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RESEARCH ARTICLE

Evaluation of phenology-based insecticide strategies for fall armyworm (*Spodoptera frugiperda*) management in maize in India

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Abstract

The invasive fall armyworm (*Spodoptera frugiperda* J.E. Smith) poses a significant threat to maize productivity in India, yet optimal insecticide application strategies aligned with crop phenology remain underexplored. A comprehensive field investigation was undertaken at the Maize Research Centre, Rajendranagar, Hyderabad, across three consecutive *Kharif* seasons (2020-2022) to assess the performance of chlorantraniliprole 18.5 % SC (soluble concentrate) (applied at 0.4 ml/L) in controlling the invasive pest *Spodoptera frugiperda* J.E. Smith (Lepidoptera: Noctuidae), commonly known as the fall armyworm (FAW), in maize. The experimental layout followed a randomized block design, incorporating multiple insecticide application timings based on crop phenology (7, 10, 14 and 20 days after germination) and pest incidence thresholds (5 % and 10 %), in addition to an untreated control for comparison. Among the evaluated strategies, the sequential application of chlorantraniliprole at the V2 (7 DAG) and V4 (14 DAG) vegetative stages proved to be the most effective. This treatment significantly minimized FAW infestation, registering a mean infestation of only 12.33 %, along with the lowest leaf injury rating (1.98) on the modified Davis scale and the highest recorded grain yield (81.30 q/ha). A closely comparable result was achieved with applications at the V3 (10 DAG) and V5 (20 DAG) stages, which showed a slightly higher mean infestation (13.71 %) but identical leaf injury scores (1.98) and a near-equivalent grain yield (81.11 q/ha). The findings underscore the importance of timely insecticide applications during the early vegetative stages, particularly V2 and V4, to suppress FAW populations effectively and optimize maize productivity. This research highlights the critical role of growth stage-based pest management in enhancing crop health and yield outcomes under FAW pressure.

Keywords: chlorantraniliprole; fall armyworm; grain yield; phenological stages; spray frequency

Introduction

Maize (*Zea mays* L.), often referred to as the "queen of cereals," is distinguished by its exceptional productivity and capacity to generate substantial biomass within a relatively short growth period (1). In India, maize was cultivated on approximately 8.27 million hectares during 2022-23, producing 11.69 million tonnes with an average productivity of 4148 kg/ha (2). In Telangana, the crop spans an area of 0.52 million hectares, producing 2.86 million tonnes with a notably higher productivity of 5533 kg/ha (2). Beyond serving as a dietary staple for much of the Asian population, maize is also critical as a raw material in the starch, oil, food and feed industries. Maize is also consumed in traditional forms such as chapatis, especially in rural and tribal regions.

However, maize cultivation is severely challenged by a complex of insect pests, with approximately 130 species reported to cause varying degrees of yield loss across India (3). Among these, the fall armyworm (FAW), *S. frugiperda* J.E. Smith (Lepidoptera: Noctuidae), has emerged as a major polyphagous pest with a pronounced affinity for maize (4, 5). In sub-Saharan Africa, FAW infestations have led to estimated economic losses of up to US$13 billion annually in maize production alone (6). The larval stages of FAW inflict extensive damage by feeding on leaf whorls, tassels, ears and severe infestations by severing seedlings at the base, compromising stand establishment and final yield (7).

The invasive success of FAW is attributed to its high fecundity, short developmental cycle, polyphagy and extraordinary migratory capacity, compounded by year-round availability of host plants and conducive agro-climatic conditions

(8, 9). Therefore, this pest management is inherently complex and necessitates a multi-pronged approach. Conventional tactics comprising host plant resistance, agronomic and cultural interventions, chemical insecticides, integrated pest management (IPM) and crop rotation are widely employed (10, 11). Chemical control remains the predominant strategy, particularly in Africa, largely due to governmental intervention following the initial outbreak (12-15). Nonetheless, reliance on synthetic insecticides raises substantial concerns regarding environmental sustainability, the emergence of resistance in pest populations and the safety of applicators, livestock and consumers (16-18).

