural fallow vegetation to minimize potential interactions between treatments. Each field was subdivided into 48 square plots measuring 5 m × 5 m. The plots were separated by 8 m alleys, while the outer plots were positioned 3 m from the field borders to reduce potential edge effects. All plots were systematically numbered to facilitate identification and data recording. It should be noted that the push–pull cropping systems included in this study were established prior to maize sowing. The associated herbaceous plants were vegetatively propagated using rhizomes collected from plants cultivated on a private farm in Abomey-Calavi. The plants used in the experiment were 3–4 months old at the time of establishment, since *Pennisetum purpureum* and *Helianthus annuus* exhibit relatively slow early growth, particularly under the rainfall regimes observed in the different study locations. Sampling was conducted at three key maize growth stages to evaluate infestation levels throughout crop development:

- the seedling stage (21 days after emergence),
- the vegetative stage (30 days after emergence), and
- the flowering stage (45 days after emergence), according to the phenology of the maize variety used.

All maize fields included in the study, including those under the push–pull system, were planted with the same maize variety to ensure comparability among treatments.

Plot Layout and Data Collection

A systematic random sampling method was considered for selecting maize samples from the assigned plots. Within a row, one maize plant was chosen in every four plants, and then the next row chosen was considered, after skipping every three rows of maize (Girma *et al*.,2018). A total of 25 plants were sampled within a plot to score incidences of FAW and to score the severity of infestation symptoms. The total number of plants sampled and plants showing FAW infestation were recorded. The severity of infestation was also scored on visual observation of the foliar damage attributed to each pest using a 1 to 5 scale, where 1 is clean with no visual infestation symptoms, 2 = very little damage, 3 = high level of damage where plants show the presence of FAW larvae feeding and most of the young leaves show infestation symptom, 4 = severe damage where almost 75% of the leaves are severely affected and excrement is visible on the infested areas and the maize whorls, and 5 = very severe damage where total plant damage due to FAW is visible. To detect the presence of parasitoids, larvae, and egg masses of the fall armyworm were collected from all infested plants, as described above, and subsequently examined under laboratory conditions. Egg masses were placed in Petri dishes and checked every two days to record any larval emergence. After five days of incubation, all unhatched eggs or egg masses were set aside and further monitored to detect the emergence of egg parasitoids associated with fall armyworm. The collected larvae were reared on germinated maize and regularly inspected to detect any signs of parasitism. Parasitoid pupae obtained from the larvae were transferred into small rearing cages until adult emergence. All parasitoid specimens obtained from FAW eggs and larvae were sent to the Insect Museum of the International Institute of Tropical Agriculture (IITA) for species-level identification.

DATA ANALYSIS

Assessment of Maize Infestation by the Fall Armyworm

The severity level of maize infestation by the fall armyworm, considered as an ordinal variable, was analyzed using an ordinal logistic regression model. The qualitative explanatory variables, namely the treatment applied, the plant developmental stage, and the study region, were included in the model as categorical factors. All statistical analyses were performed in R using the ordinal package developed by Rune Haubo Christensen (2023), which allows the estimation of cumulative link models suitable for ordinal response variables.

The estimated coefficients were used to assess the effect of each explanatory variable on the cumulative probability of observing a higher infestation level. The effects were interpreted using odds ratios derived from the model. An odds ratio greater than 1 indicated an increased probability of a higher severity level, whereas a value lower than 1 was interpreted as a protective effect.

Comparison of Fall Armyworm Larval Abundance Among Treatments

The abundance of *Spodoptera frugiperda* larvae was analyzed using generalized linear models (GLMs) suitable for count data. Several candidate models were fitted, including a Poisson mixed model, a negative binomial mixed model, and a negative binomial model without random effects. Treatment was included as a fixed effect, while the region (ATDA) was incorporated as a random effect to account for spatial heterogeneity. Model fitting was performed using the R packages lme4, developed by Douglas Bates *et al*. (2015), and glmmTMB, developed by Kasper Kristensen *et al*. (2017). Model selection was based on the Akaike Information Criterion (AIC) using the AICcmodavg package developed by Marc J. Mazerolle (2020). The model with the lowest AIC value was retained as the best-fitting model. Subsequently, comparisons among treatments were performed using adjusted means, and treatment effects were interpreted using Incidence Rate Ratios (IRR).

Quantification of Cumulative Fall Armyworm (FAW) Infestation Across Maize Cropping Systems

Cumulative infestation by the fall armyworm (*Spodoptera frugiperda*) was assessed based on weekly monitoring of infested maize plants. Data were organized according to week of collection, treatment, and region. Cumulative infestation was calculated by progressively summing the number of infested plants over time. Temporal dynamics of infestation across treatments were visualized using time-course plots, with separate representations for each municipality. Graphical visualizations were produced using the ggplot2 package in R (Wickham, 2016).

Comparison of Infestation Levels Across Maize Growth Stages in the field

Differences in fall armyworm (*Spodoptera frugiperda*) infestation levels across maize growth stages were analyzed using generalized linear mixed models (GLMMs). The response variable, corresponding to the number of infested plants per treatment, was treated as a count variable and assumed to follow either a Poisson or negative binomial distribution. The growth stage was included as a fixed effect, while the region (Region_ATDA.4) was included as a random effect to account for spatial heterogeneity. Three competing models were fitted:

1. Poisson mixed model,
2. Negative binomial mixed model to account for potential overdispersion, and
3. Negative binomial model without random effects.

Models were fitted using the R packages lme4 (Bates *et al*., 2015) and glmmTMB (Brooks *et al*., 2017). Model selection was based on the Akaike Information Criterion (AIC), with the model exhibiting the lowest AIC value considered the most parsimonious.

The goodness-of-fit of the selected model was evaluated using marginal (R^2m) and conditional (R^2c) coefficients of determination, calculated with the MuMIn package (Bartoń, 2023). Model coefficients were exponentiated to obtain incidence rate ratios (IRRs), facilitating the biological interpretation of effects. Post hoc comparisons among growth stages were performed using estimated marginal means (EMMs) calculated with the emmeans package (Lenth, 2023), with a Sidak adjustment to control the Type I error rate. Significant differences were summarized using compact letter displays with the multcomp package (Hothorn *et al*., 2008).

Determination of Maize Yield Across Different Cropping Systems

Maize yield was analyzed using a linear mixed-effects model, with treatment included as a fixed effect and region included as a random intercept. Models were fitted using the R package lme4 (Bates *et al*., 2015). Model selection based on the Akaike Information Criterion (AIC) indicated that including the treatment factor significantly improved model fit. Post hoc comparisons among cropping systems were performed using pairwise contrasts with a Sidak adjustment to control the Type I error rate. Model comparison based on the Akaike Information Criterion (AIC) indicated that the model including treatment effects with a random intercept provided a markedly better fit (AIC = −1.70) than the null model with only a random intercept (AIC = 74.26). Therefore, the mixed-effects linear model including treatment was retained to analyze variations in maize yield.

RESULTS

Assessment of Maize Infestation Levels

Table 2 summarizes the effects of treatments and maize developmental stage on the severity of fall armyworm infestation. The results revealed that several treatments significantly increased the probability of higher infestation severity. In particular, the MAB treatment increased this probability by 35% (OR = 1.35; 95% CI: 1.02–1.78; p = 0.035) compared to the reference treatment. Similar increases were observed for MMT (OR = 1.60; 95% CI: 1.21–2.11; p = 0.001), MNR (OR = 1.64; 95% CI: 1.24–2.17; p < 0.001), MT (OR = 1.41; 95% CI: 1.06–1.86; p = 0.017), and TP (OR = 1.71; 95% CI: 1.29–2.26; p < 0.001).

