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Assessment of Selective Synthetic Insecticides Against Third Instar Larvae of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) Under Laboratory Conditions

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US conducted the experiment and wrote the initial draft of this research article. The whole research was conducted under the kind supervision of MA and DH. FJ and SMH reviewed the manuscript and provided suggestions to improve the previous version. The final manuscript has been read and authorized by all authors.

Key words
Toxicity, *Spodoptera frugiperda*, Flubendiamide, Lufenuron, Lethal concentrations, Leaf dip bioassay

ABSTRACT

Maize is the third most important cereal crop in Pakistan but its productivity is endangered by the attack of the invasive insect pest, *Spodoptera frugiperda*. Synthetic insecticides are amongst the most significant short-term strategies to control *S. frugiperda*. The purpose of this study was to analyze the effectiveness of six synthetic insecticide serial dilutions from different chemical groups against *S. frugiperda* third instar larvae using a leaf dip bioassay. Data on the % mortality of five consecutive dilutions were collected after 24, 48, and 72-hour post treatment. The lethal concentr§ation values (LC_{50}) of synthetic insecticides were calculated by using polo plus software. All insecticides have different LC_{50} values that ranged from 4853.54 µl/L for chlorantraniliprole + lambda cyhalothrin and 107.70 µl/L for flubendiamide after 24 h while after 72 h LC_{50} values ranged from 1858.22 µl/L for chlorantraniliprole + lambda cyhalothrin and 37.65 µl/L for flubendiamide. Based on LC_{50} values, the ascending order of synthetic insecticides was as follows: flubendiamide, spinetoram, emamectin benzoate, fipronil, lufenuron and chlorantraniliprole + lambda cyhalothrin. The effectiveness of these synthetic insecticides was found to increase with increasing concentration and exposure time. Our research shows that synthetic insecticides effectively control the *S. frugiperda* populations. Moreover, the recommended dose of these insecticides can be used as an emergency response against FAW larvae after investigating their potency in the field.

INTRODUCTION

Spodoptera frugiperda (Lepidoptera: Noctuidae) commonly known as fall armyworm (FAW), is polyphagous in nature that feeds over 350 plant species and has been reported as a major insect pest of maize (*Zea mays*) (Udayakumar *et al*., 2021; Navik *et al*., 2021). Maize is called as the "Queen of cereals" worldwide because of its remarkable genetic yield potential in comparison to other cereals (Tefera, 2020; Lone *et al*., 2021; Nagesh and Tyde, 2023) and cultivated commercially in over 100 countries around the globe (Kumar *et al*., 2022). In addition to fibers, maize is an important source of vitamins and minerals, lipids, carbohydrates, proteins, carotenoids, phytosterols, and xanthophylls (Shah *et al*., 2016; Galani *et al*., 2022).

Livelihoods and food security are severely at risk due to the invasion of *S. frugiperda* (Womack *et al*., 2020), which is widespread globally in more than 100 countries (Yeboah *et al*., 2021). *S. frugiperda* invasion was initially recorded in Pakistan in 2019 (Ramzan *et al*., 2021; Yousaf *et al*., 2022). Due to its harmful effects on cereals crops and vegetables around the world, it has become a major threat to agricultural commodities (Yeboah *et al*., 2021; Idrees *et al*., 2022). *S. frugiperda* larvae have ability to feed on various plant parts, including young leaves, whorls of leaves, tassels, and cobs at different stages of development (Lal *et al*., 2023). Primarily, *S. frugiperda* causes harm upon host plants by consuming their reproductive as well as vegetative parts (Naharki *et al*., 2020). Larval densities ranging from 0.2 to 0.8 per crop at the late whorl stage can result in 5 to 20 % yield reductions. Defoliation can be caused by fully mature larvae, which leave the crop with a ragged and shredded appearance of the leaves (Day, 2017; Makgoba *et al*., 2021). This insect can remain

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active in different environmental conditions, particularly in response to climate changes due to its long-distance migration capabilities as well as its potential to consume a variety of host plants. This poses a significant challenge in managing its population in enormous scale maize production (Aruna *et al*., 2019). The damage rate of fodder maize in India was between 16 to 52% (Maruthadurai and Ramesh, 2020). In addition, the majority of maize farmers in Kenya and Ethiopia (93 and 97%, respectively) reported yield losses of up to 100% due to *S. frugiperda* infestations in their fields (Idrees *et al*., 2022).

Arthropods pests can be controlled by eco-friendly approaches such as natural enemies (Gu *et al*., 2018; Idrees *et al*., 2022), biopesticides (Idrees *et al*., 2021) and soft acaricides (Bakar *et al*., 2018). Although these eco-friendly approaches are the key components of Integrated Pest Management (IPM) and are effective to control various insects but their working process is little bit slow and take time to show their efficacy. Due to slow mode of action most maize farmers prefer to use synthetic insecticides as an urgent and quick response to control this notorious pest (Veres *et al*., 2020; Susanto *et al*., 2021). The usage of pesticides in agriculture was started in 1960s. Indiscriminate use of pesticides badly affected the environment. Their application in the agriculture has been directly correlated with the adverse health effects. The severity of detrimental health affects depends upon dose and duration of the exposure (Selamoglu *et al*., 2023). The lack of experience among farmers and agricultural officials to deal with *S. frugiperda* restricts the development of effective management methods (Kim *et al*., 2021). One effective approach in integrated pest management (IPM) for managing *S. frugiperda* infestations may include the application of new chemistry insecticides, which serve as a potent emergency control method (Kong *et al*., 2021). Therefore, there is an urgent dire to assess the efficacy of synthetic insecticide efficacy against laboratory populations of *S. frugiperda* (Ndolo *et al*., 2019). Third instar larvae of fall armyworm cause the most serious harm to plants and cereals globally (Tulashie *et al*., 2021). Consequently, we targeted third instar of FAW in our current study to control it by using synthetic insecticides. Therefore, the present study aimed to assess the potential of synthetic insecticides on third instar larvae of fall armyworm in Pakistan under laboratory conditions to establish an emergency control method that minimizes yield losses by controlling this harmful insect pest in Pakistan and other affected geographic areas.

