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Impact of Insecticide on Fall Armyworm Infestation at Different Maize Growth Stages: Insights from a Field Study in a Subtropical Region

Ahmed I. El-Tokhy[*1], **Khaled M. Ibrahim**[2], **Wael E. A. El-Sheikh**[1]

[1]Plant Protection Department, Faculty of Agriculture, Beni-Suef University, Beni-Suef 62511, Egypt
[2]Agronomy Department, Faculty of Agriculture, New valley University, New valley, Egypt

* Corresponding author

Ahmed I. El-Tokhy

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Abstract

The fall armyworm (FAW), *Spodoptera frugiperda,* is a significant global threat to maize production and causes adverse effects at different growth stages. We conducted this field experiment in a subtropical region to evaluate the efficacy of insecticides against FAW during various growth stages of maize in the 2022 and 2023 seasons. The results highlighted the significant influence of maize growth stages on infected plant numbers; the maturity stage exhibited the lowest infestation rates, while the late whorl stage showed the highest susceptibility, with rates of 74% and 66.7%, respectively. During the early whorl stage (VE-V6), spinosad proved the most effective insecticide, reducing the incidence to 13.5% and 18.5%, respectively. On the other hand, emamectin benzoate showed the greatest efficacy in decreasing FAW infection in the late whorl stage (V7–VT), with the lowest percentage of infected plants (57.4% and 50.4%). In the tasseling and silking stages (R1-R4), methomyl was the most effective compared to the control, significantly reducing infestation rates to 6.0% and 5.3%. Furthermore, a marked reduction in infestation rates was observed during the maturity stage (R5-R6) across all treatments, including the control. Ultimately, indoxacarb was associated with the lowest maize yield (674.5 and 650.5 kg ha^{-1}, respectively), whereas methomyl was the most productive insecticide (2683.6 and 2742.3 kg ha^{-1}, respectively). These findings are critical for understanding the relationship between insecticide efficacy and maize growth stages associated with the development of effective FAW management strategies.

Keywords: Emamectin benzoate, methomyl, maize, growth stages, *Spodoptera frugiperda*

Introduction

Maize (*Zea mays* L.) is among the most significant cereal crops around the world, which are used by hundreds of millions of people as a staple source of food; hundreds of thousands of livestock depend on maize as a critical ingredient feedstock and is, furthermore, a raw material for industrialization. Concern for maize production is justified by its global importance in both food security and economic stability. Insect pests, especially the fall armyworm, *Spodoptera frugiperda* (J.E. Smith), are a critical challenge in maize production that can lead to significant yield losses and threaten global food production (Khan et al., 2023).

Biotic and abiotic stress like drought, salinity, plant pathogens, and insect pests are common in cereal crops (including maize) in subtropical regions (Abdelaal et al., 2022; Abdou et al., 2023). From these stressful events, productivity can be greatly affected, with the fall armyworm (FAW) being one of the most destructive pests. FAW also damages at different development stages, causing significant economic losses (Nyaupane et al., 2022; Lu et al., 2023). Its rapid reproduction, migratory behavior, high dispersal ability, and capacity to fly over 116 kilometers within 48 hours before oviposition make it particularly difficult to manage (Belay et al., 2012; Chen et al., 2022).

The fall armyworm (FAW) attacks maize more frequently than other crops (Hardke et al., 2015; Lu et al., 2023). As the world warms and agricultural practices get more intense, the spread of this pest has become more rampant. FAW, originally native to tropical and subtropical regions of the Americas, has served a world tour, with its invasion of Africa in 2016 a turning point. FAW was first reported in maize fields in Aswan Governorate and later spread to Luxor Qena, Sohag, and Assuit in Upper Egypt, where it caused extensive damage to maize crops (Mohamed et al., 2022; Siazemo & Simfukwe, 2020).

The application of insecticides is one of the most typical strategies used for the control of armyworm infestations (Gichere et al., 2021; Tejeda-Reyes et al., 2023). Studies conducted earlier have demonstrated the significant efficacy that the armyworm larva suffers when exposed to spinosad, chlorantraniliprole, emamectin benzoate, and methomyl either alone or in combination (Abdel-Hafez et al., 2013; Siddiqui et al., 2023; Zhang et al., 2023). But it should not be presumed that the efficiency of these insecticides is only confined to their properties by chemical composition; other factors, such as environmental factors as well as biological factors, also contribute. As an example, physiological modifications that take place in the maize plant at their different growth stages could influence the action of insecticides in accordance with the age of the maize plants (Bialozor et al., 2020; van den Berg et al., 2021; Viteri and Linares-Ramírez, 2022).

In the past, research has focused on the impact of insecticides against FAW, but there is a lack of research that revolves around how insecticide performance is affected by different maize growth stages (Hardke et al., 2011; Stevens et al., 2012). There's a dearth of literature that has investigated the relationship of plant development with the efficacy of insecticide and the consequent yield loss that can be caused by this interaction (van den Berg et al., 2021). The aim of this study is to address this knowledge gap by evaluating the efficacy of several insecticides against FAW at different maize growth stages in a subtropical region. This allows us to determine the most suitable insecticide for each stage and optimize FAW management strategies.

Materials and methods

Insecticides

The efficacy of six commercial insecticide formulations was tested in the field. methomyl (Goldben® 90% SP, Shoura Chemical), beta-cyfluthrin (Becast silfo® 10% EC, Growth Chem for Advanced Chemicals), emamectin-benzoate (Speedo® 5.7% WG, Shoura Chemical), indoxacarb (Avaunt® 15% EC, FMC), lufenuron (Lenoflag 5% EC, CAM for Agrochemicals) and spinosad (Tracer® 24% SC, Dow Agro Science Private Ltd.) were used. These insecticides were obtained from various sources and stored in a secure location until the experiments were carried out. They were mixed with water and sprayed at the recommended rates by the Egyptian Ministry of Agriculture (Table 1).

Table (1): List of commercial insecticides tested against *S. frugiperda,* including active ingredients, application rate, and respective mode of action

Active ingredient	Rate used (a.i. gm ha^{-1})	Mode of action	
		ePM[a]	IRAC[b] site of action
Methomyl	642.85	Systemic insecticide with contact and stomach action,	Acetylcholinesterase inhibitors.
Beta-cyfluthrin	23.81	Non-systemic insecticide with contact and stomach action, long residual activity	Sodium channel modulators.
Emamectin-benzoate	20.35	Non-systemic insecticide, penetrate leaf tissue by translaminar movement.	Chloride channel activator.
Indoxacarb	17.85	Activity by contact and ingestion, affected insects cease feeding	Voltage-dependent sodium channel blocker.
Lufenuron	19.04	Act by ingestion, larvae are unable to moult and cease feeding	Inhibitors of chitin biosynthesis.
Spinosad	28.57	Active by contact and ingestion causes paralysis	Nicotinic acetylcholine receptor allosteric activator

[a]The e-pesticide manual V5.2, [b]Insecticide Resistance Action Committee 2nd edition (2010)

Study Area

The experiment was conducted at the experimental farm of the Faculty of Agriculture, New Valley University, which is located 10 km from the New Valley government road to Assiut (25°31'37.30 N, 30°36'41.20"E, altitude 283 m). The trials were carried out on August 13 during two successive summer seasons, 2022 and 2023. The average temperature and RH were 31.8±3°C, and 38.8%.