The control treatment had the most pronounced effect, more than quadrupling the probability of belonging to a higher severity level (OR = 4.27; 95% CI: 3.25–5.61; p < 0.001). In contrast, the MSB (OR = 1.27; p = 0.092) and MSBB (OR = 0.84; p = 0.22) treatments did not show a significant effect on infestation severity.

Table 2. Effects of treatments and maize developmental stage on fall armyworm infestation severity.

Predictor	Coefficient	OR-IC95	p-value
1|2	0,348±0,129	1,42(1,10–1,82)	7.06e-03**
2|3	2,196±0,135	8,99(6,90–11,72)	0.00e+00***
3|4	4,445±0,174	85,20(60,62–119,74)	0.00e+00***
Treatment			
MAB	0,298±0,142	1,35(1,02–1,78)	3.54e-02*
MMT	0,468±0,142	1,60(1,21–2,11)	1.00e-03**
MNR	0,496±0,142	1,64(1,24–2,17)	4.62e-04***
MSB	0,239±0,142	1,27(0,96–1,68)	9.23e-02
MSBB	-0,176±0,144	0,84(0,63–1,11)	2.20e-01
MT	0,341±0,143	1,41(1,06–1,86)	1.69e-02*
Untreated control	1,451±0,139	4,27(3,25–5,61)	0.00e+00***
TP	0,536±0,144	1,71(1,29–2,26)	1.95e-04***

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Developmental stage			
Vegetatif stage	0,546±0,085	1,73(1,46–2,04)	1,63e-10***
Seedling stage	-0,021±0,080	0,98(0,84–1,14)	7,87e-01

Code de signification : 0 '***' 0,001 '**' 0,01 '*' 0,05 '.' 0,1 ' ' 1

NB: Control: Agricultural practices only (Control plot), MSB: Maize + soybean + cashew balm, MAB: Maize + groundnut + BotaniGard, MNR: Maize + cowpea + *Ricinus communis*, MMT: Maize + mucuna + *Thevetia neriifolia*, MSBB: Maize + sorghum + cashew balm + BotaniGard, MT: Maize + TopBio, CS: Crushed charcoal + table salt, TPP: Climate-adapted push–pull technology

Comparison of *Spodoptera frugiperda* larval abundance among treatments

Model comparison based on the Akaike Information Criterion (AIC) indicated that the mixed Poisson model provided the best fit (AIC = 541.21) compared to the mixed negative binomial model (AIC = 543.21) and the simple negative binomial model (AIC = 542.88). Therefore, the mixed Poisson model was used to analyze treatment effects on larval abundance.

Table 3 presents the estimated effects of the different treatments on *Spodoptera frugiperda* larval abundance. Results show that all tested treatments significantly reduced the mean number of larvae compared to the Control+A treatment ($p < 0.05$). The strongest reductions were observed with CS+A (IRR = 0.27), MSBB+A (IRR = 0.29), and MT+A (IRR = 0.37), corresponding to a decrease of more than 60% in larval abundance.

Table 3. Effect of treatments on *Spodoptera frugiperda* larval abundance

Variation	Estimate	Odds (IRR)	Std.Error	Z-value	Pr(>|z|)
Intercept	2,328	10,260	0,084	27,843	<2e-16***
CS+A	-1,323	0,270	0,176	-7,531	5.03e-14***
MAB+A	-0,643	0,530	0,137	-4,682	2.85e-06***
MMT+A	-0,594	0,550	0,135	-4,399	1.09e-05***
MNR+A	-0,706	0,490	0,140	-5,038	4.70e-07***
MSB+A	-0,926	0,400	0,151	-6,122	9.24e-10***
MSBB+A	-1,253	0,290	0,171	-7,329	2.31e-13***
MT+A	-0,994	0,370	0,155	-6,411	1.44e-10***
TPP+A	-0,655	0,520	0,138	-4,753	2.01e-06***

Codes de signification : 0 '***' 0,001 '**' 0,01 '*' 0,05 '.' 0,1 ' ' 1

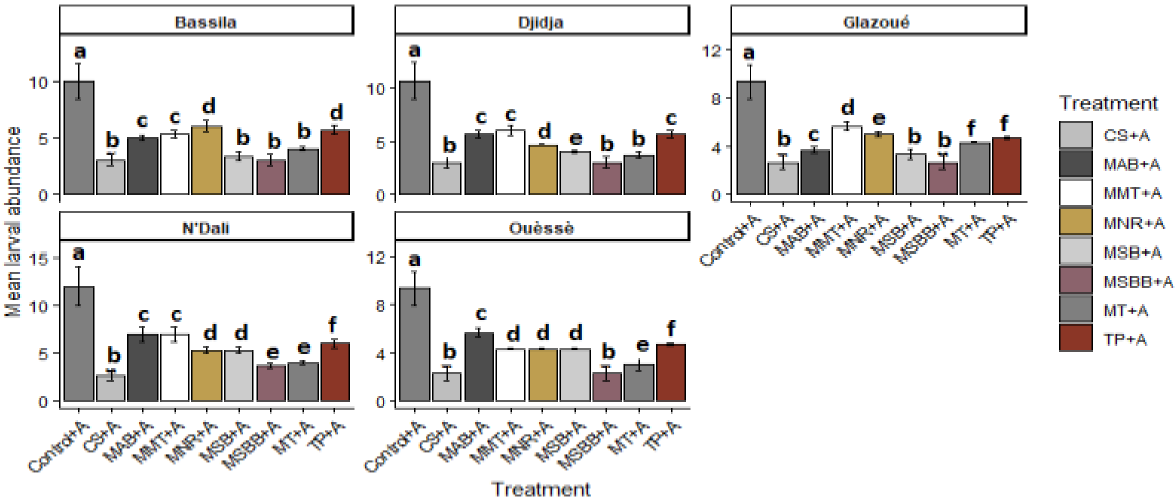
NB: Control: Agricultural practices only (Control plot), MSB: Maize + soybean + cashew balm, MAB: Maize + groundnut + BotaniGard, MNR: Maize + cowpea + *Ricinus communis*, MMT: Maize + mucuna + *Thevetia neriifolia*, MSBB: Maize + sorghum + cashew balm + BotaniGard, MT: Maize + TopBio, CS: Crushed charcoal + table salt, TPP: Climate-adapted push–pull technology.

Post-hoc Analysis of Differences among Treatments

Figure 2 illustrates the variation in mean *Spodoptera frugiperda* larval abundance across treatments. Multiple comparisons of means (Tukey's test, α = 0.05) revealed significant differentiation among treatments.

The CS+A treatment exhibited the lowest mean abundance (3 larvae), forming a statistically distinct group (group "a"). Treatments MSBB+A, MT+A, MSB+A, and MNR+A had intermediate abundances and belonged to overlapping groups ("ab" and "abc"), indicating moderate infestation levels. Treatments TPP+A, MAB+A, and MMT+A showed significantly higher abundances, grouped in classes "bc" and "c". The Control+A treatment was clearly distinct from all other treatments, with the highest mean abundance (10 larvae), forming a separate statistical group ("d").