Insecticides induce direct mortality in non-target beneficial arthropods and disrupt their behavioural and physiological functions including mobility, reproduction, immune responses and longevity even at sublethal exposures (19). Their inherently toxic nature, while effective against target pests, frequently extends to non-target organisms, including humans (20). Location-specific intercropping in maize reduced FAW damage, enhanced populations of natural enemies like coccinellids, spiders and earwigs, suppressed weeds through increased competition for light and ultimately resulted in improved maize yield and a higher benefit-cost ratio. Tailored intercropping practices in maize helped reduce FAW damage, boosted populations of natural enemies like coccinellids, spiders and earwigs and suppressed weed growth by increasing competition for light. As a result, maize yield improved and the benefit-cost ratio was enhanced. (21).

In response, research and development efforts have shifted toward innovating biorational insecticide compounds characterized by their specificity and reduced ecological footprint (22). These include insect growth regulators functioning as ecdysone agonists, juvenile hormone analogs and chitin synthesis inhibitors, which modulate pest populations through interference with developmental processes (23, 24). Despite the demonstrated efficacy of synthetic insecticides in FAW control (6, 25, 26), critical gaps persist in understanding the maize phenological stages most susceptible to FAW and therefore requiring intervention once pest populations exceed economic threshold levels. Field surveys conducted in Ghana in 2018 reported that farmers applied chemical and biopesticides as many as 12 times per cropping season, which not only elevates production costs but also jeopardizes natural enemy populations and disrupts ecological balance (11). Given these challenges, the present study was designed to identify the optimal timing and frequency of synthetic insecticide applications to effectively suppress FAW infestation with minimal environmental impact and economic input. The overarching goal is to establish an integrated management approach that is ecologically sustainable, economically feasible and technically sound for the long-term control of FAW in maize ecosystems.

Materials and Methods

A comprehensive field investigation was executed at the Maize Research Centre, Agricultural Research Institute, Rajendranagar, Hyderabad, geographically positioned at 17°32′N latitude and 78°40′E longitude. The location at 17°32′ N, 78°40′ E, situated at approximately 536 m above mean sea level, features a monsoon-driven *Kharif* season and moderate elevation. These conditions are ideal for maize cultivation but also favour the development and spread of FAW, making early monitoring, timely pest management and integrated control strategies essential to safeguard crop productivity.

The site lies within the southern agro-climatic zone of Telangana and characterized by a semi-arid tropical climate, with an average ambient temperature of 22 °C across the *Kharif* seasons of 2020, 2021 and 2022. Before trial establishment, experimental plots underwent primary tillage with a tractor-mounted plough followed by secondary tillage using a harrow to achieve optimal soil tilth for sowing. Before sowing, composite soil samples were collected from each plot at 0-20 cm depth and analysed to determine baseline fertility. The analysis included soil pH (6.5 ± 0.1), organic carbon (0.8 %), available nitrogen (220 kg ha^{-1}), phosphorus (Olsen-P, 18 mg kg^{-1}) and potassium (exchangeable K, 150 mg kg^{-1}). Based on these results, fertilizer application was tailored to meet maize crop requirements. Fertilizers were applied uniformly across all experimental plots following the standard nutrient management practices.

Aside from the experimental application of chlorantraniliprole 18.5 % SC at a concentration of 0.4 mL/L water, applied at distinct phenological growth stages, no additional insecticides or pesticides were used. An untreated control was included to assess the comparative effectiveness of the insecticide treatment. All other agronomic practices were kept consistent across treatments. The treatments were arranged in a randomized block design with three replications.

The hybrid maize cultivar DHM 117 was selected for its broad agronomic acceptance across major maize-growing states in India, including Telangana Andhra Pradesh, Bihar, Rajasthan, Madhya Pradesh, Maharashtra and West Bengal. This genotype exhibits a maturity duration of 110 days, superior seed quality, tolerance to drought, resistance to lodging and resilience against major foliar and stalk diseases such as post-flowering stalk rot and leaf blight. It possesses a genetic yield potential of 100 q/ha and well adapted across diverse agro-ecological zones of the Indian subcontinent.