Field experimental design and treatments

A randomized complete block design with four replications was used to evaluate six insecticides and one control treatment. In the two seasons, each plot consisted of 10 rows, 3 m long and 0.70 m wide; the plot size area was 21 m². Planting is done on hills spaced at 0.25 m with two kernels per hill. The seedlings were thinned to one plant per hill after 21 days from the planting date. Ten plants in the middle row were taken to measure the agronomic traits studied. Each plot was separated from the adjacent plot by a 1.3 m high plastic belt to minimize the interference of spray drift from one treatment to another. The single yellow maize hybrid (SC168) obtained from the Ministry of Agriculture and Land Reclamation was used. All Agricultural practice was done according to standard recommendations for maize production. Insecticide treatments were carried out using a knapsack sprayer. The plants in the untreated control group were chosen to be slightly farther from those in the treatment groups, and water was applied only with same amount that used in the other treatments. The insecticides treatments were imposed four times during the growth stages where the 1st spray was applied at the early whorl stage in the vegetative growth stage (V4: 12 days), whereas the 2nd and 3rd spray were applied late whorl stage in the vegetative growth stage (V8: 28 d and V14:49 days, respectively). The 4th spray was applied at the tassel and silk stage in the development stage (R3:77 days), in which the hollow cone nozzle was modified to direct the spray fluid solely to the whorl. In contrast, vegetative growth.

Determination of maize growth stages

The vegetative growth stages were identified using leaf collar methods, as measured by the number of maize leaves exhibiting collars (Nielsen 2019a and b). The maize growth stages are divided into the vegetative stage (V), which includes the early whorl (V3–V6) and late whorl (V7–VT) stages, and the reproductive development stage (R), which includes the tassel and silk (R1–R4), and maturity stages (R5–R6).

Monitoring of fall armyworm (FAW), *S. frugiperda* infestation

Visual monitoring of infested plants was performed by examining the presence of survivor *Spodoptera frugiperda* larvae for each plant during each stage of plant development after each treatment. The inspector used two patterns to walk through the replicate trial units and thoroughly examine the plants for any infestation (Figure 1). The "W" pattern was used to explore the infested maize field at early and late vegetative stages, while the "ladder" pattern was used at VT and reproductive stages (Prasanna et al. 2018). Five points (A–E) were examined for each experimental unit, with five plants at each point. The number of maize plants infected with FAW was recorded, and the infection rate was determined using the following equation: % FAW infestation =

$$\frac{Infested\ plants}{Total\ plants}X100$$

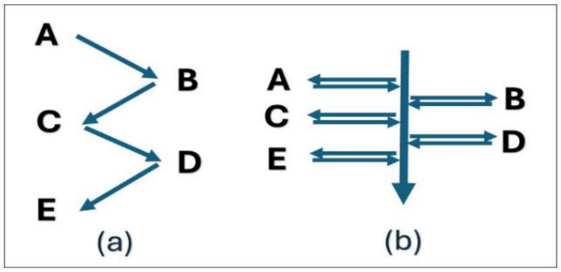

Figure (1): Patterns of inspection used to monitor Spodoptera frugiperda infestation: (a) "W" pattern during the early and late vegetative stages, and (b) "ladder" pattern at VT and reproductive stages. In each pattern, five points (A–E) were located with 4-5 plants estimated distance between points.

Statistical analysis

The data were analyzed using Tow-way ANOVA to determine differences in the percentage of maize plants infested with *S. frugiperda* after insecticide treatment under field conditions. All the statistical analysis was carried out using Proc Mixed of SAS package version 9.2 (SAS 2008), and the means were compared by Duncan comparison at the 5% level of significance. The % FAW infestation was subjected to transformation as described by Steel (1981) and Koch (1968), where each value (x) was transformed to $\sqrt{x+0.5}$, and then these transformed values were statistically analyzed.

Results

The efficacy of insecticides against FAW at various ages of maize growth stages.

The data about the infestation of maize plants, compiled in Tables 2 and 3, for the two seasons 2022 and 2023, at the age of V4: 12 days, during the vegetative growth stages (early whorl), showed no significant differences, suggesting a homogeneous distribution of FAW in the experimental units prior to treatments.

Vegetative growth stages (V)

Early whorl stage (V3–V6)

At the early whorl stage (V3-V6) of maize, specifically at the V5 stage (14 days) following the initial insecticides application (1st T), notable differences in FAW infestation were observed among treatments (Tables 2 and 3). The control group exhibited high infestation rates at this stage, with an average of 88.5% in 2022 and 90.0% in 2023. Compared to the control, methomyl, indoxacarb, and spinosad resulted in a significant reduction in the percentage of infected plants. Specifically, methomyl had the lowest infestation, with infection rates of 1.0% in 2022 and 2.0% in 2023. Indoxacarb had infestation rates of 5.0% in 2022 and 3.0% in 2023 and spinosad showed 8.0% in 2022 and 6.0% in 2023. No significant difference was observed among methomyl, indoxacarb, and spinosad in reducing the infestation rate.