MATERIALS AND METHODS

Insect rearing

Spodoptera frugiperda larvae were collected from an infested maize field (31.40008° N, 73.04712° E) of Entomological Research Institute, Faisalabad and brought to the rearing laboratory. Glass petri plates (9cm in diameter) were used to rear the larvae and fed fresh maize leaves in a climate chamber maintained at 25±2 °C, 65±5% RH, and a 16:8h (L:D) photoperiod (Ahmed *et al*., 2022). The larvae diet was replaced on a regular basis. The pupae were placed in glass plates on wet Whatman's No. 1 filter paper (Cytiva, Whatman 1001-045). A honey solution (10%) was administered to newly emerged adult moths, and each was placed in a plastic rearing cage with tissue paper strips for egg laying. *S. frugiperda* egg masses were collected from the cages, placed in petri plates coated with artificial diet (Soya bean 120g, corn flour 150g, yeast 50g, ascorbic acid 7.3 g, sorbic acid 2.4g, methyl paraben 4.4g, vitamin mixture 5g, agar 25g, sodium salt 0.5g, streptomycin 0.5g, and distilled water 500ml) and then reared to produce successive generations (Tahir *et al*., 2019).

Synthetic insecticides

Six synthetic insecticides from different chemical groups were investigated against 3^{rd} of *S. frugiperda* 3^{rd} instar larvae purchased from certified insecticide dealers at the local grain market in Faisalabad, Punjab, Pakistan. Table I summarizes the names of the insecticides, their

Table I. Synthetic insecticides, dose ml/acre, mode of action and brand names evaluated against *Spodoptera frugiperda* third instar larvae.

S. No	Insecticides	Dose (ml/acre)	Mode of action	Brand name
1	Chlorantraniliprole + Lambda cyhalothrin	160ml	Ryanodine receptor modulators	Ampligo
2	Fipronil	480ml	Blocks GABA receptors	Rector
3	Emamectin benzoate	200ml	Glutamate gated chloride channel allosteric modulators	Proclaim
4	Flubendiamide	25ml	Ryanodine receptor modulators	Belt
5	Lufenuron	240ml	Inhibitors of chitin biosynthesis	Match
6	Spinetoram	100ml	Nicotinic acetylcholine receptor allosteric modulators	Radiant

dosages (ml/acre), mode of actions, and the brand names. Before the bioassay, a series of five consecutive concentrations of each insecticide were prepared by repeatedly diluting them with distilled water.

Laboratory bioassay of synthetic insecticides against Spodoptera frugiperda

The relative efficacy of each insecticide was assessed by exposing 3rd instar *S. frugiperda* larvae to five serial concentrations using the standard leaf immersion method (IRAC method No. 7). Distilled water was used to prepare serial dilutions of each insecticide, and the concentrations were measured in microliters per liter (µl/L). After a thorough rinse with distilled water, the maize leaves were sliced into small discs (5cm diameter). Freshly prepared discs of maize leaves were dipped for 10s in five concentrations of each aqueous insecticide solution. Following this, leaf discs were allowed to dry naturally at room temperature on sheets of filter paper before being placed in glass petri plates. Water-soaked leaf discs were served as a control. Five *S. frugiperda* larvae from insect culture were released in each petri plate after 4-h starvation period. Each treatment was repeated five times, containing 25 larvae. The mortality rates of larvae were recorded after 24, 48 and 72 h exposure period. If larvae wiggled in response to light probing with a camel hair brush, they were considered as alive; otherwise, they were considered as dead. Every step of the bioassay was performed in a laboratory at 25±2°C temperature, 60±5% RH, and 16 h:8 h (Light: Dark) photoperiod (Ahmed *et al*., 2022).

Statistical analysis

The recorded mean numbers of fall armyworm and the percentage of larval mortality was subjected to a one-way analysis of variance (ANOVA) using generalized linear model. The lethal concentration (LC_{50}), fiducial limits, chi-square value, standard error, and slope were calculated using Probit analysis software. The P-values were estimated using SPSS software (Version 24.0, Armonk, New York, USA) (Liu *et al*., 2022). Percent mortality graphs were made by using graphpad prism software (Massachusetts, USA).

RESULTS

Toxicity of synthetic insecticides against the third instar larvae of Spodoptera frugiperda

All insecticides were found to be effective to control the *S. frugiperda* third instar larvae. The LC_{50} values of synthetic insecticides along with fiducial limits, standard error, slope, degree of freedom, chi-square value and p-value after 24 h are mentioned in Table II. All insecticides have different LC_{50} values that ranged from 4853.54 µl/L for chlorantraniliprole + lambda cyhalothrin and 107.70 µl/L for flubendiamide. However, it was found that flubendiamide with a low LC_{50} value was more toxic to the *S. frugiperda* 3rd instar larva while other insecticides with a high LC_{50} value showed low toxicity.

After 48 h exposure period, the LC_{50} values of synthetic insecticides along with fiducial limits, standard error, slope, degree of freedom, chi-square value and p-value are mentioned in Table III. The insecticides have varying LC_{50} values, with chlorantraniliprole + lambda cyhalothrin at 2857.75 µl/L and flubendiamide at 30.112 µl/L. Based on the low LC_{50} values, flubendiamide exhibits significant potency as an active ingredient against the *S. frugiperda*.

Table IV presents the LC_{50} values of synthetic insecticides against the third instar larvae of *S. frugiperda*, as well as the corresponding fiducial limits, slope, standard error, chi-square value, and degree of freedom after 72 h post-treatment of insecticides. All insecticides have different LC_{50} values that ranged from 1858.22 µl/L for chlorantraniliprole+lambda cyhalothrin and

Table II. Response of *Spodoptera frugiperda* third instar larvae to synthetic insecticides after 24 h.

