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Research Article

Toxicity and Feeding Deterrence Properties of Selected Insecticides against Fall Armyworm (*Spodoptera frugiperda* J.E. Smith): Implications for Pest Management in Agriculture

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NA performed experiments and data curation. NM and NA wrote the manuscript. MIU designed the experiment. M Afzal and MIU supervised the project. M Arshad and NM analysed the data. SK and M Afzal reviewed the final manuscript.

Keywords
Concentrations, Insecticides, Mortality, Pest control, *Spodoptera frugiperda*

Abstract | The Fall armyworm, *Spodoptera frugiperda* J.E. Smith (Lepidoptera: Noctuidae), is a significant agricultural pest that can cause extensive damage to maize crop. We determined the effectiveness of various insecticides against *S. frugiperda* and their ability to deter feeding. Radiant and voliam flexi had the highest mortality rates of 95.0% and 91.7%, respectively, at higher concentrations, while Coragen and Proclaim were moderately effective, with mortality rates ranging from 36.7% to 81.7%. The least effective insecticides were Match and Sunitol, with mortality rates ranging from 26.7% to 58.3%. Radiant (-24.57%) and Voliam flexi (-22.19%) were more efficient in terms of feeding deterrence as compared to other insecticides. These results indicate that Radiant and Voliam flexi could be useful in managing *S. frugiperda* infestations. This study provides essential information regarding the efficacy of commonly used insecticides against *S. frugiperda*, a highly detrimental agricultural pest with global prevalence.

Novelty Statement | In this study, we present a novel and promising approach to combat the devastating Fall armyworm, a notorious agricultural pest with a widespread global impact. Our study provides essential insights into the efficacy of widely employed insecticides, offering practical guidance for addressing a critical issue in the field of agriculture.

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Introduction

The fall armyworm, *Spodoptera frugiperda* J.E. Smith (Lepidoptera: Noctuidae), is a major insect pest that poses a significant threat to various crops, such as maize,

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rice, sorghum, and cotton (Barros *et al*., 2010; Altaf *et al*., 2022). Severe damage occurs by feeding of larval stages of *S. frugiperda* on the leaves, stems, and reproductive parts of the host plants, resulting in significant yield losses and economic damage (Ganiger *et al*., 2018; Makgoba *et al*., 2021). The larvae cause damage by extensive tissue destruction and defoliation, particularly targeting the tender parts of the plant, such as young leaves, developing tassels, and silks, which reduces photosynthesis and nutrient uptake by the plants (De Almeida Sarmento *et al*., 2002) Furthermore, the feeding activity triggers several plant defense mechanisms, such as toxic secondary metabolite production and increased lignification of the cell walls, further reducing the nutritional value of the plant tissues (Divekar *et al*., 2022). The damage is often deteriorated by the migratory behavior of *S. frugiperda* larvae, which enables them to spread rapidly across large areas, causing significant crop losses and exacerbating food insecurity (Goergen *et al*., 2016).

S. frugiperda is responsible for significant economic losses, with estimates losses of $2.5 to $6.2 billion annually (Singh *et al*., 2022). In Africa, where *S. frugiperda* was first reported in 2016, has resulted in estimated losses of up to $6.1 billion in maize production (CABI, 2017). Similarly, in India, reports indicate losses of up to 25% in maize production due to this pest (Overton *et al*., 2021). The recent invasion of this new pest poses a significant threat to food security and livelihoods in many countries (Womack *et al*., 2020). Its presence has become widespread in more than 100 countries (He *et al*., 2021). The pest's impact on global food security is a growing concern, and effective control measures are urgently needed to mitigate its damage. Hence, it is crucial to establish effective management strategies to control this pest and protect the livelihoods of farmers.

As an emergency response to combat invasive pests, many farmers tend to rely on traditional insecticides as their preferred method of control (Veres *et al*., 2020). Different classes of insecticides, such as pyrethroids, organophosphates, carbamates, and neonicotinoids, have been used to control *S. frugiperda* (Belay *et al*., 2012). Spinetoram has been reported to achieve over 90% control rates against *S. frugiperda* in corn in Brazil (Muraro *et al*., 2019), while chlorantraniliprole was found to be effective against *S. frugiperda* in maize in India (Deshmukh *et al*., 2020).

In tackling the invasive *S. frugiperda* population, the use of synthetic insecticides has proven to be an effective emergency-based control method and a crucial component of integrated pest management strategies (Kong *et al*., 2021). Consequently, evaluating the efficacy of synthetic insecticides against laboratory populations of *S. frugiperda* is a high-priority task (Ndolo *et al*., 2019). Hence, there is an urgent need to identify effective insecticides that can manage the infestation while reducing the associated environmental and health risks linked with insecticide overuse. This study aims to evaluate the efficacy of selected insecticides against *S. frugiperda* and provide insights for developing effective pest management strategies.