Table (2): Mean percentage (±SEM*) of infested plants by *S. frugiperda* at the vegetative growth stages (early whorl) after application of synthetic insecticides in the field study in 2022

Insecticides	**Vegetative growth stages (Early whorl stage)**			**Means**
	V4 12 d **1st T**	**V5** 14 d	**V6** 21 d	
Methomyl 90%	84.0±3.27^{a}	1.0±1.00^{d}	40.0±2.83^{c}	20.5±1.50^{d}
Beta-cyfluthrin 10%	81.0±3.42^{a}	13.0±3.00^{c}	51.0±1.00^{b}	32.0±1.83^{b}
Emamectin benzoate 5.7%	84.0±1.63^{a}	23.0±1.91^{b}	31.0±2.25^{d}	27.0±1.91^{bc}
Indoxacarb 15 %	81.0±1.91^{a}	5.0±2.52^{d}	59.0±3.00^{b}	32.0±0.82^{b}
Lufenuron 5%	79.0±4.43^{a}	21.0±1.91^{b}	24.0±2.83^{de}	22.5±1.50^{cd}
Spinosad 24 %	84.0±1.63^{a}	8.0±2.83^{cd}	19.0±4.12^{e}	13.5±1.50^{e}
Control	81.0±2.52^{a}	90.0±2.58^{a}	87.0±3.42^{a}	88.5±2.63^{a}

***Standard error mean, V vegetative growth stage, d plant age by days, 1st T first treatment of insecticides. Means followed by the same superscript letters are not significantly different at 5%, according to Duncan's multiple range test.**

Table (3): Mean percentage (±SEM*) of infested plants by *S. frugiperda* at the vegetative growth stage (early whorl) after application of synthetic insecticides in the field study in 2023

Insecticides	**Vegetative growth stages (Early whorl stage)**			**Means**
	V4 12 d **1st T**	**V5** 14 d	**V6** 21 d	
Methomyl 90%	66.0±3.83^{ab}	2.0±1.15^{d}	51.0±1.91^{b}	26.5±1.50^{cd}
Beta-cyfluthrin 10%	74.0±2.58^{a}	20.0±2.83^{b}	54.0±3.46^{b}	37.0±1.73^{b}
Emamectin benzoate 5.7%	71.0±1.90^{ab}	16.0±2.83^{bc}	53.0±9.57^{b}	34.5±4.65^{bc}
Indoxacarb 15 %	61.0±2.52^{b}	3.0±1.91^{d}	45.0±6.19^{bc}	24.0±2.58^{d}
Lufenuron 5%	70.0±3.83^{ab}	9.0±2.52^{cd}	38.0±5.03^{bc}	23.5±3.30^{d}
Spinosad 24 %	67.0±3.79^{ab}	6.0±2.58^{d}	31.0±5.97^{c}	18.5±3.20^{d}
Control	68.0±3.65^{ab}	90.0±2.58^{a}	90.0±3.83^{a}	90.0±2.45^{a}

***Standard error mean, V vegetative growth stage, d plant age by days, 1st T first treatment of insecticides, Means followed by the same superscript letters are not significantly different at 5%, according to Duncan's multiple range test.**

Late whorl stage (V7–VT)

During the late whorl stage of vegetative growth (V8: 28 days), the infestation rate of FAW in the control group reached between 75% and 99%. Across all treatments, no significant differences were observed compared to the control, indicating the limited effectiveness at this growth stage. Among the treatments, spinosad showed the lowest infestation rates, at 75% and 85% for the respective seasons (Tables 4, 5).

At the V10 stage (38 days), following the second treatment (2nd T), the control group exhibited an infection rate of 98% to 100%. In contrast, insecticides such as emamectin benzoate, methomyl, beta-cyfluthrin, and lufenuron demonstrated significant efficacy, with average infestation rates of 3.0%, 4.0%, 8.0%, and 10.0% in the first season and 3.0%, 6.0%, 10.0%, and 6.0% in the second season, respectively. However, there were no significant differences in efficacy among these treatments. Conversely, By the VT stage (56 days), following the third treatment (3rd T), the control group maintained high infestation rates of 100% and 97% for the first and second seasons, respectively. While the insecticides lufenuron and emamectin benzoate achieved the lowest infection rates, these were still substantial, ranging from 58% to 61% in the first season and 69% to 52% in the second season. These findings suggest limited efficacy of the insecticides in reducing FAW infestation at this growth stage.

Table (4): Mean percentage (±SEM*) of infested plants by *S. frugiperda* at the vegetative growth stage (late whorl) after application of synthetic insecticides in field study in 2022

Insecticides	Vegetative growth stages (Late whorl stage)					Means
	V8 28 d	**V10** 38 d	**V12** 42 d	**V14** 49 d	**VT** 56 d	
	2nd T*			**3rd T**		
Methomyl 90%	94.0±1.15^{a}	04.0±1.63^{d}	42.0±6.00^{d}	98.0±1.15^{a}	90.0±5.29^{ab}	65.6±2.17^{d}
Beta-cyfluthrin 10%	99.0±1.00^{a}	08.0±2.83^{d}	78.0±3.46^{b}	100±0.00^{a}	87.0±3.79^{b}	74.4±1.70^{c}
Emamectin benzoate 5.7%	92.0±4.32^{a}	03.0±3.00^{d}	34.0±2.58^{d}	97.0±1.00^{a}	61.0±3.00^{c}	57.4±1.15^{e}
Indoxacarb 15 %	99.0±1.00^{a}	57.0±4.12^{b}	97.0±1.91^{a}	100±0.00^{a}	83.0±5.00^{b}	87.2±2.04^{b}
Lufenuron 5%	99.0±1.00^{a}	10.0±3.83^{d}	41.0±3.00^{d}	91.0±3.00^{a}	58.0±2.58^{c}	59.8±1.32^{e}
Spinosad 24 %	85.0±3.00^{b}	42.0±4.16^{c}	61.0±5.26^{c}	98.0±1.15^{a}	84.0±4.32^{b}	74.0±0.52^{c}
Control	99.0±1.00^{a}	98.0±2.00^{a}	100±0.00^{a}	100±0.00^{a}	100±0.00^{a}	99.4±0.38^{a}

***Standard error mean, V vegetative growth stage, VT vegetative-tassel, d plant age by days, 2nd T, 3rd T second and third treatment of insecticides. Means followed by the same superscript letters are not significantly different at 5%, according to Duncan's multiple range test.**

Table (5): Mean percentage (±SEM*) of infested plants by *S. frugiperda* at the vegetative growth stage (late whorl) after application of synthetic insecticides in the field study in 2023

Insecticides	Vegetative growth stages (Late whorl stage)					Means
	V8 28 d	V10 38 d	V12 42 d	V14 49 d	VT^{3} 56 d	
	2nd T			**3rd T**		
Methomyl 90%	79.0±1.00^{bc}	06.0±1.15^{d}	23.0±5.97^{b}	87.0±5.51^{c}	85.0±5.26^{b}	55.0±1.76^{dc}
Beta-cyfluthrin 10%	81.0±1.00^{bc}	10.0±2.58^{d}	23.0±3.00^{b}	94.0±2.58^{abc}	78.0±2.58^{bc}	57.2±0.69^{c}
Emamectin benzoate 5.7%	79.0±2.52^{bc}	03.0±1.00^{d}	25.0±10.12^{b}	93.0±2.52^{abc}	52.0±3.65^{d}	50.4±1.42^{d}
Indoxacarb 15 %	85.0±3.00^{b}	69.0±3.79^{b}	88.0±10.71^{a}	98.0±1.15^{ab}	82.0±6.22^{b}	84.4±3.40^{b}
Lufenuron 5%	95.0±3.00^{a}	06.0±3.46^{d}	23.0±7.72^{b}	100±0.00^{a}	69.0±3.00^{c}	58.6±1.15^{c}
Spinosad 24 %	75.0±3.79^{c}	40.0±2.83^{c}	23.0±1.00^{b}	90.0±1.15^{bc}	78.0±3.83^{bc}	61.2±1.48^{c}
Control	100±0.00^{a}	100±0.00^{a}	97.0±1.91^{a}	100±0.00^{a}	97.0±1.91^{a}	98.8±0.77^{a}