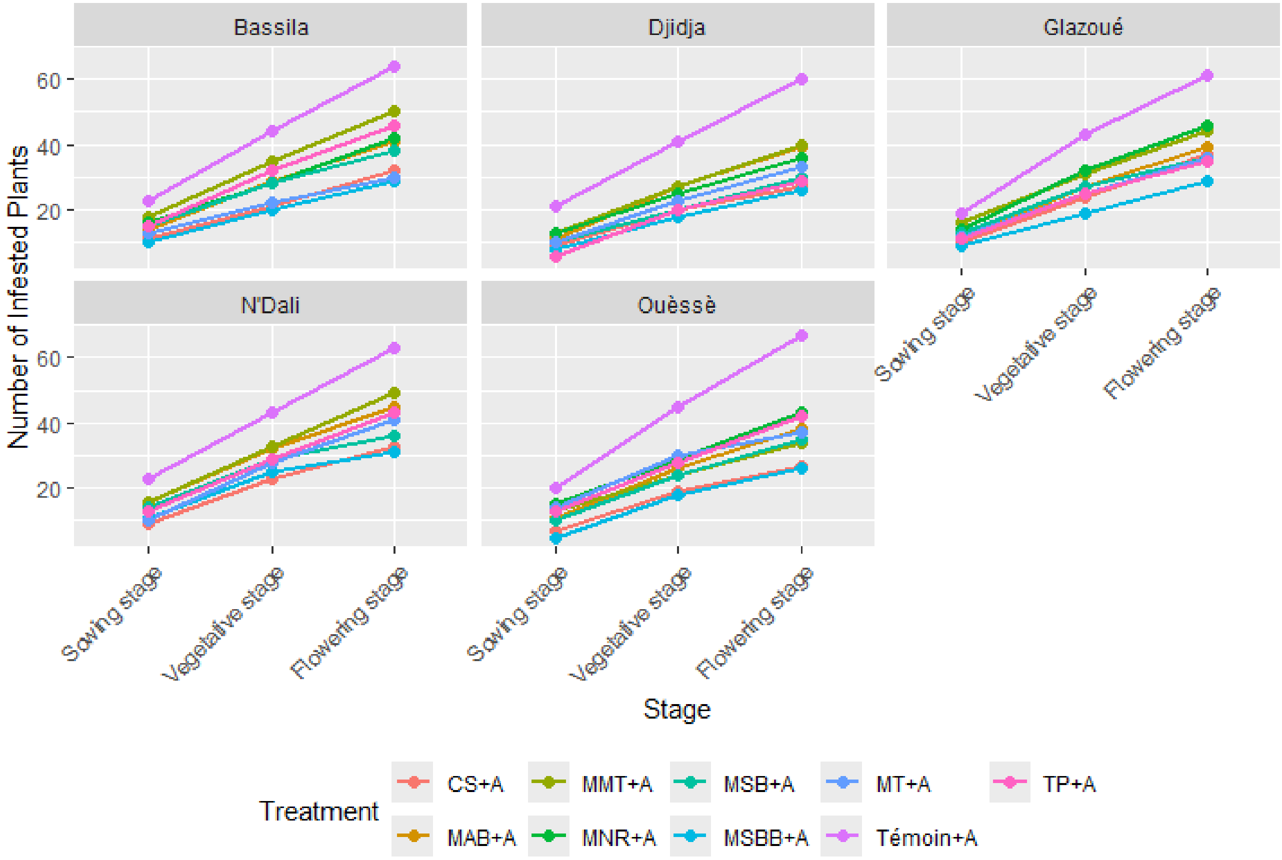
Figure 2. Mean abundance of *FAW* larvae according to applied treatments. Error bars represent 95% confidence intervals.



Cumulative Infestation of Fall Armyworm (FAW) across Cropping Systems

Figure 3 shows the cumulative progression of fall armyworm (FAW) infestation over the three developmental stages of maize plants according to cropping systems and study regions. Across all regions (Bassila, Djidja, Glazoué, N'Dali, and Ouèssè), a progressive increase in the cumulative number of infested plants was observed over time, indicating a continuous dynamic of infestation.

Figure 3. Cumulative infestation of fall armyworm (FAW) across different cropping systems.



NB: Control: Agricultural practices only (Control plot), MSB: Maize + soybean + cashew balm, MAB: Maize + groundnut + BotaniGard, MNR: Maize + cowpea + *Ricinus communis*, MMT: Maize + mucuna + *Thevetia neriifolia*, MSBB: Maize + sorghum + cashew balm + BotaniGard, MT: Maize + TopBio, CS: Crushed charcoal + table salt, TPP: Climate-adapted push–pull technology

Comparison of Infestation Levels across Maize Developmental Stages

Model comparison based on the Akaike Information Criterion (AIC) indicated that the mixed Poisson model provided the best fit (AIC = 661.78) compared to the mixed negative binomial model (AIC = 663.78) and the simple negative binomial model (AIC = 663.17). Therefore, the mixed Poisson model was used to analyze the effects of treatments and developmental stages on infestation severity.

Table 4 presents the estimated effects of treatments and maize developmental stages on infestation severity. Results showed that several treatments significantly altered infestation levels compared to the CS+A treatment. In particular, treatments MAB+A, MMT+A, MNR+A, and TPP+A significantly increased the probability of higher infestation, with respective increases of 29% (IRR = 1.29; p = 0.015), 39% (IRR = 1.39; p = 0.002), 35% (IRR = 1.35; p = 0.005), and 25% (IRR = 1.25; p = 0.038). The Control+A treatment had the strongest effect, doubling the probability of higher infestation (IRR = 2.02; p < 0.001). In contrast, treatments

MSB+A (IRR = 1.12; p = 0.297), MSBB+A (IRR = 0.90; p = 0.384), and MT+A (IRR = 1.13; p = 0.250) did not have a significant effect on infestation levels.

Table 4. Effects of Treatments and Maize Developmental Stage on Infestation

Variations	Estimate	Odds (IRR)	Erreur Standard	z-value	Pr(>|z|)
Intercept	2,244	9,430	0,089	25,252	<2e-16***
Traitment					
MAB+A	0.258	1.290	0.107	2.425	0.015326*
MMT+A	0.330	1.390	0.105	3.144	0.001665**
MNR+A	0.297	1.350	0.106	2.812	0.004918**
MSB+A	0.115	1.120	0.110	1.044	0.297
MSBB+A	-0.101	0.900	0.116	-0.870	0.384
MT+A	0.126	1.130	0.110	1.150	0.250
Témoin+A	0.703	2.020	0.098	7.178	7.07e-13***
TPP+A	0.223	1.250	0.107	2.077	0.037763*
Developmental stage					
Vegetatif stage	0.202	1.220	0.058	3.483	0.000496***
Seedling stage	0.078	1.080	0.060	1.311	0.190

Codes de significations : 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

NB: Control: Agricultural practices only (Control plot), MSB: Maize + soybean + cashew balm, MAB: Maize + groundnut + BotaniGard, MNR: Maize + cowpea + *Ricinus communis*, MMT: Maize + mucuna + *Thevetia neriifolia*, MSBB: Maize + sorghum + cashew balm + BotaniGard, MT: Maize + TopBio, CS: Crushed charcoal + table salt, TPP: Climate-adapted push–pull technology

Structuring of Mean Infestation According to Treatments and Maize Developmental Stages

Figure 4 illustrates the structuring of mean infestation levels according to treatments at each maize developmental stage. Other treatments occupied intermediate positions.