Insecticides	N[a]	LC_{50} (µl/L)[b]	95% F.L. [c]		Calculated values by probit analysis			P-value
			Lower	Upper	Slope ± SE[d]	X^2 [e]	Df[f]	
Chlorantraniliprole + Lambda cyhalothrin	25	4853.54	2415.53	9752.23	1.28±0.16	1.00	3	0.000
Fipronil	25	2236.13	647.22	7725.89	0.66±0.28	0.99	3	0.002
Emamectin benzoate	25	2079.77	552.18	7833.31	0.61±0.29	0.99	3	0.003
Flubendiamide	25	107.70	31.08	373.19	0.66±0.27	0.99	3	0.001
Lufenuron	25	4305.38	1976.83	9376.79	1.08±0.17	0.96	3	0.000
Spinetoram	25	978.69	420.85	2275.99	0.98±0.19	0.99	3	0.000

a, Number of FAW larvae used in experiment; b, LC_{50} values of synthetic insecticides; c, 95% Fiducial limits; d, Slope and standard error; e, Chi-square value; f, Degree of freedom.

Table III. Response of *Spodoptera frugiperda* third instar larvae to synthetic insecticides after 48 h.

Insecticides	N[a]	LC_{50} (µl/L)[b]	95% F.L. [c]		Calculated values by probit analysis			P value
			Lower	Upper	Slope ± SE[d]	X^{2} [e]	Df[f]	
Chlorantraniliprole + Lambda cyhalothrin	25	2857.75	1247.21	6547.84	1.1±0.18	1.00	3	0.000
Fipronil	25	1015.04	326.32	3157.21	0.71±0.25	0.99	3	0.012
Emamectin benzoate	25	575.09	184.48	1792.74	0.74±0.25	1.00	3	0.007
Flubendiamide	25	30.112	6.86	132.12	0.57±0.33	1.00	3	0.013
Lufenuron	25	2301.89	965.77	5486.52	0.95±0.19	0.98	3	0.000
Spinetoram	25	366.38	123.59	1086.16	0.76±0.24	0.99	3	0.000

a, Number of FAW larvae used in experiment; b, LC_{50} values of synthetic insecticides; c, 95% Fiducial limits; d, Slope and standard error; e, Chi-square value; f, Degree of freedom.

Table IV. Response of *Spodoptera frugiperda* third instar larvae to synthetic insecticides after 72 h.

Insecticides	N[a]	LC_{50} (µl/L)[b]	95% F.L. [c]		Calculated values by probit analysis			P value
			Lower	Upper	Slope ± SE [d]	X^{2} [e]	Df[f]	
Chlorantraniliprole + Lambda cyhalothrin	25	1858.22	661.42	5220.50	0.79±0.23	0.996	3	0.014
Fipronil	25	410.64	204.96	822.72	1.28±0.15	0.98	3	0.000
Emamectin benzoate	25	286.95	108.53	758.63	0.94±0.21	1.00	3	0.019
Flubendiamide	25	37.65	16.67	85.01	1.19±0.18	0.99	3	0.000
Lufenuron	25	1509.39	621.64	3664.96	0.93±0.19	0.998	3	0.000
Spinetoram	25	224.97	114.86	440.64	1.44±0.15	1.00	3	0.000

a, Number of FAW larvae used in experiment; b, LC_{50} values of synthetic insecticides; c, 95% Fiducial limits; d, Slope and standard error; e, Chi-square value; f, Degree of freedom.

37.65 µl/L for flubendiamide. Based on LC_{50} values flubendiamide was more toxic to 3rd instar larvae of *S. frugiperda* at 37.65 µl/L as compared to the others.

Figure 1A illustrates the percentage mortality of third instar *S. frugiperda* larvae in response to five serial dilutions of chlorantraniliprole+lambda cyhalothrin (400, 800, 1600, 3200, and 6400µl/L). After 24 h post treatment maximum mortality (56±0.33%) was caused by 6400µl/L followed by 3200µl/L (40±0.28%), 1600 µl/L (28±0.22%), 800 µl/L (16±0.18%), 400 µl/L (8±0.22%). Five serial dilutions 400, 800, 1600, 3200 and 6400µl/L caused 64±0.33, 52±0.22, 40±0.00, 28±0.22, 20±0.00 % mortality after 48 h, while after 72 h % mortality was 72±0.36, 60±0.40, 52±0.22, 40±0.28, 36±0.33%, respectively. In control only 4±0.18% mortality was recorded after 72 h.

Percent mortality of *S. frugiperda* larvae in response to five successive dilutions of fipronil (300, 600, 1200, 2400, and 4800µl/L) is shown in Figure 1B. The concentrations of 4800µl/L caused maximum mortality (60±0.28%) after 24 h of treatment, followed by 2400µl/L (48±0.22%), 1200µl/L (44±0.18%), 600µl/L (36±0.18%), 300µl/L (28±0.22%), and control (0±0.00%). The % mortality was 68±0.22, 60±0.40, 56±0.33, 40±0.28, and 36±0.18 % after 48 h post treatment to five successive serial dilutions of 300, 600, 1200, 2400, and 4800µl/L, respectively. After 72 h exposure, the percentage of mortality was 96±0.18, 88±0.36, 76±0.18, 56±0.33, and 52±0.22 % while 4±0.18 % mortality was recorded in control treatment.

Percent mortality of *S. frugiperda* larvae in response to five successive dilutions of emamectin benzoate (500, 1000, 2000, 4000, and 8000µl/L) is shown in Figure 1C. The concentrations of 8000µl/L caused maximum mortality (64±0.18%) after 24 h of treatment, followed by 4000µl/L (56±0.18%), 2000µl/L (52±0.22%), 1000µl/L (40±0.28%), 500 µl/L (36±0.18%), and control (0±0.00%). The percentage mortality was 80±0.28, 72±0.22, 68±0.22, 56±0.33, and 48±0.22% after 48 h post treatment to five successive serial dilutions of 500, 1000, 2000, 4000, and 8000µl/L, respectively. After 72 h exposure, the percentage of mortality was 96±0.18, 88±0.36, 84±0.18, 72±0.46, and 64±0.18 % while 4±0.18 % mortality was observed in the control group.