***Standard error mean, V vegetative growth stage, VT vegetative-tassel, d plant age by days, 2nd T, 3rd T second and third treatment of insecticides. Means followed by the same superscript letters are not significantly different at 5%, according to Duncan's multiple range test.**

Reproductive development stages (R)

Tassel and silk (R1–R4) and maturity stages (R5–R6)

The findings in Tables 6 and 7 highlight a natural decrease in FAW infestation rates in the control group across the tassel and silk stages. Infestation rates in the control group dropped from 100% and 81% at the R1 stage (63 days) to 59% and 48% at the R3 stage (77 days) during the first and second seasons, respectively. This decline continued at the R4 stage (96 days), where infestation rates further decreased to 13% and 16%, and by the maturity stages (R5: 112 days and R6: 119 days), the rates fell to 0.0% and 1.0% without any insecticide intervention.

In the fourth treatment (4th T) applied during the tassel and silk stage (R3: 77 days), there was no significant differences were observed between the effectiveness of different insecticides. By the end of the tassel and silk stage (R4: 96 days) and through the maturity stages (R5 and R6), the infestation rates in the treated groups aligned closely with those of the control group, reflecting a natural decline in FAW infestations regardless of insecticide application.

Table (6): Mean percentage (±SEM*) of infested plants by *S. frugiperda* at reproductive development stages (tassel/silk and maturity) after application of synthetic insecticides in the field study in 2022

Insecticides	**Reproductive development Stages**						
	Tassel/Silk				**Maturity**		
	R1	**R3**	**R4**	**Means**	**R5**	**R6**	**Means**
	63d	77 d	96 d		112 d	119 d	
		4th T					
Methomyl 90%	5.0±1.00^{c}	5.0 ±1.00^{d}	08.0±1.63^{b}	06.0±0.38^{g}	7.0±1.91^{cd}	4.0±1.63^{a}	5.5±0.50^{c}
Beta-cyfluthrin 10%	7.0±1.91^{c}	28.0±3.26^{c}	10.0±1.15^{b}	15.0±1.83^{f}	10.0±1.15^{abc}	2.0±2.00^{a}	6.0±0.82^{bc}
Emamectin - benzoate 5.7%	11.0±1.91^{c}	26.0±4.76^{c}	27.0±3.00^{a}	21.3±1.44^{e}	13.0±1.00^{ab}	4.0±1.63^{a}	8.5±0.96^{ab}
Indoxacarb 15 %	59.0±6.61^{b}	44.0±5.89^{b}	24.0±1.63^{a}	42.3±3.05^{c}	15.0±1.91^{a}	3.0±1.00^{a}	9.0±1.29^{a}
Lufenuron 5%	63.0±3.0^{b}	68.0±3.26^{a}	24.0±1.63^{a}	51.6±0.33^{b}	4.0±1.63^{d}	0.0±0.00^{a}	2.0±0.82^{d}
Spinosad 24 %	14.0±1.15^{c}	68.0±2.82^{a}	11.0±1.00^{b}	31.0±0.84^{d}	8.0±1.63^{bcd}	0.0±0.00^{a}	4.0±0.82^{cd}
Control	100±0.00^{a}	59.0±4.73^{a}	13.0±1.00^{b}	57.3±1.44^{a}	4.0±2.31^{d}	0.0±0.00^{a}	2.0±1.15^{d}

***Standard error mean, R reproductive development stages, d plant age by days, 4th T fourth treatment of insecticides. Means followed by the same superscript letters are not significantly different at 5%, according to Duncan's multiple range test.**

Table (7): Mean percentage (±SEM*) of infested plants by *S. frugiperda* at reproductive development stages (tassel/silk and maturity) after application of synthetic insecticides in the field study in 2023

Insecticides	**Reproductive development Stages**						
	Tassel/Silk				**Maturity**		
	R1	**R3**	**R4**	**Means**	**R5**	**R6**	**Means**
	63d	77 d	96 d		112 d	119 d	
		4th T					
Methomyl 90%	2.0±1.15^{e}	6.0 ±1.15^{e}	08.0±1.63^{c}	05.3±0.54^{e}	6.0±2.00^{ab}	3.0±1.00^{a}	4.5±1.29^{ab}
Beta-cyfluthrin 10%	9.0±2.52^{de}	32.0±1.63^{cd}	12.0±1.63^{bc}	17.7±1.47^{d}	8.0±1.63^{ab}	2.0±1.15^{a}	5.0±1.00^{ab}
Emamectin benzoate 5.7%	13.0±1.91^{d}	29.0±3.42^{d}	19.0±1.00^{a}	20.3±0.64^{d}	12.0±1.63^{a}	3.0±1.91^{a}	7.5±1.26^{a}
Indoxacarb 15 %	54.0±2.00^{b}	41.0±3.42^{bc}	19.0±3.00^{a}	38.3±1.28^{b}	11.0±2.52^{a}	5.0±1.91^{a}	8.0±2.16^{a}
Lufenuron 5%	42.0±2.58^{c}	78.0±4.16^{a}	21.0±1.91^{a}	47.0±0.83^{a}	3.0±1.91^{b}	3.0±1.00^{a}	3.0±1.29^{ab}
Spinosad 24 %	12.0±2.83^{d}	51.0±3.42^{b}	17.0±1.91^{ab}	26.7±1.44^{c}	5.0±2.52^{ab}	3.0±1.91^{a}	4.0±2.16^{ab}
Control	81.0±4.43^{a}	48.0±5.16^{b}	16.0±2.83^{ab}	48.3±3.00^{a}	3.0±3.00^{b}	1.0±1.00^{a}	2.0±1.41^{b}

***Standard error mean, R reproductive development stage, d plant age by days, 4th T fourth treatment of insecticides. Means followed by the same superscript letters are not significantly different at 5%, according to Duncan's multiple range test.**

Fall armyworm, *S. frugiperda* infestation during the main growth stages of maize

The study found that there was a significant and noticeable connection between the maize plant's growth stage and the level of FAW infestation. The data in Figure 2 from the two seasons (2022 and 2023) indicated that the maturity stage exhibited the lowest FAW infection rates, at 5.3% and 4.9%, respectively. In contrast, the late vegetative growth stage was most susceptible to FAW infestation, with infection rates reaching 74% and 66.7% during the respective seasons. Based on the severity of FAW infestation at different growth stages, the study ranked the plant growth stages in a descending order as follows: vegetative growth (late whorl) stage > vegetative growth (early whorl) stage > reproductive (tassel and silk) stage > reproductive (maturity) stage.