Materials and Methods

Insect colony

The collection of egg masses and larvae of *S. frugiperda* was done from a maize field (32°07'57.3"N 72°41'30.2"E) located at the research farm of the University of Sargodha. The collected eggs and larvae were then reared in the Entomology laboratory. The artificial diet was prepared and offered to neonate larvae. The diet was prepared as suggested by Sorur *et al*. (2011). After moths emerged, they were paired and confined to oviposition jars, and sugar solution (10%) was provided for feeding. To facilitate oviposition, muslin cloth was hung in plastic jars. The F_3 generation of *S. frugiperda* was selected in further experiments.

Insecticides

In this study, three concentrations of each insecticide; Match (1.0ml/L, 2ml/L and 4ml/L), Voliam flexi (0.4ml/L, 0.8ml/L and 1.6ml/L), Proclaim (1.0ml/L, 2.0ml/L and 4.0ml/L), Coragen (0.25ml/L, 0.5ml/L and 1.0ml/L), Sunitol (2ml/L, 4ml/L and 8ml/L) and Radiant (0.5ml/L, 1.0ml/L and 2.0ml/L) were used. The detail of the selected insecticides, including their different groups and modes of action are presented in Table 1.

Table 1: Detail of selected insecticides tested against *Spodoptera frugiperda* larvae.

Trade name	Active ingredient	IRAC group	Formulation	Company name	Mode of action	Label dose (ml)
Match	Leufeneuron	15 Benzoylureas	50 EC	Syngenta	IGR	200
Coragen	Chlorantraniliprole	1B Organophosphate	20 SC	FMC	Muscle poison	50
Proclaim	Emmamectin benzoate	6Avermectins	019 EC	Syngenta	Muscle poison	200
Voliam flexi	Thiamethoxam+chlorantraniliprole	4A neonicotinoid+28 diamide	300 EC	Syngenta	Nerve & muscle	80
Radiant	Spintoram	5 Spinosyn	120 SC	Arysta	Neurotoxic	80
Sunitol	Emmamectin+Betacyfluthrin	6 Emamectin benzoate + 3A Pyrethroids	4.3 EC	Tara group	Nerve & muscle	400

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Table 2: Percent corrected mortality (means±SE) of *Spodoptera frugiperda* larvae after application of different insecticides at different time interval.

Treatment	Conc. (ml/1000ml)	Corrected larval mortality (%)			
		12 HAA	24 HAA	48 HAA	72 HAA
Radiant	0.50	36.7±6.273a-d	53.3±6.494b-e	75.0±5.637abc	78.3±5.363abc
	1.00	50.0±6.509ab	66.7±6.137abc	66.7±6.137a-d	91.7±3.598a
	2.00	63.3±6.273a	90.0±3.905a	93.3±3.247a	95.0±2.837a
Voliam flexi	0.40	13.3±4.425d	33.3±6.137d-g	41.7±6.418de	50±6.509d-g
	0.80	35.0 ±6.209bcd	58.3±6.418bcd	66.7±6.137a-d	70.0±5.966a-d
	1.60	51.7±6.505ab	76.7±5.506ab	91.7±3.598a	91.7±3.598a
Coragen	0.25	20.0±5.207cd	25.0±5.637efg	35.0±6.209e	38.3±6.329efg
	0.50	25.0±5.637bcd	48.3±6.505b-f	51.7±6.505cde	53.3±6.494c-g
	0.10	45.0±6.476abc	58.3±6.418bcd	81.7±5.037ab	81.7±5.037ab
Proclaim	1.00	13.3±4.425d	21.7±5.363fg	31.7±6.056e	36.7±6.273efg
	2.00	21.7±5.363cd	40.0±6.377c-g	53.3±6.494b-e	55.0±6.476b-f
	4.00	38.3±6.329a-d	53.3±6.494b-e	73.3±5.757abc	80.0±5.207abc
Match	1.00	11.7±4.179d	16.7±4.851g	30.0±5.966e	36.7±6.273efg
	2.00	11.7±4.179d	16.7±4.851g	35.0±6.209e	40.0±6.377efg
	4.00	16.7±4.851d	23.3±5.506fg	50.0±6.509cde	58.3±6.418b-e
Sunitol	2.00	13.3±4.425d	23.3±5.506fg	26.7±5.757e	26.7±5.757g
	4.00	13.3±4.425d	23.3±5.506fg	28.3±5.866e	30.0±5.966fg
	8.00	13.3±4.425d	28.3±5.866efg	35.0±6.209e	35.0±6.209efg
$F_{10, 1079}$		1.94	2.17	2.66	2.07
P-value		0.0363	0.017	0.0032	0.0245

P < 0.05 shows significance, HAA, H after application.