Figure 1D shows the percentage mortality of third instar *S. frugiperda* larvae in response to five serial dilutions of flubendiamide (62.5, 125, 250, 500, and 1000µl/L). After 24 h post treatment maximum mortality (72±0.22%) was caused by 1000µl/L followed by 500µl/L (68±0.22%), 250 µl/L (64±0.18%), 125µl/L (48±0.22%), 62.5µl/L (44±0.18%). Five serial dilutions 62.5, 125, 250, 500, and 1000µl/L caused 80±0.28, 76±0.18, 72±0.22, 64±0.18, 56±0.18% mortality after 48 h, while after 72 h % mortality was 100±0.00, 96±0.18, 84±0.18, 76±0.18, 68±0.22, respectively. In control only 4±0.18 % mortality was recorded after 72 h.

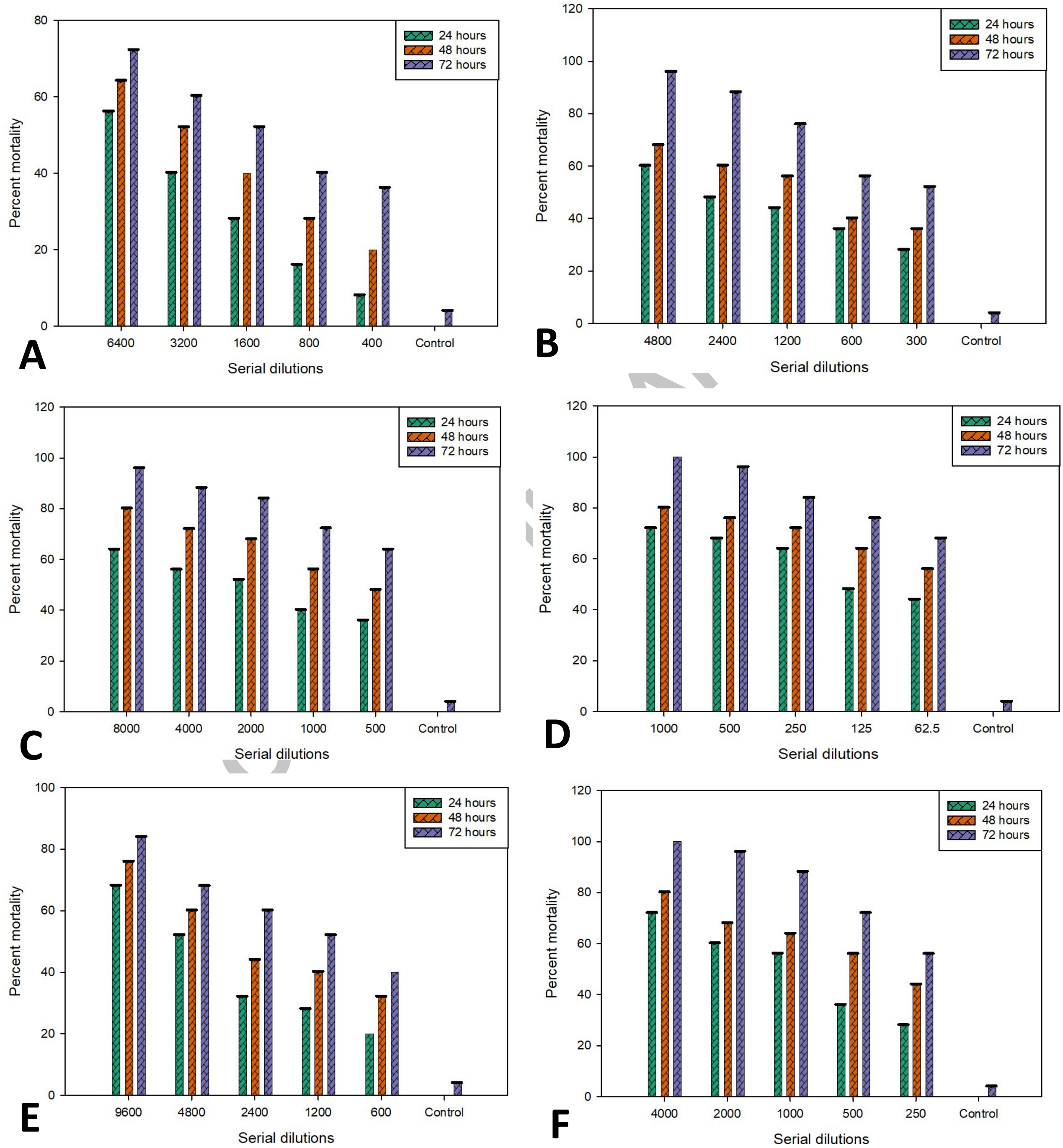

Fig. 1. Effect of chlorantraniliprole + λ cyhalothrin (A), fipronil (B), emamectin benzoate (C), flubendiamide (D), lufenuron (E) and spinetoram (F) on third instar larvae of *Spodoptera frugiperda.*

Figure 1E depicts the percentage mortality of third instar *S. frugiperda* larvae in response to five serial dilutions of lufenuron (600, 1200, 2400, 4800, and 9600µl/L). After 24 h post treatment maximum mortality (68±0.36%) was caused by 9600µl/L followed by 4800µl/L (52±0.22%), 2400 µl/L (32±0.22%), 1200µl/L (28±0.22%), 600µl/L (20±0.00%). Five serial dilutions 600, 1200, 2400, 4800, and 9600µl/L caused 76±0.18, 60±0.28, 44±0.18, 40±0.28, 32±0.22 % mortality after 48 h, while after 72 h % mortality was 84±0.18, 68±0.22, 60±0.28, 52±0.22, 40±0.00, respectively. In control only 4±0.18 % mortality was recorded after 72 h.