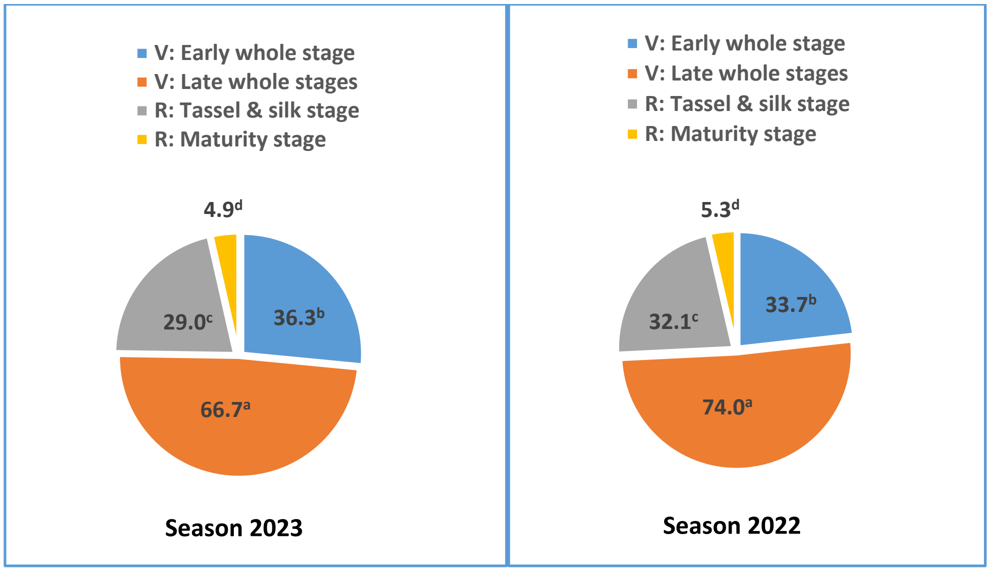

Figure (2): Mean percentage (±SEM[*]) of infested plants by *S. frugiperda* during different growth stages of maize planting in 2022 and 2023.
[*]Standard error of mean, V vegetative growth stages, R reproductive development stages. Means followed by the same superscript letters are not significantly different (Duncan's MRT) at < 0.05.

Impact of various insecticides on *S. frugiperda* infestation

A study examining the impact of insecticides on the Fall Armyworm (FAW) without considering the effect of plant growth stage revealed significant reductions in the number of infested maize plants compared to the control (Fig. 3). Methomyl had the most significant impact, with infection rates reaching their lowest levels of 24.4% and 23.1% during the two seasons, respectively. Emamectin benzoate had the next greatest effect on approximately 28% of the FAW-infested plants, while spinosad and beta-cyfluthrin had similar significant effects. In contrast, indoxacarb had the least impact, with infestation rates of 42.6% and 38.6%, which were higher than other insecticide treatments compared to the control (61.8% and 59.8%, respectively).

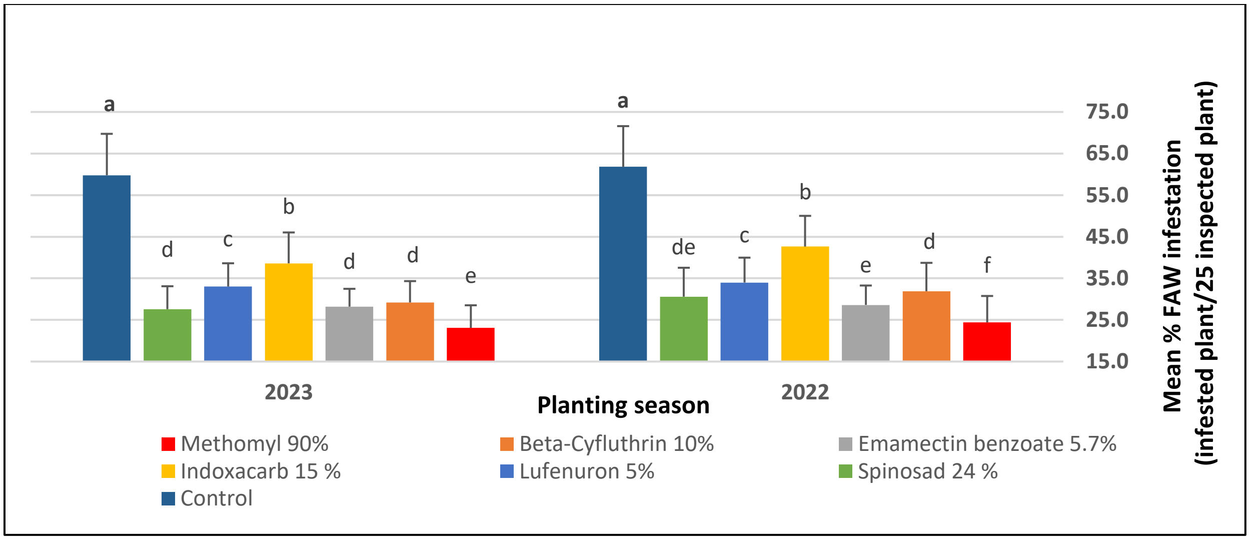

Figure (3): Impact of different insecticides against *S. frugiperda* infestation (means ± SEM[*]) in maize planting in 2022 and 2023.

[*]Standard error of mean. Means followed by the same letters are not significantly different at 5%, according to Duncan's multiple range test.

Interaction effects between *S. frugiperda* infestation levels and maize growth stages

The results in Figures 4 and 5 for the 2022 and 2023 seasons indicate that in the control group, FAW infestation rates during the early whorl stage of vegetative growth were 88.5% and 90.0%, respectively. In comparison, spinosad significantly reduced infestation rates to 13.5% and 18.5%, demonstrating its superior efficacy at this stage. Treatments with methomyl and lufenuron yielded moderate reductions in infestation, with rates of 20.51% and 22.5% in the first season, and 26.5% and 23.5% in the second season. Conversely, beta-cyfluthrin was the least effective insecticide, with the highest infestation rates among the treatments (32% and 37%) but still significantly lower than the control.