Mortality bioassay

The insecticidal toxicity of each insecticide was evaluated using the direct spray method on third instar larvae obtained from the rearing colony. Prior to application of the insecticide, larvae were starved for 24 h. Each concentration was replicated three times, with each replication consisting of 20 larvae. A volume of 5ml of each concentration was sprayed on Petri plates containing 60 larvae, and the treated larvae were then transferred to new Petri plates. Control larvae were treated with water. After washing, the fresh maize leaves were dried, and provided as food to the larvae. Mortality was recorded at 12, 24, 48, and 72 h after treatment application.

Feeding deterrence bioassay

The most effective insecticides from mortality bioassay were further tested for feeding deterrence activity. For the feeding deterrence bioassay, maize leaf discs were dipped in recommended concentrations of insecticides, and their weight was measured prior to application. The treated leaves were then dried and provided to third-instar larvae. After 48 h of consumption, the remaining leaves were weighed. The feeding deterrence index was calculated by following formula (Hummelbrunner and Isman, 2001).

$$\text{Antifeedant index} = \frac{C - T}{C + T} \times 100$$

Data analysis

A two-factor factorial analysis of variance (ANOVA) was performed to analyze the effects of insecticides and concentrations on mortality and the means were compared by Tukey's honest significant difference (HSD) test. The statistical analyses were performed using Minitab 17.0 software.

Results

Laboratory evaluation of synthetic insecticides against S. frugiperda

All insecticides caused significant larval mortality at 12h (F = 1.94; P < 0.05), 24h (F = 2.17; P < 0.05), 48h (F = 2.66; P < 0.05), and 72h (F = 2.07; P < 0.05) after application. The mortality increased over time for all insecticides. Radiant at the recommended concentration (0.50 ml/500ml) caused 91.7% larval mortality after 72 h of application. At the higher concentration (1.00 ml/500ml), the mortality rate was 90.0% at 24 h and increased to 95.0% at 72 h. The higher concentration (0.60 ml/500ml) of Voliam flexi and Coragen (0.25 ml/500ml) caused 91.7% and 81.7% mortality, respectively, after 48 h of application. The mortality rate was 80.0% at 72 h by application of Proclaim (2.00 ml/500ml). The least effective insecticides were Match and Sunitol, with mortality rates of only 58.3% and 35.0% at higher concentrations (2.00 ml/500ml for Match and 4.00 ml/500ml for Sunitol) (Table 2).

Both insecticides were found to exhibit some level of feeding deterrence. Radiant showed a feeding deterrence of -24.57% while Voliam flexi exhibited a feeding deterrence of -22.19%. These results indicate that both insecticides had a suppressing effect on the feeding activity of *S. frugiperda* when compared to the control group (Figure 1).

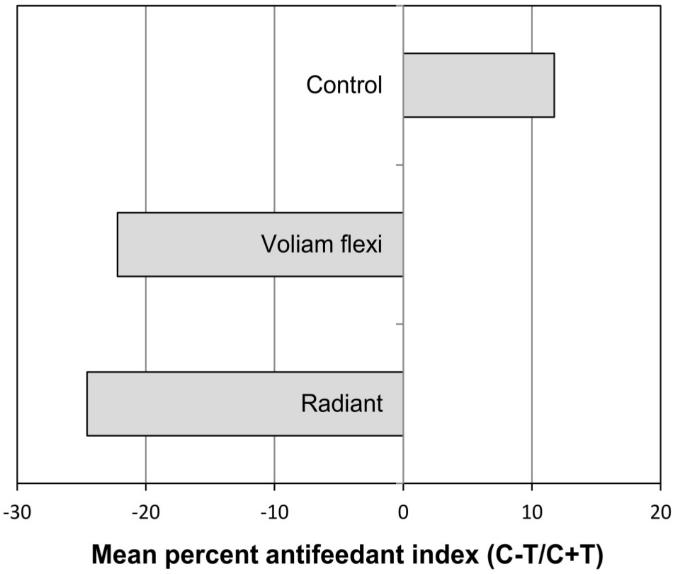

Figure 1: Antifeedant activity of two insecticides against *Spodoptera frugiperda*, showing the percent of feeding deterrence after 48 h. C, control; T, treated.