During the vegetative stage, a similar pattern was observed, with MSBB+A associated with the lowest infestation levels and Control+A exhibiting the highest values. Treatments MAB+A, MNR+A, and MMT+A formed a statistically homogeneous group characterized by intermediate to high infestations.

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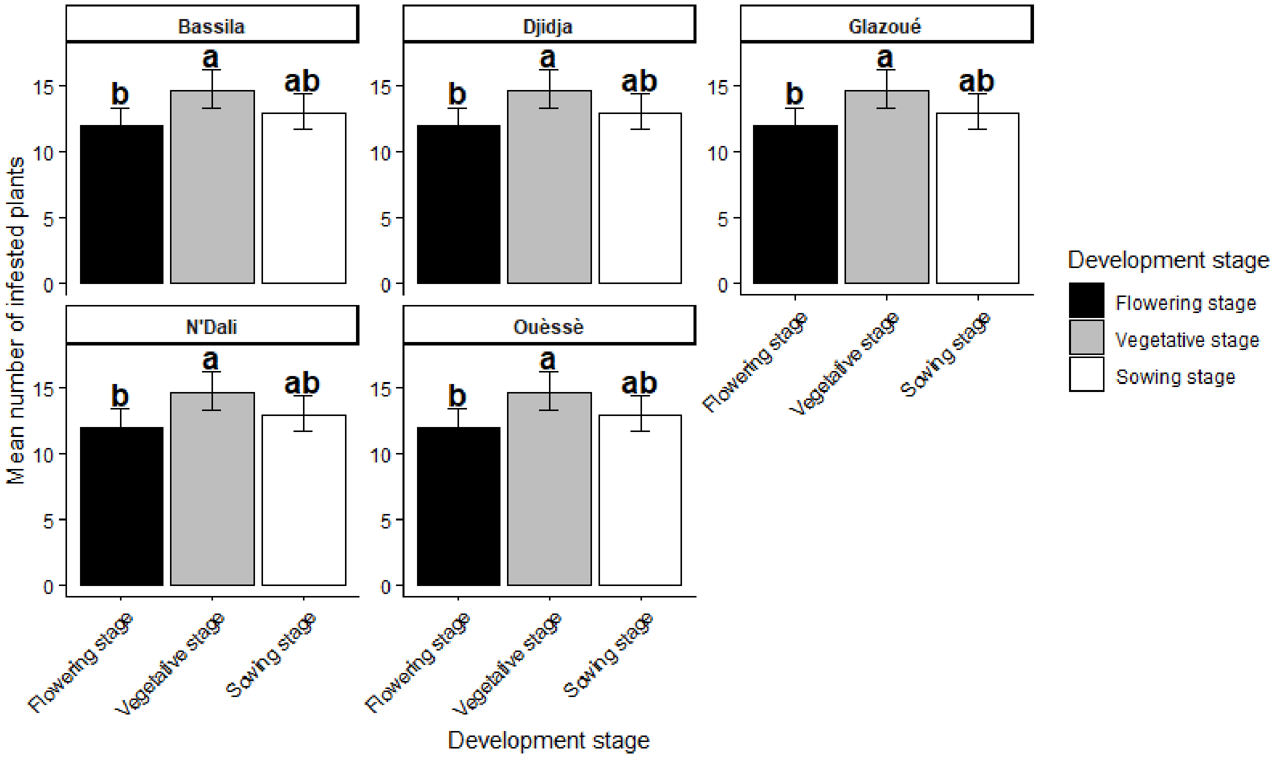
At the seedling stage, the same trends were maintained: MSBB+A was associated with significantly lower infestation, while Control+A remained the most infested. The remaining treatments were distributed in intermediate groups with no significant differences among them.

Figure 4. Mean Abundance of *Spodoptera frugiperda* Larvae According to Treatments and Maize Growth Stages



NB. Control: Agricultural practices only (Control plot), MSB: Maize + soybean + cashew balm, MAB: Maize + groundnut + BotaniGard, MNR: Maize + cowpea + *Ricinus communis*, MMT: Maize + mucuna + *Thevetia neriifolia*, MSBB: Maize + sorghum + cashew balm + BotaniGard, MT: Maize + TopBio, CS: Crushed charcoal + table salt, TPP: Climate-adapted push–pull technology.

Determination of Maize Yield across Different Cropping Systems

Table 5 presents the estimated effects of the different cropping systems on maize yield. Results indicate that several treatments significantly affected yield compared to CS+A. Treatments MAB+A, MMT+A, and MNR+A caused significant reductions in yield, with decreases of 0.54 t ha^{-1}, 0.72 t ha^{-1}, and 0.64 t ha^{-1}, respectively ($p < 0.001$). Similarly, treatments MSB+A and TP+A were associated with moderate but significant decreases in yield. In contrast, the MT+A treatment showed a significant increase in yield, with an average gain of 0.28 t ha^{-1} ($p = 0.018$). The TPP+AgroBio treatment tended to reduce yield, but this effect did not reach statistical significance.

Table 5. Effect of cropping systems on maize yield (mixed-effects linear model)

Variations	Estimate	Erreur Standard	T-value	Pr(>|t|)
Intercept	4.004	0.087	45.997	<2e-16***
MAB+A	-0,544	0.112	-4.855	1.81e-05***
MMT+A	-0.724	0.112	-6.463	9.82e-08***
MNR+A	-0.644	0.112	-5.748	1.01e-06***
MSB+A	-0.264	0.112	-2.355	0.0234*
MSBB+A	0.036	0.112	0.324	0.7479
MT+A	0.276	0.112	2.467	0.0179*
Témoin+A	-1.424	0.112	-12.713	9.31e-16***
CS+A	-0.271	0.129	-2.099	0.0421*
TPP+A+AgroBio	-0.294	0.148	-1.979	0.0546,

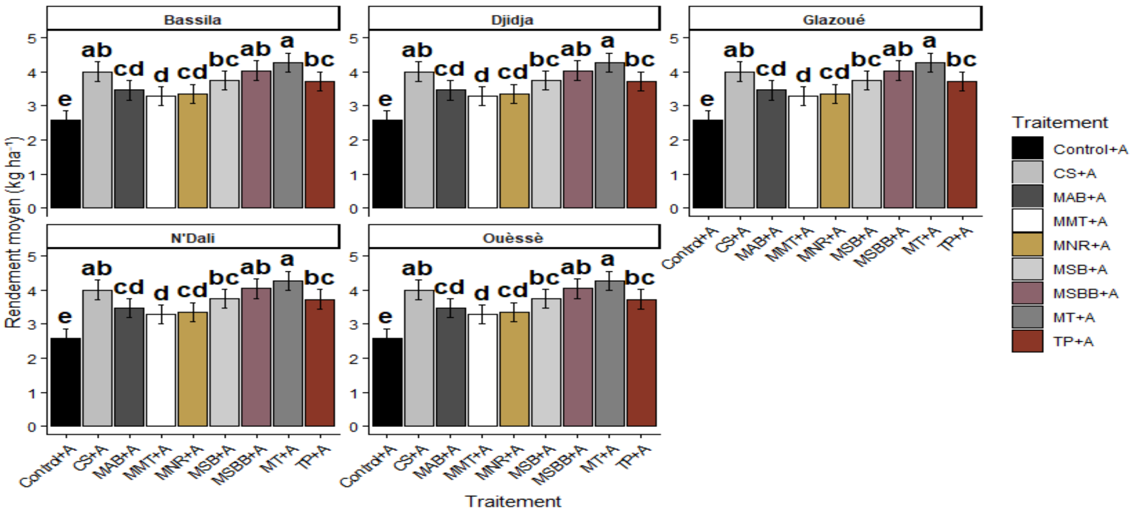
Codes de signification: 0 ‘***’ 0,001 ‘**’ 0,01 ‘*’ 0,05 ‘.’ 0,1 ‘ ’ 1