During the late whorl stage of vegetative growth, the control group maintained high infestation rates of 99.4% and 98.8% in the two seasons. Among the insecticides, emamectin benzoate was the most effective, reducing infestation rates to 57.4% and 50.4%. Lufenuron and methomyl exhibited similar efficacy, with no significant differences between them, while indoxacarb performed the poorest, with infestation rates of 87.2% and 84.4%, only slightly lower than the control.

At the tassel and silk stages, infestation rates in the control group declined to 57.3% and 48.3% in the two seasons. Methomyl demonstrated the greatest efficacy at this stage, with rates of 6.0% and 5.3%, followed by beta-cyfluthrin (15% and 17.7%) and emamectin benzoate (21.3% and 20.3%). Lufenuron was the least effective treatment, with infestation rates of 51.7% and 47%, only marginally better than the control.

By the maturity stage, a natural decline in FAW infestation was observed in the control group, with rates dropping to nearly 0.0% and 1.0%. Similarly, there were no significant differences in the number of infected plants between the treated groups and the control, reflecting the minimal need for intervention at this stage.

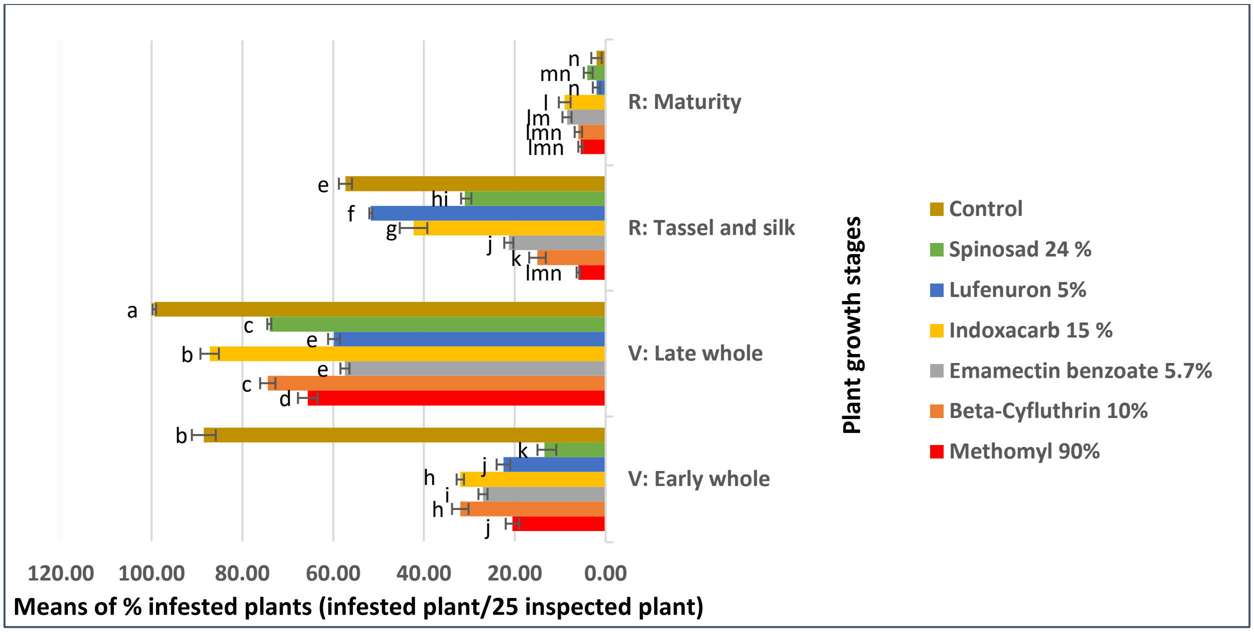

Figure (4): Interaction effect between efficacy of insecticides and plant growth stages on % *S. frugiperda* (±SEM*) in 2022 field testing.
*** Standard error of mean, V vegetative growth stages, R reproductive development stages. Means followed by the same letters are not significantly different at 5%, according to Duncan's multiple range test.**

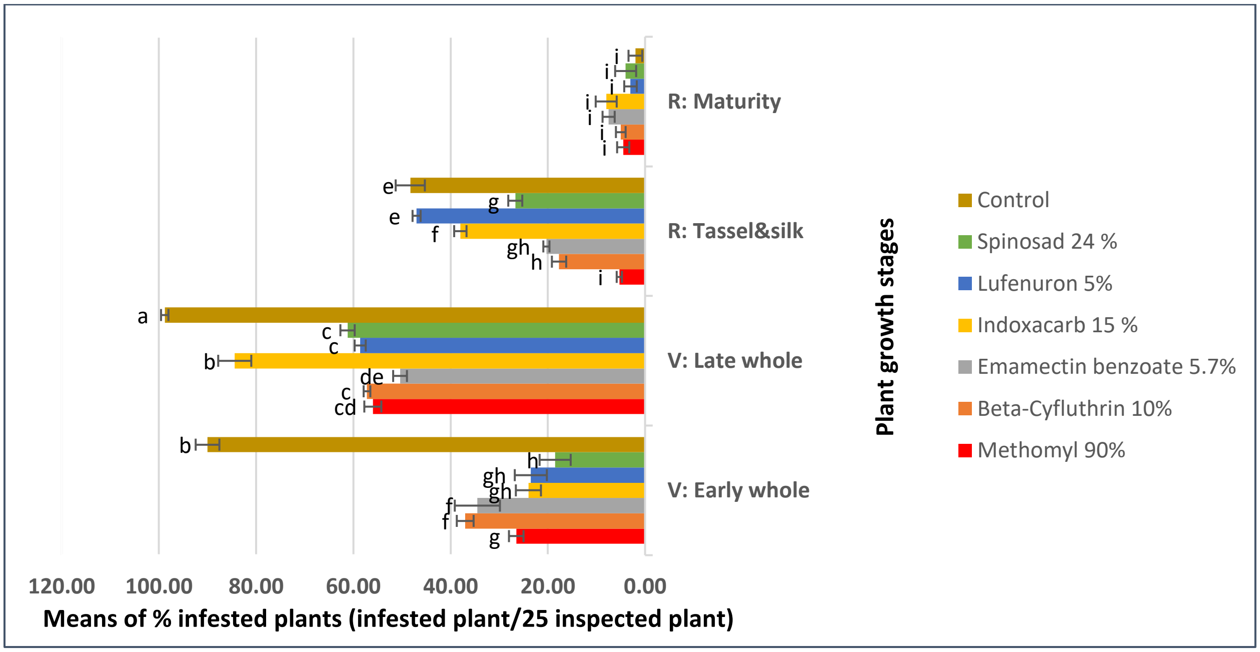

Figure (5): Interaction effect between efficacy of insecticides and plant growth stages on % *S. frugiperda* (±SEM*) in 2023 field testing.
*** Standard error of mean, V vegetative growth stages, R reproductive development stages. Means followed by the same letters are not significantly different at 5%, according to Duncan's multiple range test.**