Percent mortality of *S. frugiperda* larvae in response to five successive dilutions of spinetoram (250, 500, 1000, 2000, and 4000µl/L) is shown in Figure 1F. The concentrations of 4000µl/L caused maximum mortality (72±0.22%) after 24 h of treatment, followed by 2000µl/L (60±0.28%), 1000µl/L (56±0.33%), 500µl/L (36±0.18%), 250 µl/L (28±0.22%), and control (0±0.00%). The % mortality was 80±0.28, 68±0.22, 64±0.18, 56±0.18, and 44±0.18 after 48 h post treatment to five successive serial dilutions of 250, 500, 1000, 2000, and 4000µl/L, respectively. After 72 h exposure, the percentage of mortality was 100±0.00, 96±0.18, 88±0.36, 72±0.22, and 56±0.18 % while 4±0.18 % mortality was observed in the control group.

DISCUSSION

The present study was carried out to investigate the toxicity potential of six synthetic insecticides (Chlorantraniliprole+Lambda cyhalothrin, Fipronil, Emamectin benzoate, Flubendiamide, Lufenuron and Spinetoram) against the third instar larvae of *S. frugiperda*. These insecticides have different mode of actions and are easily available to the farmers at the local insecticides market to control the different insect pests including fall armyworm. The results of this study demonstrates the efficacy of synthetic insecticides against 3rd instar larvae of *S. frugiperda* under laboratory conditions. Many researchers across the world have been conducting laboratory and field studies to develop registered insecticides for the emergency control of fall armyworm.

Chlorantraniliprole+lambda cyhalothrin was found to be less toxic to fall armyworm 3rd instar larvae as compared to other insecticides. The LC_{50} values for the combination of chlorantraniliprole+lambda cyhalothrin were 4853.54, 2857.75, and 1858.22 µl/L after 24, 48, and 72 h, respectively, and were significantly higher compared to the other insecticides. The current study results align with those of Tidke *et al.* (2021) in assessing the comparative effectiveness of synthetic insecticides against *S. frugiperda* larvae. The obtained LC_{50} value demonstrated that chlorantraniliprole+lambda cyhalothrin was least effective to control the *S. frugiperda* under laboratory conditions.

Fipronil is an extensively utilized broad-spectrum insecticide to manage insect pests on various crops. It disrupts the central nervous system (CNS) of insects through the blockage of chloride channels that are regulated by glutamate or γ-aminobutyric acid (GABA). The LC_{50} values for the fipronil were 2236.13, 1015.04, and 410.64 µl/L after 24, 48, and 72 h, respectively, and were significantly lower compared to the combination of chlorantraniliprole+lambda cyhalothrin. The findings of current study were in accordance with the findings reported by Zhan *et al.* (2021) used γ-aminobutyric acid receptors targeted insecticides like fipronil, fluralaner, and broflanilide against the FAW. The LD_{50} value for fipronil was found to be 23.577 mg/kg, indicating that it was effective against the FAW. The outcomes of our research were similar to Mumtaz *et al.* (2023), who examined the toxicity of synthetic insecticides against *S. frugiperda*. According to their findings, fipronil caused a moderate level of mortality in *S. frugiperda* larvae.

Emamectin benzoate is an insecticide that belongs to avermectin class that was particularly formulate for the lepidopteran insect pests (Stavrakaki *et al.*, 2022). Through translaminar action, it penetrates the leaf tissues and builds a reservoir there. The mode of action is distinctive within the spectrum of insecticides. It inhibits muscular contraction by allowing a constant influx of chlorine ions at the H-Glutamate and GABA receptor sites (Liu *et al.*, 2022). The LC_{50} values for emamectin benzoate were 2079.77 µl/L at 24 h, 575.09 µl/L at 48 h, and 286.95 µl/L at 72 h. The current study findings align with those of Susanto *et al.* (2021), who investigated the effectiveness of synthetic insecticides against *S. frugiperda* larvae. Emamectin benzoate shown superior efficacy in laboratory, greenhouse, and field trials compared to indoxocarb, phoxim, chlorfenapyr, and methomyl. The results of current study regarding the effectiveness of emamectin benzoate against *S. frugiperda* are in compliance with numerous studies conducted by Mian *et al.* (2022), Ali *et al.* (2023), Liu *et al.* (2022), and Amein *et al.* (2023). The results of our study were consistent with Chang *et al.* (2023), who reported that emamectin benzoate is effective against *S. frugiperda* larvae and can be used in integrated pest management. A research performed by Koffi *et al.* (2022) too supported the findings of current study that emamectin benzoate are effective to control the pests like FAW.

Flubendiamide is a broad-spectrum insecticide that can be applied to a variety of perennial and annual crops

(Jeschke, 2024). Flubendiamide LC_{50} values were 107.70, 30.112, and 37.65 after 24, 48, and 72 h, respectively. It was found to be highly toxic against *S. frugiperda* 3rd instar larvae. Our study's results, as determined by the LC_{50} values, contradict the findings of Hardke *et al*. (2011), which indicated that spinetoram and chlorantraniliprole had lower LC_{50} values than flubendiamide. In contrast, flubendiamide exhibited the lowest LC_{50} values among the six synthetic insecticides evaluated in our study.

The LC_{50} values for lufenuron were 4305.38 µl/L after 24 h, 2301.89 µl/L after 48 h, and 1509.39 µl/L after 72 h. The current study findings correlate with Lv *et al*. (2023) study, which demonstrated that lufenuron exhibited significant insecticidal effects on *S. frugiperda* larvae, with an LC_{50} value of 0.99mg/L. Lufenuron is a benzoylurea insecticide which suppresses chitin synthesis in insects (Lv *et al*., 2022; Ma *et al*., 2024). Gichere *et al*. (2022) evaluated the potential of different insecticides on *S. frugiperda* by using leaf dip bioassay under laboratory conditions and showed high toxicity of lufenuron as compared to the imidacloprid, indoxocarb and lambda-cyhalothrin.