NB. Control: Agricultural practices only (Control plot), MSB: Maize + soybean + cashew balm, MAB: Maize + groundnut + BotaniGard, MNR: Maize + cowpea + *Ricinus communis*, MMT: Maize + mucuna + *Thevetia neriifolia*, MSBB: Maize + sorghum + cashew balm + BotaniGard, MT: Maize + TopBio, CS: Crushed charcoal + table salt, TPP: Climate-adapted push–pull technology.

Structuring of Mean Maize Yield According to Treatments

Figure 5 highlights a significant differentiation in maize yields among cropping systems. The Control+A treatment showed the lowest yield, forming a statistically distinct group (“a”). Treatments MMT+A and MAB+A also exhibited relatively low yields, grouped in lower-intermediate classes. In contrast, the MT+A treatment had the highest mean yield and formed a statistically distinct group (“e”).

Figure 5. Mean Maize Yield According to Different Cropping Systems”.



Effect of Treatments on the Presence of Parasitoids in Maize Fields

A logistic regression model was used to evaluate the effect of treatments on the probability of parasitoid presence. The response variable was binary (presence/absence), and coefficients were interpreted through odds ratios (OR) only when effects were statistically significant ($p < 0.05$). Among the treatments evaluated, MMT+A, CS+A, and MSB+A had a significant effect on parasitoid presence (Estimate = 1.7918; p = 0.0315). The associated odds ratio (OR = 6.0) indicates that these treatments increased the likelihood of parasitoid presence sixfold compared to the reference treatment. Other treatments did not show a statistically significant effect on the probability of parasitoid presence ($p > 0.05$).

Table 6. Effect of Various Treatments on the Likelihood of Parasitoid Occurrence in Maize Fields

Variations	Estimate	Odds_Ratio	Standard Error	Z-value	Pr(>|z|)
Intercept	-1.3863	0.250	0.6455	-2.148	0.0317*
CS+A	0.6931	2.000	0.8466	0.819	0.0325*
MAB+A	0.6931	2.000	0.8466	0.819	0.4129
MMT+A	1.7918	6.000	0.8333	2.150	0.0315*
MNR+A	1.2528	3.500	0.8274	1.514	0.1300
MSB+A	1.2528	3.500	0.8274	1.514	0.0319*
MSBB+A	0.9808	2.667	0.8333	1.177	0.2392
MT+A	0.3747	1.455	0.8704	0.430	0.6668
TPP+A	0.9808	2.667	0.8333	1.177	0.2392

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Parasitism Rates of Major Natural Enemy Groups of *Spodoptera frugiperda* across Localities (ATDA4) in Benin

Table 7 presents the six parasitoid species of fall armyworm (*Spodoptera frugiperda*) identified in maize fields from the south to the north of the Agricultural Development Territorial Agency Pole 4 (ATDA4) in Benin. The predominant parasitoid species recorded in these regions included *Cotesia icipe*, *Charops* sp., and *Chelonus bifoveolatus*. *Drino quadrizonula* and *Pristomerus pallidus* were observed in only two of the five districts studied, specifically in the central localities of Glazoué and Ouèssè. Parasitism rates of these species on *S. frugiperda* larvae varied among districts, indicating spatial heterogeneity in parasitoid activity**.**

Tableau 7: Parasitism recorded from *S. frugiperda* in the field in different districts in Benin countries

Country	Districts	Paraistoids	Order: family	Host stages Parasitized	% Parasitism
Benin	DJIDJA	*Chelonus bifoveolatus* Szépligeti	Hymenoptera : Braconidae	Larval	3.6

		Cotesia icipe Fernandez-Triana & Fiobe	Hymenoptera: Braconidae	Larval	5.8
		Drino quadrizonula (Thomson)	Diptera : Tachinidae	Larval	2.7
		Coccygidium luteum (Brullé)	Hymenoptera : braconidae	Larval	1.1
		Charops sp.	Hymenoptera : Ichneumonidae	Larval	2.3
Benin	GLAZOUE	*Cotesia icipe* Fernandez-Trian	Hymenoptera : Braconidae	Larval	2.9
		Coccygidium luteum (Brullé)	Hymenoptera : braconidae	Larval	1.2
		Chelonus bifoveolatus Szépligeti	Hymenoptera : Braconidae	Larval	7.2
		Drino quadrizonula (Thomson)	Diptera : Tachinidae	Larval	2.8
		Charops sp.	Hymenoptera : Ichneumonidae	Larval	2.6
		Pristomerus pallidus (Kriechbaumer)	Hymenoptera : ichneumonidae	Larval	1.3
Benin	OUESSE	Chelonus bifoveolatus Szépligeti	Hymenoptera : Braconidae	Larval	3.3
		Cotesia icipe Fernandez-Triana & Fiobe	Hymenoptera: Braconidae	Larval	5.15
		Drino quadrizonula (Thomson)	Diptera : Tachinidae	Larval	0.70
		Coccygidium luteum (Brullé)	Hymenoptera : braconidae	Larval	3.4
		Charops sp.	Hymenoptera : Ichneumonidae	Larval	1.3
		Pristomerus pallidus (Kriechbaumer)	Hymenoptera : ichneumonidae	Larval	0.80
Benin	BASSILA	Chelonus bifoveolatus Szépligeti	Hymenoptera : Braconidae	Larval	2.8
		Cotesia icipe Fernandez-Triana & Fiobe	Hymenoptera: Braconidae	Larval	4.9

		Drino quadrizonula (Thomson)	Diptera : Tachinidae	Larval	0.80
		Coccygidium luteum (Brullé)	Hymenoptera : braconidae	Larval	2.7
		Charops sp.	Hymenoptera : Ichneumonidae	Larval	1.3
Benin	N'DALI	*Cotesia icipe* Fernandez-Triana & Fiobe	Hymenoptera: Braconidae	Larval	3.7
		Charops sp.	Hymenoptera : Ichneumonidae	Larval	2.3
		Chelonus bifoveolatus Szépligeti	Hymenoptera : Braconidae	Larval	1.89

DISCUSSION

Influence of Cropping Systems and Maize Developmental Stage on Fall Armyworm Infestation in ATDA 4, Benin

The different cropping systems implemented for managing fall armyworm (FAW) in the Agricultural Development Territorial Agency Pole 4 (ATDA 4) of Benin contributed to a significant reduction in FAW abundance (Figure 2). Analysis of the results also revealed that the maize developmental stage significantly influenced infestation severity. The vegetative stage was associated with a 73% increase in the probability of reaching a higher severity level compared to the seedling stage (OR = 1.73; 95% CI: 1.46–2.04; $p < 0.001$), whereas the seedling stage showed no significant effect (OR = 0.98; $p = 0.787$).