Impact of *S. frugiperda* infestation on maize yield and potential growth

Maize plants treated with methomyl, beta-cyfluthrin, and emamectin benzoate exhibited superior vegetative growth characteristics, such as plant height, cob length, and cob diameter, without any significant differences among them. However, in the second season, the methomyl treatment had the greatest effect on these traits (Tables 8 and 9). These effects were closely associated with crop yield rates, as illustrated in Figure 6. Among the two seasons, the highest productivity was achieved with methomyl (2683.6 and 2742.3 kg ha^{-1}), followed by beta-cyfluthrin (2595.3 and 2512.6 kg ha^{-1}) and then emamectin benzoate (1613.1 and 1643.1 kg ha^{-1}). On the other hand, compared with the control treatment (534 and 543.3 kg ha^{-1}), indoxacarb had the lowest yield rates, with values of 674.5 and 650.5 kg ha^{-1}, respectively, and had the lowest vegetative growth characteristics.

Table (8): Means (±SEM*) of plant height, cob length, cob diameter, and yield of maize plants in 2022 season

Insecticides	Growth and Yield Characteristics			
	Plant Height cm	Cob Length cm	Cob Diameter cm	Yield Kg/ha
Methomyl 90%	138.0±3.87^{a}	17.95±0.47^{a}	6.30±0.41^{a}	2683.6±96.1^{a}
Beta-cyfluthrin 10%	147.3±3.01^{a}	18.10±0.80^{a}	6.40±0.40^{a}	2595.3±132.1^{a}
Emamectin benzoate 5.7%	135.8±2.95^{a}	18.90±0.41^{a}	5.85±0.39^{a}	1613.1±27.8^{b}
Indoxacarb 15 %	99.0±4.42^{b}	12.28±0.83^{b}	4.60±0.24^{bc}	674.5±56.1^{cd}
Lufenuron 5%	139.3±1.93^{a}	13.10±0.24^{b}	5.45±0.17^{ab}	880.5±43.0^{c}
Spinosad 24 %	103.4±4.52^{b}	12.33±0.52^{b}	4.90±0.17^{b}	851.4±43.1^{c}
Control	97.0±5.21^{b}	10.33±0.31^{c}	3.90±0.18^{c}	534.0±20.4^{d}

*Standard error mean
Means followed by the same superscript letters are not significantly different at 5%, according to Duncan's multiple range test.

Table (9): Means (±SEM*) of plant height, cob length, cob diameter, and yield of maize plants in 2023 season

Insecticides	Growth and Yield Characteristics			
	Plant Height cm	Cob Length cm	Cob Diameter cm	Yield Kg/ha
Methomyl 90%	150.4±1.90^{a}	18.4±0.332^{a}	6.70±0.15^{a}	2742.3±78.2^{a}
Beta-cyfluthrin 10%	141.3±3.17^{b}	16.02±0.25^{b}	6.00±0.30^{b}	2512.6±81.1^{b}
Emamectin benzoate 5.7%	139.0±1.47^{b}	17.55±0.63^{a}	5.90±0.11^{b}	1643.1±40.6^{c}
Indoxacarb 15 %	100.4±0.66^{c}	12.32±0.29^{c}	4.73±0.25^{cd}	650.5±25.4^{e}
Lufenuron 5%	134.1±2.12^{b}	12.25±0.29^{c}	5.18±0.11^{c}	880.8±29.0^{d}
Spinosad 24 %	105.4±2.02^{c}	12.00±0.37^{c}	4.93±0.18^{cd}	874.8±11.6^{d}
Control	89.3±3.64^{d}	8.77±0.48^{d}	4.45±0.25^{d}	543.3±7.10^{e}

*Standard error mean
Means followed by the same superscript letters are not significantly different at 5%, according to Duncan's multiple range test.

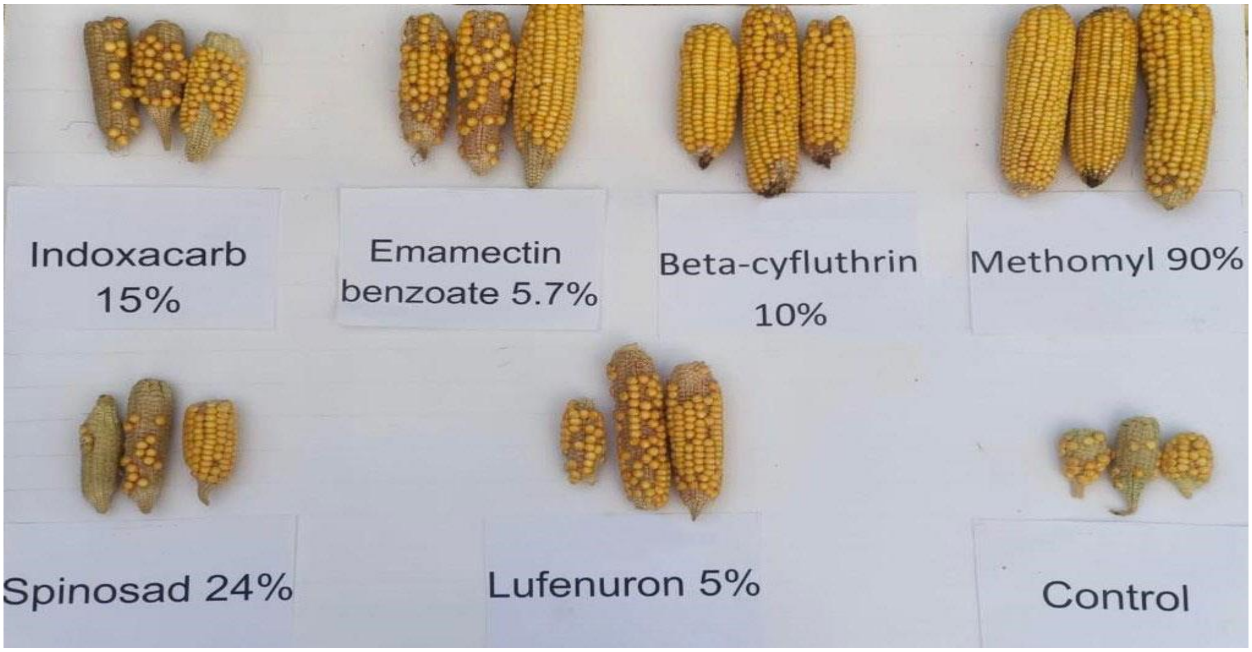

Figure (6): Effect of insecticide treatments on maize yield cobs under *S. frugiperda* infestation