The LC_{50} values for the spinetoram were 978.69, 366.38, and 224.97 µl/L after 24, 48, and 72 h, respectively. Based on LC_{50} values, the ascending order of synthetic insecticides was as follows: flubendiamide, spinetoram, emamectin benzoate, fipronil, lufenuron and chlorantraniliprole + lambda cyhalothrin. The findings of the present study are in comparison with those conducted by Tidke *et al*. (2021), who reported that spinetoram had lower LC_{50} value as compared to the combination of chlorantraniliprole+lambda cyhalothrin and highly toxic to the third instar larvae of *S. frugiperda* under laboratory conditions. Our findings are aligned with Idrees *et al*. (2022), who assessed the effectiveness of synthetic insecticides against the second instar larvae of *S. frugiperda* and reported the highest efficacy of spinetoram in term of percent mortality in comparison to other test insecticides. They concluded that spinetoram effectively controls the *S. frugiperda* population. The results of another study conducted by Sisay *et al*. (2019) also support our findings.

CONCLUSION

Our study clearly shows that synthetic insecticides are effective in controlling *S. frugiperda* population. Among all tested insecticides Spinetoram was the most effective insecticide followed by flubendiamide, emamectin benzoate, fipronil, lufenuron and chlorantraniliprole+lambda cyhalothrin. The results of present study highlighted the significant increase in mortality of third instar *S. frugiperda* larvae with increasing concentrations of insecticides and exposure duration. Moreover, recommended dose of these insecticides can be used an emergency response against *S. frugiperda* larvae after investigating their efficacy in the field.

DECLARATIONS

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Ethics approval

Not applicable.

Statement of conflict of interest

The authors have declared no conflict of interest.

REFERENCES

Ahmed, K.S., Idrees, A., Majeed, M.Z., Majeed, M.I., Shehzad, M.Z., Ullah, M.I. and Li, J., 2022. Synergized toxicity of promising plant extracts and synthetic chemicals against fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) in Pakistan. *Agronomy*, **12:** 1289. https://doi.org/10.3390/agronomy12061289

Ali, M., Basit, M.A., Maqsood, S., Safdar, H. and Javaid, A., 2023. Assessment of selected insecticides against fall armyworm [*Spodoptera frugiperda* (JE Smith); Lepidoptera, Noctuidae] on maize crop in Lahore. *Pl. Prot.,* **7**: 237-244.

Amein, N., Abdelal, A. and Said, E., 2023. Effectiveness of teflubenzuron, emamectin benzoate, and alfa-cypermethrin on fall armyworm, *Spodoptera frugiperda* (JE Smith) (Noctuidae: Lepidoptera), under laboratory and field conditions. *Egypt. Acad. J. Biol. Sci., A Ent.,* **16:** 133-139. https://doi.org/10.21608/eajbsa.2023.290568

Aruna-Balla, B.M., Bagade, P. and Rawal, N., 2019. Yield losses in maize (*Zea mays*) due to fall armyworm infestation and potential IoT-based interventions for its control. *J. Ent. Zool. Stud.,* **7:** 920-927.

Bakar, M.A., Aqueel, M.A., Raza, A.B.M., Arshad, M., Mahmood, R. and Qadir, Z.A., 2018. Comparative efficacy of five commercial synthetic acaricides against *Varroa destructor* (Anderson and Trueman) in *Apis mellifera* L. colonies. *Pakistan J. Zool.*, **50:** 857-861. https://doi.org/10.17582/journal.pjz/2018.50.3.857.861

Chang, H., Guo, J., Qi, G., Gao, Y., Wang, S., Wang, X. and Liu, Y., 2023. Comparative analyses of the effects of sublethal doses of emamectin benzoate and tetrachlorantraniliprole on the gut microbiota of *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *J. Insect Sci.*, **23:** 7-16. https://doi.org/10.1093/jisesa/iead039

Day, R., Abrahams, P., Bateman, M., Beale, T., Clottey, V., Cock, M. and Witt, A., 2017. Fall armyworm: Impacts and implications for Africa. *Outlooks Pest Manage.*, **28:** 196-201. https://doi.org/10.1564/v28_oct_02

Galani, Y.J.H., Orfila, C. and Gong, Y.Y., 2022. A review of micronutrient deficiencies and analysis of maize contribution to nutrient requirements of women and children in Eastern and Southern Africa. *Crit. Rev. Fd. Sci. Nutr.*, **62:** 1568-1591. https://doi.org/10.1080/10408398.2020.1844636

Gichere, S.N., Khakame, K.S. and Patrick, O., 2022. Susceptibility evaluation of fall armyworm (*Spodoptera frugiperda*) infesting maize in Kenya against a range of insecticides. *J. Toxicol.*, **2022:** 1-11. https://doi.org/10.1155/2022/8007998

Gu, X., Cai, P., Yang, Y., Yang, Q., Yao, M., Idrees, A. and Chen, J., 2018. The response of four braconid parasitoid species to methyl eugenol: Optimization of a biocontrol tactic to suppress *Bactrocera dorsalis*. *Biol. Contr.*, **122:** 101-108. https://doi.org/10.1016/j.biocontrol.2018.04.002

Hardke, J.T., Temple, J.H., Leonard, B.R. and Jackson, R.E., 2011. Laboratory toxicity and field efficacy of selected insecticides against fall armyworm (Lepidoptera: Noctuidae). *Fla. Entomol.*, pp. 272-278. https://doi.org/10.1653/024.094.0221

Idrees, A., Qadir, Z.A., Afzal, A., Ranran, Q. and Li, J., 2022. Laboratory efficacy of selected synthetic insecticides against second instar invasive fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae) larvae. *PLoS One*, **17:** e0265265. https://doi.org/10.1371/journal.pone.0265265