The highest oviposition by FAW during the early maize growth stage (0–21 days) can be attributed to the pest's preference for fresh vegetative tissues (Tepa *et al.*, 2021). Additionally, the chemical ecology of young maize plants, which attract more FAW females for oviposition, warrants particular attention (Midega *et al.*, 2018). Accumulation of silica in mature and more resistant maize plants could explain the reduced oviposition by FAW females and the increased host tolerance during the post-flowering stage (Tepa *et al.*, 2021; Mitchell *et al.*, 2016).

Odds ratios, all below one, indicate a significant decrease in larval abundance depending on the treatment applied (Table 3). Treatments such as maize + peanut + BotaniGard 22WP + Agrobio, maize + mucuna + Topbio + Agrobio, crushed charcoal + table salt, and Push-Pull + Agrobio also showed significant effects, with reductions ranging from 45% to 48% (Table 3). Conversely, Push-Pull + Agrobio, maize + peanut + cashew balm + Agrobio, and maize + mucuna + Topbio + Agrobio showed significantly higher abundances. Overall, this structuring indicates that all applied treatments significantly reduced larval abundance compared to the control, with variable effectiveness depending on the treatment (Figure 2). The intercept reflects the mean infestation level observed under the Control+A treatment (Table 3).

It is well established that pest populations are lower in diversified ecosystems or intercropped fields (Perrin and Phillips, 1978; Risch, 1979; Degri *et al.*, 2014). This study corroborates these findings, showing that intercropping maize with legumes resulted in significantly lower FAW infestation compared to maize monoculture. Girma *et al.* (2018) reported that among legumes intercropped with maize, FAW infestation levels were relatively similar (65% for beans, 74% for soybean, and 64% for peanut), with no significant differences. These authors also concluded that there was no significant difference in FAW infestation between climate-smart push-pull technology (PPT) and conventional PPT. However, infestation severity was lowest in the climate-smart PPT, with highly significant differences ($P < 0.001$) compared to maize intercropped with legumes and maize monoculture (Girma *et al*., 2018).

Regardless of the site, the negative control plot (agronomic practice only) with Agrobio consistently showed the highest cumulative infestation levels, with a rapid increase from the seedling to flowering stages (Figure 3).

Effect of Alternative Cropping Systems on Cumulative FAW Infestation and Companion Plant Interactions

In contrast, systems incorporating alternative cropping practices, notably CS+A, MSBB+A, and MT+A, exhibited lower cumulative infestation levels and a more moderate increase over time. Observed trends were generally consistent across regions, although infestation rates varied slightly depending on the local agroecological context. The regions of Bassila, N'Dali, and Ouèssè showed the highest cumulative values at the end of the period, whereas Djidja and Glazoué had relatively lower levels (Figure 3).

The Push-Pull technology (comprising *Pennisetum purpureum* + Maize + *Helianthus annuus* + Agrobio), implemented within the framework of conservation agriculture, provided additional benefits, particularly during the initial establishment phase when *P. purpureum* had just been planted. Once *H. annuus* was established, it offered protective effects that complemented the advantages of conservation agriculture. Infestation severity was consistently higher in maize monocultures than in all other treatments (Figure 3). Consequently, the choice of companion plants is a critical factor in the agroecological management of FAW (Altieri, 1980; van Huis, 1981). Although FAW can feed on more than 300 host plants (Gutiérrez *et al*., 2019; Khan *et al*., 2007), maize remains its preferred host.

The study demonstrated that sorghum and cowpea (*Vigna unguiculata*) remained the FAW's preferred alternative hosts, although larval mortality on these plants was as high as that observed on *H. annuus*. Larvae feeding on these plants also exhibited lower weight gain compared to maize. Plant defenses against herbivores can be mechanical or chemical, resulting from numerous chemical and morphological adaptations (Łaźniewska *et al*., 2012; War *et al*., 2012). *P. purpureum* and *H. annuus* exerted stronger deterrent effects on FAW larvae, which was also reflected in higher larval mortality relative to the negative control. Morales *et al.* (2025) reported in a prolonged 15-day experiment that larval mortality on *P. purpureum* was relatively low compared to other grasses, suggesting that this plant could serve as an alternative host for FAW larvae in the absence of their primary host. This could facilitate pest establishment, development, and spread, as noted by Chen *et al.* (2023).

The results of this study provide further insights into FAW management across monoculture systems, cowpea intercropping, and push-pull systems (Figure 4). Compared to monoculture (Table 4), intercropping systems disrupt mechanisms that mediate insect-host plant interactions (Table 4). In maize monocultures, newly hatched FAW larvae disperse by crawling or flying, resulting in higher potential for plant damage and pest spread.

Effects of Treatments on FAW Infestation, Maize Yield, and Parasitoid Presence

The treatments maize + sorghum + BotaniGard + Agrobio, maize + sorghum + cashew balm + BotaniGard 22WP + Agrobio, and maize + cowpea + Topbio did not show a significant effect on infestation levels. Regarding maize developmental stage, the vegetative phase was associated with a significant 22% increase in the probability of observing higher infestation (IRR = 1.22; $p < 0.001$), whereas the seedling stage did not differ significantly from the reference condition (IRR = 1.08; $p = 0.190$) (Table 4).

During the flowering stage, the MSBB+A treatment exhibited the lowest larval abundance and formed a statistically distinct group (“a”), while the Control+A treatment showed the highest infestation, forming a separate group (“c”) (Figure 4). Treatments MSBB+A and CS+A occupied intermediate levels, with no significant difference between them.

Regarding yield, the TPP+A treatment achieved higher maize yield than several other treatments, though still lower than that observed under MT+A (Figure 5). The MSBB+A treatment did not differ significantly from CS+A. The Control+A treatment showed the most pronounced yield reduction, with an average loss of 1.42 t ha^{-1} ($p < 0.001$) (Table 5).

Analysis of parasitoid presence in maize fields showed that among all treatments evaluated, MMT+A, CS+A, and MSB+A had a significant effect on parasitoid occurrence (Table 6). The associated odds ratio (OR = 6.0) indicates that these treatments increased the likelihood of parasitoid presence sixfold compared to the reference treatment. In general, intercropping provides a protective microclimate that enhances the richness and abundance of beneficial insects (Matova *et al.*, 2020). The notable presence of parasitoids in fields treated with Topbio, cashew balm, and crushed charcoal + table salt highlights the synergistic effect of these products in the natural regulation of FAW. This research identified nearly fifteen species of natural enemies, including both parasitoids and predators. The predators identified belonged primarily to the families Araneae, Carabidae, Coccinellidae, Forficulidae, Formicidae, Mantidae, Pentatomidae, and Reduviidae. Among these groups, the Forficulidae (60%), the

Formicidae (20%), and the Coccinellidae (25%) were the most abundant in the corn fields studied.

Overall, these results highlight the importance of the diversity and abundance of natural enemies in the ecological regulation of *S. frugiperda* populations. They also emphasize the need to promote agricultural practices that support the conservation of functional biodiversity, an essential condition for the development of sustainable integrated management strategies for the fall armyworm in maize production systems in Benin.