Discussion

This study gives important insights into the management of fall armyworms by examining the effectiveness of insecticides that have relatively different mechanisms of action. Additionally, the correlation between their efficacy and the different plant growth stages led to a noticeable difference in crop yield. There is a substantial association between corn plant growth stages and fall armyworm (FAW) infestation rates (Seye et al., 2023; Srinivasan et al., 2022). A study showed that FAW infestations are significantly greater during the vegetative stages of maize plants, particularly the late whorl stage. High infestation started in the early vegetative stage between the first and second weeks after emergence (V4: 12 d). Fall armyworm larvae are particularly drawn to young vegetative maize plants due to their preference for softer and more tender tissues, as noted by Mutyambai et al., (2022). This stage of growth, characterized by young and actively growing plants, offers ideal feeding conditions for the larvae. However, as the plants mature, they develop tougher and drier tissues, and the plant's sap decreases, serving as a deterrent to armyworm infestations fall. As a result, the maturity stage had the fewest plants with armyworm larvae infection (Mutyambai et al., 2022). These results emphasize how crucial it is to consider crop maturity when putting pest management strategies in place to reduce fall armyworm (FAW) infection in maize fields. It is important to know how effective insecticides are at different phases of plant growth. According to this study, pesticide use can lower insect populations and related plant protection expenses during the key stages of fall armyworm infestation (Srinivasan et al., 2022). Field experiments revealed that maize plants are most vulnerable to fall armyworm infestation during the vegetative stages from V4 to VT, with the highest number of infestations occurring at the V4 stage. Additionally, a previous study highlighted that the V4 to V8 growth stages are crucial for ear formation and eventual crop yield (Costa et al., 2020).

This study revealed significant variations in insecticide effectiveness across different maize growth stages, which aligns with previous observations by van den Berg et al., (2021) who have highlighted the importance of understanding the stage of plant development in pesticide application. These variations are influenced by several factors, including the mode of action of the insecticides (e.g., contact vs. systemic) and their interaction with the physiological changes in the maize plant during its development. Notably, spinosad showed the best control in the early vegetative (early whorl) stage, as demonstrated by lower infestation rate, which is also consistent with reports by Dubey et al., (2020) who reported that spinosad is effective in early growth stages. However, spinosad showed reduced efficacy during the late vegetative (late whorl) stage, which can be associated with the physiological changes in the plant. Conversely, methomyl and emamectin benzoate were more effective in reducing the number of infested plants at the late stages, which can be attributed to their mode of action that includes systemic activity and penetration into the leaf tissue (Liu et al., 2022). This is particularly noteworthy, as challenges arise due to the size and density of plants during these maize growth stages, posing difficulties for insecticide application. Emamectin benzoate effectively slows the population growth of the fall armyworm (FAW) by delaying its development through lengthening the pupal stage, delaying egg laying, and reducing fecundity in both the parent insects and their offspring. In contrast, indoxacarb exhibited the lowest efficacy across various late growth stages (Zhang et al. 2023; Liu et al. 2022). The reduced efficacy of indoxacarb against fall armyworms may stem from its limited mode of action, via contact or ingestion, and limited penetration into dense foliage, as suggested by previous research findings (Hafeez et al., 2022; Wu et al., 2023).

All insecticides had no significant impact on reducing the number of plants infected with FAW in the maturity stage (R5:R6). The natural defense mechanisms and physiological factors of mature maize plants, such as decreased sap and dryness of leaves, ears, and cob silks, make these plant parts less attractive to armyworms (Wiseman et al., 1996). Overall, fall armyworm infection decreased across all the experimental plots during this growth stage, including in the control treatment without any insecticide intervention. Additionally, the natural decline in infestation rates at the maturity stage suggests that interventions at this stage may be less critical, allowing for resource optimization earlier in the growth cycle. Nevertheless, despite this decrease, the denser and broader plant canopy at this stage of growth may make insecticides less effective because it will be difficult for the insecticide to penetrate and reach the intended armyworm larvae (Young et al., 1979).

We can finally clarify the intricate link between the growth stages of maize plants, the effectiveness of pesticides, and crop productivity. Methomyl had the most significant effect on reducing the number of infected plants, followed by emamectin benzoate and beta-cyfluthrin. This effect was especially noticeable during the late vegetative growth (late whorl) and reproductive (tassel and silk) stages, which are known for their high sensitivity and correlation with the impact on maize production (Patel and Zaman, 2022; van den Berg et al., 2021). The mechanisms of action and dispersion of methomyl and emamectin-benzoate inside plant sap and leaf tissue contribute to their long-term effectiveness. Moreover, lambda-cyhalothrin, cypermethrin, and other insecticides with similar mechanisms of action are effective against FAW, suggesting that beta-cyfluthrin could also be beneficial for increasing maize yields if applied at the appropriate time (Mazed et al., 2022; Utono and Adamu, 2023). Despite spinosad showing superior efficacy during the early vegetative growth stage, its effectiveness notably decreased during the late vegetative growth stage, leading to a significant reduction in productivity. Notably, among the insecticides tested, indoxacarb had the lowest efficacy across the different growth stages, contributing to decreased crop yield without significant deviation from the control treatment (Hafeez et al., 2022).

Overall, there were noticeable impacts of both the growth stage of the maize plants and the application of insecticides on FAW infestation. Moreover, the overall effect on crop productivity may be related to insecticide performance across different growth stages. Nevertheless, although insecticides may generally be effective, they can encounter challenges during crucial stages of plant growth, potentially impacting productivity even as the number of infected plants decreases. These findings indicate that selecting the most appropriate insecticide should be guided not only by the pest but also by the growth stage of the plant (Mazed et al., 2022).

Conclusion

Implementing growth-stage-specific insecticide rotation strategies is essential for sustainable FAW management. The study's findings suggest that the late vegetative growth stage (late whorl) is especially susceptible to FAW attraction due to increased sap and soft tissue availability. Each growth stage involves distinct physiological and structural changes in the plant, requiring the selection of insecticides tailored to their characteristics and mode of action. Methomyl showed superior efficacy during the reproductive stage (tassel and silk) due to its systemic properties, while emamectin benzoate was most effective during the late vegetative growth stage. We recommend applying Spinosad during the early vegetative growth stage (early whorl). Furthermore, one should exercise caution when using insecticides during the maturity stage. This information can be valuable for farmers and agricultural professionals in developing more effective strategies for managing fall armyworms and maximizing crop yields.

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Competing interest

The author has no relevant financial or nonfinancial interests to disclose.

Ethical statement

The author has not conducted any research on humans or animals that is included in this article

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