Discussion

Spodoptera frugiperda is a destructive insect pest that feeds on a range of crops and results in significant economic losses in agriculture (Mohamed *et al*., 2022; Ojumoola *et al*., 2022). The use of insecticides is a common approach to control the population insect pests in the field. In this study, we evaluated the efficacy of selected insecticides against *S. frugiperda* and found that Radiant and Voliam flexi were the most effective insecticides, causing high mortality rates across all concentrations and time intervals. Our results are consistent with previous studies that have reported the efficacy of insecticides against *S. frugiperda* (Fernandes *et al*., 2019; Idrees *et al*., 2022). Paredes-Sánchez *et al*. (2021) studied the effectiveness of insecticides in controlling *S. frugiperda* in maize fields, and they reported that early applications are crucial to prevent crop damage. Belay *et al*. (2012) examined the impact of various insecticides on controlling *S. frugiperda* larvae by directly spraying third instar larvae. The mortality rate exceeded 80% in treatments involving chlorantraniliprole, flubendamide, spinosad, indoxacarb, and fenvalerate, 96 h after the application.

Radiant, which contains the active ingredient spinetoram, showed higher efficacy against *S. frugiperda* in our study. Spinetoram is a member of the spinosyn group of insecticides, which are derived from the natural product spinosad produced by the actinomycete *Saccharopolyspora spinosa* (Kirst, 2010). Spinosad exerts its insecticidal effect by interacting with the nicotinic acetylcholine receptors in the nervous system of insects, leading to overstimulation and paralysis (Salgado, 1998). Spinosyns have been shown to be highly effective against a wide range of insect pests, including *S. frugiperda* (Zhao *et al*., 2020; Bacci *et al*., 2016). The fast-acting and broad-spectrum properties of spinosyns have made them a popular choice for controlling insect pests in various crops, including corn, cotton, and vegetables (Kodandaram *et al*., 2010).

Similarly, Voliam flexi, which contains two active ingredients, chlorantraniliprole, and lambda-cyhalothrin, also showed higher efficacy against *S. frugiperda* in our study. Chlorantraniliprole belongs to the anthranilic diamide group of insecticides (Bentley *et al*., 2010), while lambda-cyhalothrin is a pyrethroid insecticide (Fetoui *et al*., 2010). Chlorantraniliprole binds to the ryanodine receptor on the sarcoplasmic reticulum of muscle cells, leading to uncontrolled release of calcium ions and subsequent paralysis of the insect (Lahm *et al*., 2009). Lambda-cyhalothrin acts on the nervous system by interacting with sodium channels, leading to overstimulation and subsequent paralysis of the insect (Ali, 2012). Together, the two active ingredients in Voliam flexi work synergistically to provide broad-spectrum control of various insect pests, including *S. frugiperda*. Previous studies have also reported higher efficacy of these insecticides against other pests, such as *Helicoverpa armigera* and *S. litura* (Tong *et al*., 2013; Sharif *et al*., 2022).

Furthermore, coragen and proclaim also demonstrated good effectiveness against *S. frugiperda* with both insecticides causing 80.0% mortality rates at higher concentrations and longer exposure times. Previous studies have also reported similar results, demonstrating the efficacy of coragen and proclaim against *S. frugiperda* (Mian *et al*., 2022). The lower efficacy of match and sunitol may be due to various factors, including the pest's resistance to the active ingredient in these insecticides or their mode of action (Dively *et al*., 2020; Monis *et al*., 2022).

In addition, radiant and voliam flexi demonstrated more feeding deterrence against *S. frugiperda* compared to other insecticides. These findings align with previous studies that have also reported the feeding deterrence property of Radiant against *S. litura* and *Spilarctia obliqua* (Thakur and Srivastava, 2019). The activation of the ryanodine receptor is responsible for the effects of chlorantraniliprole, including feeding cessation, lethargy, muscle paralysis, and eventual mortality (Cao *et al*., 2010). The mechanisms underlying this deterrent action are not fully understood but may involve effects on taste receptors or other physiological pathways (Koul, 2008). Our findings suggest that both Radiant and Voliam flexi could be valuable tools for integrated pest management programs

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targeting *S. frugiperda*. However, the study was conducted in a controlled laboratory condition, which may not fully replicate the complex and dynamic conditions found in actual field settings. Insects' behaviors, such as feeding and mortality rate, might differ when subjected to field conditions that include factors like weather fluctuations, plant diversity, and natural predators.

Conclusions and Recommendations

In conclusion, Radiant and Voliam flexi were the most effective insecticides, followed by Coragen and Proclaim, in controlling *S. frugiperda*. These insecticides have fast-acting and broad-spectrum properties, making them ideal for controlling a range of insect pests in various crops. However, the long-term effects of their use on the environment and non-target organisms should also be considered. Further studies are needed to evaluate the efficacy of these insecticides in the field and their potential impact on the environment.

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Conflict of interest

The authors have declared no conflict of interest.

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