Idrees, A., Qadir, Z.A., Akutse, K.S., Afzal, A., Hussain, M., Islam, W. and Li, J., 2021. Effectiveness of entomopathogenic fungi on immature stages and feeding performance of fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae) larvae. *Insects*, **12**: 1044. https://doi.org/10.3390/insects12111044

Jeschke, P., 2024. Recent developments in fluorine-containing pesticides. *Pest Manage. Sci.,* **80:** 3065-3087. https://doi.org/10.1002/ps.7921

Kim, J., Nam, H.Y., Kwon, M., Kim, H.J., Yi, H.J., Haenniger, S. and Heckel, D.G., 2021. Development of a simple and accurate molecular tool for *Spodoptera frugiperda* species identification using LAMP. *Pest Manage. Sci.*, **77**: 3145-3153. https://doi.org/10.1002/ps.6350

Koffi, D., Kyerematen, R., Osae, M., Amouzou, K. and Eziah, V.Y., 2022. Assessment of *Bacillus thuringiensis* and emamectin benzoate on the fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) severity on maize under farmers' fields in Ghana. *Int. J. Trop. Insect Sci.*, 1-8. https://doi.org/10.1007/s42690-021-00683-5

Kong, F., Song, Y., Zhang, Q., Wang, Z. and Liu, Y., 2021. Sublethal effects of chlorantraniliprole on *Spodoptera litura* (Lepidoptera: Noctuidae) moth: Implication for attract-and-kill strategy. *Toxics*, **9:** 20-29. https://doi.org/10.3390/toxics9020020

Kumar, R.M., Gadratagi, B.G., Paramesh, V., Kumar, P., Madivalar, Y., Narayanappa, N. and Ullah, F., 2022. Sustainable management of invasive fall armyworm, *Spodoptera frugiperda*. *Agronomy*, **12:** 2150. https://doi.org/10.3390/agronomy12092150

Lal, B., Singh, D. and Bhadauria, N.S., 2023. Nature of damage and its management of fall armyworm (*Spodoptera frugiperda*) on maize crop: A review. *J. Exp. Agric. Int.*, **45:** 1-8. https://doi.org/10.9734/jeai/2023/v45i122259

Liu, Z.K., Li, X.L., Tan, X.F., Yang, M.F., Idrees, A., Liu, J.F. and Shen, J., 2022. Sublethal effects of emamectin benzoate on fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Agriculture*, **12:** 959-970. https://doi.org/10.3390/agriculture12070959

Lone, A.A., Dar, Z.A., Gull, A., Gazal, A., Naseer, S., Khan, M.H. and Iqbal, A.M., 2021. Breeding maize for food and nutritional security. In: *Cereal grains.* IntechOpen, London. pp. 39-54.

Lv, H., Ling, S., Guo, Z., Zheng, C., Ma, H., Li, J. and Ma, K., 2023. Effects of lufenuron treatments on the growth and development of *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Comp. Biochem. Physiol. C. Toxicol. Pharmacol.*, **263:** 109499. https://doi.org/10.1016/j.cbpc.2022.109499

Lv, S.L., Xu, Z.Y., Li, M.J., Mbuji, A.L., Gu, M., Zhang, L. and Gao, X.W., 2022. Detection of chitin synthase mutations in lufenuron-resistant *Spodoptera frugiperda* in China. *Insects*, **13:** 963. https://doi.org/10.3390/insects13100963

Ma, L., Zhao, Z., Yang, R., Su, Q., Peng, Y. and Zhang, W., 2024. Dissecting the manipulation of lufenuron on chitin synthesis in *Helicoverpa armigera*. *Pestic. Biochem. Physiol.*, **202:** 105962. https://doi.org/10.1016/j.pestbp.2024.105962

Makgoba, M.C., Tshikhudo, P.P., Nnzeru, L.R. and Makhado, R.A., 2021. Impact of fall armyworm (*Spodoptera frugiperda*) (JE Smith) on small-scale maize farmers and its control strategies in the Limpopo province, South Africa. *Jàmbá: J. Disas Risk Stu.*, **13:** 1016-1024. https://doi.org/10.4102/jamba.v13i1.1016

Maruthadurai, R. and Ramesh, R., 2020. Occurrence, damage pattern and biology of fall armyworm, *Spodoptera frugiperda* (JE smith) (Lepidoptera: Noctuidae) on fodder crops and green amaranth in Goa, India. *Phytoparasitica*, **48:** 15-23. https://doi.org/10.1007/s12600-019-00771-w

Mian, F.M., Khan, I., Ullah, N., Gondal, A.H., Ajmal, M.S., Qureshi, M.S. and Jabbar, A., 2022. Efficacy of insecticides against fall armyworm, *Spodoptera frugiperda* (Lepidoptera, Noctuidae) in maize. *J. Bioresour. Manage.,* **9:** 133-139.

Mumtaz, H., Majeed, M.Z., Afzal, M., Arshad, M., Mehmood, A. and Qasim, M., 2023. The efficacy of selected synthetic insecticide formulations against fall armyworm *Spodoptera frugiperda* (JE Smith) under laboratory, semi-field and field conditions. *Pakistan J. Zool.,* **56:** 147-155. https://doi.org/10.17582/journal.pjz/20220822120846

Nagesh, C. and Tayde, A.R., 2023. Efficacy of different chemicals and neem products against fall army worm, (*Spodoptera frugiperda* (JE Smith)) in maize (*Zea mays* L.). *Biol. Forum. Int. J.* **15:** 432-436.