CONCLUSION

This study identifies maize cropping systems that contribute to a significant reduction in fall armyworm (*Spodoptera frugiperda*), thereby lowering the pest’s damage threshold and improving yield under organic agriculture. The study also elucidates the mechanisms involved in FAW management within push-pull systems and legume intercropping. The repellent effect of *Pennisetum purpureum* forces gravid moths to lay their eggs on *Helianthus annuus*. Intercropping limits the dispersal potential of neonates while reducing oviposition by fall armyworm moths. This cropping system also disrupts the developmental cycle of FAW.

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These results underscore the need for targeted monitoring and management strategies for fall armyworm in maize-dominated agroecosystems and other host plants. Integrating less favorable host plants and using plant extracts such as cashew balm, *Ricinus communis*, *Thevetia neriifolia*, as well as biocontrol products like the entomopathogenic fungus BotaniGard 22 WP and Topbio extracts from *Cymbopogon nardus*, within crop rotation or intercropping systems could help reduce pest pressure. Several natural enemies have been identified in various corn fields following the adoption of various agroecological farming systems, which justifies the adoption of these farming systems by farmers for the natural control of the fall armyworm. This research provides critical insights for the fundamental understanding necessary to develop more effective integrated strategies for FAW management.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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REFERENCES

1- Akutse K.S. et al., 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
2- Altieri, M.A., and M.Z. Liebman. 1986. Insect, weed, and plant disease management in multiple cropping systems. In: C.A. Francis, editor, Multiple cropping systems. Macmillan, New York. p. 183–218.
3- Altieri, M.A. 1980a. Diversification of corn agroecosystems as a means of regulating fall armyworm populations. The *Florida Entomol*. 63:18-–24.
4- Altieri, M.A. 1980b. The need for an agroecological approach to pest management. Environ. Manage. 4:467–468.
5- Assefa F., 2018. Status of fall armyworm (*Spodoptera frugiperda*), biology and control measures on maize crop in Ethiopia: a review. *Int. J. Entomol. Res*., 06(02), 75-85, https://doi.org/10.33687/entomol.006.02.2498
6- Assefa, F., & Ayalew, D. (2019). Status and control measures of fall armyworm (*Spodoptera frugiperda*) infestations in maize fields in Ethiopia: A review. *Cogent Food & Agriculture, 5*(1), 1641902. https://doi.org/10.1080/23311932.2019.1641902
7-
8- Bateman M.L. et al., 2018. Assessment of potential biopesticide options for managing fall armyworm (*Spodoptera frugiperda*) in Africa. *J. Appl. Entomol.*,142, 805-819, https://doi.org/10.1111/jen.12565
9- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67(1), 1–48.
10- Bartoń, K. (2023). MuMIn: Multi-Model Inference. R package version.

11- Brooks, M. E., Kristensen, K., van Benthem, K. J., et al. (2017). glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *The R Journal*, 9(2), 378–400.

12- Bhusal S. & Chapagain E., 2020. Threats of fall armyworm (*Spodoptera frugiperda*) incidence in Nepal and its integrated management-a review. *J. Agric. Nat. Resour*., 3(1), 345-359 https://doi.org/10.3126/janr.v3i1.27186

13- Carvalho IF, Erdmann LL, Machado LL, Rosa APSA, Zotti MJ, and Neitzke CG. Metabolic resistance in the fall armyworm: an overview. *J Agric Sci* 10:426 (2018)

14- Cean, M., A. Taddei, R.A. Gottsberger, H. Reisenzein und E.I.V. Georgescu (2024). First report of the fall armyworm *S. frugiperda* (JE Smith, 1797) in Romania. EPPO Bulletin. https://doi: 10.1111/epp.13017

15- Cherry A.J., Lomer C.J., Djegui D. & Schulthess F., 1999. Pathogen incidence and their potential as microbial control agents in IPM of maize stem borers in West Africa. *BioControl*, 44, 301-327, https://doi.org/10.1023/A:1009991724251

16- Cherry A.J., Banito A., Djegui D. & Lomer C., 2004. Suppression of the stem-borer *Sesamia calamistis* (Lepidoptera; Noctuidae) in maize following seed-dressing, topical application, and stem injection with African isolates of *Beauveria bassiana*. *Int. J. Pest Manage*., 50(1), 67-73, https://doi.org/10.1080/096708703100 01637426

17- Chinwada P., 2018. *Évaluation de la prévalence de la chenille légionnaire d'automne à Madagascar – Rapport de mission*. Rome : FAO.

18- Cokola M.C., 2019. Monitoring, caractérisation moléculaire et lutte biologique contre Spodoptera frugiperda *(Lepidoptera: Noctuidae)*. Travail de fin d'étude : Université de Liège - Gembloux Agro-Bio Tech, Gembloux (Belgique)

19- C., Shimelis H. & Laing M.D., 2020. Fall armyworm invasion in Africa: implications for maize production and breeding. *J. Crop Improv*., 35(1), 111-146, doi.org/10.1080/15427528.2020.1802800

20- CSP, 2019. Liste des pesticides autorisés par la 45e session ordinaire du Comité Sahélien des Pesticides. Ouagadougou : Comité Permanent Inter-États de Lutte Integrated pest management of the fall armyworm

21- Cruz, I., M. Figueiredo, A.C. Oliveira, and C.A. Vasconcelos (1999). Damage of *Spodoptera frugiperda* (Smith) in different maize genotypes cultivated in soil under three levels of aluminum saturation. *Int. J. Pest Manag*. 45: 293-296. https://DOI: 10.1080/096708799227707

22- de Groote H, Kimenju SC, Munyua B, Palmas S, Kassie M and Bruce A. (2020). Spread and impact of fall armyworm (Spodoptera frugiperda J.E. Smith) in maize production areas of Kenya. *Agric Ecosyst Environ* 292:106804

23- EPPO (European Plant Protection Organization) (2025) EPPO Global Database *Spodoptera frugiperda* (LAPHFR). Available at: https://gd.eppo.int/taxon/LAPHFR/distribution (accessed September 2025).

24- FAO (Food and Agriculture Organization) (2023) Fall Armyworm. Available at: http://www.fao.org/fall-armyworm/background/en/ (accessed December 2023).

25- FAO (Food and Agriculture Organization) (2024) Fall Armyworm. Available at: https://www.fao.org/fall-armyworm/monitoring-tools/faw-map/en/ (accessed December 2024).

26- Forim, M. R., Matos, A. P., Silva, M. F. D. G. F., Cass, Q. B., Vieira, P. C., & Fernandes, J. B. (2010). The use of HPLC in the control of neem commercial products quality: Reproduction of the insecticide action. *Quimica Nova, 33*, 1082–1087. https://doi.org/10.1590/S0100-40422010000500014

27- Girma, H., M.R. Rao, and S. Sithanantham. 2000. Insect pests and beneficial arthropod population under different hedgerow intercropping systems in semiarid Kenya. Agrofor. Syst. 68(12):93–102

28- Girma, H. 2006. Ill-health in agroforestry a challenge in scaling up agroforestry innovations. World Agroforestry Center, ICRAF, Nairobi, Kenya.

29- Gutiérrez-Moreno R, Mota-Sanchez D, Blanco CA, Whalon ME, TeránSantofimio H, Rodriguez-Maciel JC et al., Field-evolved resistance of the fall armyworm (Lepidoptera: Noctuidae) to synthetic insecticides in Puerto Rico and Mexico. *J Econ Entomol* 112:792–802 (2019).