Naharki, K., Regmi, S. and Shrestha, N., 2020. A review on invasion and management of fall armyworm *Spodoptera frugiperda* in Nepal. *Rev. Fd. Agric.*, **1:** 6-11. https://doi.org/10.26480/rfna.01.2020.06.11

Navik, O., Shylesha, A.N., Patil, J., Venkatesan, T., Lalitha, Y. and Ashika, T.R., 2021. Damage, distribution and natural enemies of invasive fall armyworm *Spodoptera frugiperda* (JE smith) under rainfed maize in Karnataka, India. *Crop Prot.*, **143:** 105536. https://doi.org/10.1016/j.cropro.2021.105536

Ndolo, D., Njuguna, E., Adetunji, C.O., Harbor, C., Rowe, A., Den Breeyen, A. and Hospet, R., 2019. Research and development of biopesticides: Challenges and prospects. *Outlooks Pest Manage.,* **30:** 267-276. https://doi.org/10.1564/v30_dec_08

Ramzan, M., Ilahi, H., Adnan, M., Ullah, A. and Ullah, A, 2021. Observation on fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae) on maize under laboratory conditions. *Egypt. Acad. J. biol. Sci.*, **14:** 99-104. https://doi.org/10.21608/eajbsa.2021.152337

Selamoglu, Z., Altawell, N., Sri, R.M., Ravichandran, S. and Rai, A., 2023. Use of pesticides leads to environmental degradation. *Int. J. environ. Chem.*, **9:** 75-78.

Shah, R.T., Prasad, K. and Kumar, P., 2016. Maize—A potential source of human nutrition and health: A review. *Cogent Fd. Agric.*, **2:** 1166995. https://doi.org/10.1080/23311932.2016.1166995

Sisay, B., Tefera, T., Wakgari, M., Ayalew, G. and Mendesil, E., 2019. The efficacy of selected synthetic insecticides and botanicals against fall armyworm, *Spodoptera frugiperda*, in maize. *Insects*, **10:** 45-53. https://doi.org/10.3390/insects10020045

Stavrakaki, M., Ilias, A., Ioannidis, P., Vontas, J. and Roditakis, E., 2022. Investigating mechanisms associated with emamectin benzoate resistance in the tomato borer *Tuta absoluta*. *J. Pest Sci.*, 1-15. https://doi.org/10.1007/s10340-021-01448-2

Susanto, A., Setiawati, W., Udiarto, B.K. and Kurniadie, D., 2021. Toxicity and efficacy of selected insecticides for managing invasive fall armyworm, *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) on maize in Indonesia. *Res. Crops*, **22:** 652-665. https://doi.org/10.31830/2348-7542.2021.114

Tahir, M., Wakil, W., Ali, A. and Sahi, S.T., 2019. Pathogenicity of *Beauveria bassiana* and *Metarhizium anisopliae* isolates against larvae of the polyphagous pest *Helicoverpa armigera*. *Entomol. Gen.*, **38:** 225-242. https://doi.org/10.1127/0171-8177/2019/0460

Tefera, A.A., 2020. A review on quality protein maize. *Int. Res. J. Pl. Sci.*, **11:** 1-6.

Tidke, V.N., Kulkarni, U.S. and More, S.R., 2021. Screening of insecticides against fall armyworm, *Spodoptera frugiperda* (JE Smith). *J. Ent. Zoo. Stud.*, **9:** 278-284.

Tulashie, S.K., Adjei, F., Abraham, J. and Addo, E., 2021. Potential of neem extracts as natural insecticide against fall armyworm (*Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae). *Case Stud. Chem. environ. Eng.*, **4:** 100130. https://doi.org/10.1016/j.cscee.2021.100130

Udayakumar, A., Shivalingaswamy, T.M. and Bakthavatsalam, N., 2021. Legume-based intercropping for the management of fall armyworm, *Spodoptera frugiperda* L. in maize. *J. Pl. Dis. Prot.*, **128:** 775-779. https://doi.org/10.1007/s41348-020-00401-2

Veres, A., Wyckhuys, K.A., Kiss, J., Tóth, F., Burgio, G., Pons, X. and Furlan, L., 2020. An update of the Worldwide Integrated Assessment (WIA) on systemic pesticides. Part 4: Alternatives in major cropping systems. *Environ. Sci. Pollut. Res.*, **27:** 29867-29899. https://doi.org/10.1007/s11356-020-09279-x

Womack, E.D., Williams, W.P., Smith, J.S., Warburton, M.L. and Bhattramakki, D., 2020. Mapping quantitative trait loci for resistance to fall armyworm (Lepidoptera: Noctuidae) leaf-feeding damage in maize inbred Mp705. *J. econ. Ent.*, **113**: 956-963. https://doi.org/10.1093/jee/toz357

Yeboah, S., Ennin, S.A., Ibrahim, A., Oteng-Darko, P., Mutyambai, D., Khan, Z.R. and Niassy, S., 2021. Effect of spatial arrangement of push-pull companion plants on fall armyworm control and agronomic performance of two maize varieties in Ghana. *Crop Prot.*, **145:** 105612. https://doi.org/10.1016/j.cropro.2021.105612

Yousaf, S., Rehman, A., Masood, M., Ali, K. and Suleman, N., 2022. Occurrence and molecular identification of an invasive rice strain of fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) from Sindh, Pakistan, using mitochondrial cytochrome c oxidase I gene sequences. *J. Pl. Dis. Prot.*, **129**: 71-78. https://doi.org/10.1007/s41348-021-00548-6

Zhan, E.L., Wang, Y., Jiang, J., Jia, Z.Q., Tang, T., Song, Z.J. and Zhao, C.Q., 2021. Influence of three insecticides targeting GABA receptor on fall armyworm *Spodoptera frugiperda*: Analyses from individual, biochemical and molecular levels. *Pestic. Biochem. Physiol.*, **179:** 104973. https://doi.org/10.1016/j.pestbp.2021.104973

Zhang, L., Liu, B., Zheng, W., Liu, C., Zhang, D., Zhao, S. and Xiao, Y., 2020. Genetic structure and insecticide resistance characteristics of fall armyworm populations invading China. *Mol. Ecol. Resour.*, **20**: 1682-1696. https://doi.org/10.1111/1755-0998.13219