30-

31- Hailu G. et al., 2018. Maize-legume intercropping and push-pull for management of fall armyworm, stemborers, and striga in Uganda. *Agron. J.*, 110(6), 2513-2522, https://doi.org/10.2134/agronj2018.02.0110

32- Hothorn, T., Bretz, F., & Westfall, P. (2008). Simultaneous inference in general parametric models. *Biometrical Journal*, 50(3), 346–363.

33- James B. et al., 2010. *Gestion intégrée des nuisibles en production maraîchère : guide pour les agents de vulgarisation en Afrique de l'Ouest*. Ibadan: Institut International d'Agriculture Tropicale (IITA)

34- Kebede Y., Baudron F., Bianchi F. & Tittonell P., 2018. Unpacking the push-pull system: assessing the contribution of companion crops along a gradient of landscape complexity. *Agric. Ecosyst. Environ.*, 268, 115-123, https:// doi.org/10.1016/j.agee.2018.09 .012

35- Khan ZR, Midega CAO, Hassanali A, and Pickett JA, Field developments on Striga control by Desmodium intercrops in a 'push-pull' strategy, in Integrating New Technologies for Striga Control: Towards Ending the Witch-Hunt 241–252 (2007)

36- Khan, Z.R., C.A.O. Midega, T.J.A. Bruce, A.M. Hopper, and J.A. Pickett. 2010. Exploiting phytochemicals for developing a 'push-pull'crop protection strategy for cereal farmers in Africa. J. Exp. Bot. 61(15):4185–4196.Oxford Univ. Press. https://doi.org/10.1093/jxb/ erq229 (accessed 27 Aug. 2018).

37- Kumela, T., J. Simiyu, B. Sisay, P. Likhayo, E. Mendesil, L. Gohole, and T. Tefera. 2018. Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (Spodoptera frugiperda) in Ethiopia and Kenya. *Int. J. Pest Manage.* https:// doi:10.1080/096 70874.2017.1423129

38- Łaźniewska J, Macioszek V, K, and Kononowicz AK, Plant-fungus interface: the role of surface structures in plant resistance and susceptibility to pathogenic fungi. *Physiol Mol Plant Pathol* 78:24–30 (2012).

39- Lenth, R. V. (2023). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version.

40- Lestari, P., A. Budiarti, Y. Fitriana, F. Susilo, I.G.Swibawa, H. Sudarsono, R. Suharjo, A. M.Hariri, L. Wibowo and M. Hartaman (2020). Identification and genetic diversity of *Spodoptera frugiperda* in Lampung Province, *Indonesia. Biodiversitas J. Biol*. Divers. 21.

41- Lytra, I., V. Evangelou, S. Antonatos, I. Georgopoulou, E. Tselou, D. Dimopoulou, and D.P.Papachristos (2024). First data on the occurrence and population dynamics of the fall armyworm *S. frugiperda* (Lepidoptera: Noctuidae) in Greece. EPPO Bulletin. https://DOI:10.1111/epp.13021

42- Mazerolle, M. J. (2020). AICcmodavg: Model selection and multimodel inference based on (Q)AIC(c). R package version.

43- Marchand, P. A. (2017). Basic and low-risk substances under European Union pesticide regulations: A new choice for biorational portfolios of small and medium-sized enterprises. *Journal of Plant Protection Research, 57*(4), 433–440. https://doi.org/10.1515/jppr-2017-0056

44- Matova P.M. et al., 2020. Fall-armyworm invasion, control practices, and resistance breeding in Sub-Saharan Africa. *Crop Sci*., 60, 2951-2970, https:// doi.org/10.1002/csc2.20317

45- Midega C.A.O. et al., 2018. A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (J E Smith), in maize in East Africa. *Crop Prot*., 105, 10-15, https:// doi.org/10.1016/j.cropro.2017.11.003

46- Montezano D G, Specht A, Sosa-Gómez D R, Roque-Specht V F, Sousa-Silva J C, Paula-Moraes S V D, Peterson J A, Hunt T E. 2018. Host plants of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the Americas. *African Entomology*, 26, 286–301.

47- Nayanya, G., C.B. More, and C. Schal. 2000. Integration of Repellents, attractants, and insecticides in a "push-pull strategy for managing German cockroach (Dictyopera: Blattellidae) populations. *J. Med. Entomol*. 37(3):427–434

48- Niassy, S., Agbodzavu, M. K., Kimathi, E., Mutune, B., AbdelRahman, E. F. M., Salifu, D., … Subramanian, S. (2021b). Bioecology of fall armyworm *Spodoptera frugiperda* (J. E Smith), its management and potential patterns of seasonal spread in Africa. *PLoS One, 16*(6), e0249042. https://doi.org/10.1371/journal.pone.0249042

49- Ogenga-Latigo, M.W., C.W. Balidawa, and J.K.O. Ampofo. 1992. Influence of maize row spacing on infestation and damage of intercropped beans by bean aphids (*Aphis fabae* Scop.) incidence of aphids. Field Crops Res. 30:111–121. https:// doi:10.1016/0378-4290(92)90060-M

50- Pavela, R. (2016). History, presence and perspective of using plant extracts as commercial botanical insecticides and farm products for protection against insects – a review. *Plant Protection Science, 52*(4), 229–241. https://doi.org/10.17221/31/2016-PPS

51- Rioba, N. B., & Stevenson, P. C. (2020). Opportunities and scope for botanical extracts and products for the management of fallarmyworm (*Spodoptera frugiperda*) for smallholders in Africa.*Plants, 9*(2), 207. https://doi.org/10.3390/plants9020207

52- Seran, T.H., and I. Brintha. 2010. Review of maize-based intercropping. J.Agron. 9:135–145. doi:10.3923/ja.2010.135.145

53- Silvie, P. J., Martin, P., Huchard, M., Keip, P., Gutierrez, A., & Sarter, S. (2021). Prototyping a knowledge-based system to identify botanical extracts for plant health in sub-Saharan Africa. *Plants, 10*(5), 896. https://doi.org/10.3390/plants10050896

54- Sisay, B., Tefera, T., Wakgari, M., Ayalew, G., & Mendesil, E.(2019a). The efficacy of selected synthetic insecticides and botanicals against fall armyworm, *Spodoptera frugiperda,* in maize. *Insects, 10*(2), 45–58. https://doi.org/10.3390/ insects10020045

55- Tay, W.T., R.L. Meagher Jr, C. Czepa, K., and A.T. Groot (2023). *Spodoptera frugiperda*: ecology, evolution, and management options of an invasive species. Annual Review of Entomology, 68(1), 299-317. https:// DOI: 10.1146/annurev-ento-070720-014201

56- Van Huis, A. (1981). Integrated pest management in the small farmer's maize crop in Nicaragua. Meded. Landbouwhogeschool Wageningen 81-6. The Netherlands. 221 pp.

57- Vega F.E., 2018. The use of fungal entomopathogens as endophytes in biological control: a review. *Mycologia*, 110(1), 4-30, https://doi.org/10.1080/00275514.2017.1418578

58- War AR, Paulraj MG, Ahmad T, Buhroo AA, Hussain B, Ignacimuthu S et al., Mechanisms of plant defense against insect herbivores. Plant Signal Behav 7:1306–1320 (2012).

59- Wickham, H. (2016). ggplot2: Elegant Graphics for Data Analysis. Springer.