Sowing was carried out during the optimal monsoonal window-on 15 July 2020, 21 June 2021 and 1 July 2022 using a row-to-row and plant-to-plant spacing of 60 cm × 20 cm. Each experimental unit comprised a plot of 50 m^2 (10 m × 5 m), with a buffer spacing of 1.5 m between plots to minimize inter-treatment interference (Fig. 1). Standard agronomic and cultural practices including nutrient management, irrigation scheduling and weed control were meticulously followed throughout the crop cycle to ensure uniform plant stand and vigour.

Nutrient management

A total of 200-60-50 kg/ha of NPK was applied following the soil fertility status. Phosphorus and potassium were applied as a basal dose when sowing using di-ammonium phosphate (DAP) and muriate of potash (MOP). Nitrogen was applied in three equal split doses: before sowing, at 30-35 days after sowing (DAS) and the tasselling stage, using urea.

Weed management

Weed control was carried out using a combination of chemical and mechanical methods. Atrazine was applied at 2.5 kg/ha as a

Fig. 1. (**A**) Field view of the experimental trial. (**B**) Fall army worm, *S. frugiperda* larva, (**C**) Spraying of insecticide at 20 DAG (V5 Stage) (**D**) Control treatment plot.

pre-emergence herbicide immediately after sowing, contingent on adequate soil moisture. For post-emergence control, atrazine and mesotrione were applied at a rate of 3.5 L/ha between 20 and 25 DAS. Mechanical weed management was also performed through inter cultivation with a tractor-drawn cultivator at 30-35 DAS.

Irrigation management

Irrigation was carried out using surface flooding, applied as needed based on crop requirements and prevailing weather conditions. Special attention was given during critical growth stages, including knee-high, tasselling, silking and grain filling. The experiment was conducted during the *Kharif* season, with irrigation frequency adjusted according to rainfall and soil moisture availability.

Treatment applications were performed using a Knapsack sprayer with a hollow cone nozzle, delivering a spray volume of 500 L/ha. Foliar applications of chlorantraniliprole were executed during calm, warm and sunny periods to maximize coverage and efficacy, spanning crop developmental stages from emergence (VE) to six-leaf stage (V6). Treatment timings and specific details are outlined in Table 1. Treatments were consistently followed across all three cropping years. Pest incidence and crop damage parameters, including percentage infestation, foliar injury rating and ear damage were recorded following standardized protocols recommended by International Wheat and Maize Improvement Centre (CIMMYT) and Indian Institute of Maize Research (IIMR) (9, 27).

Observations were collected pre-treatment and ten days post-application, based on visual assessments of 20 randomly selected plants per plot, excluding border plants. Marketable grain yield refers to the harvested portion meeting quality standards for sale or consumption, excluding damaged, diseased or pest-infested ears. It was measured at harvest and expressed in quintals per hectare (q/ha). The resulting data were statistically analysed using analysis of variance within a randomized block design (RBD) framework. Before analysis, percentage-based data were angular transformed, rating-based data were square root transformed to normalize variance and back-transformed post-analysis for interpretation. Treatment means were compared using Duncan's multiple range test (DMRT) at a significance threshold of $p \leq 0.05$ to delineate statistically significant differences among treatments.

Results

The pooled analysis of three years of data demonstrated that, before insecticide application, the mean percent infestation of FAW and the corresponding leaf injury ratings (LIR) were statistically uniform across all treatment plots. All treatments exceeded the economic threshold (ET) level of 5 % infestation up to 30 DAG. Chlorantraniliprole 18.5 % SC, when applied at different DAG, significantly reduced both percent infestation and LIR compared to the untreated control, with notable effects observed at 10 days post-treatment (Table 1).

One day before treatment, mean percent FAW infestation ranged from 21.86 % to 52.10 %, while LIR values varied from 2.97 to 3.56 across treatments, showing no statistically significant differences. Ten days after treatment, the application of chlorantraniliprole at 7 and 14 DAG resulted in the lowest mean infestation (12.33 %), followed by applications at 10 and 20 DAG (13.71 %), 10 % incidence (14.04 %) and Davis score 2 (15.54 %). Treatments at 7 DAG (15.88 %), 14 DAG (19.87 %), 5 % incidence (21.15 %), 10 DAG (30.63 %) and 20 DAG (31.26 %) also showed a reduction in FAW infestation. The highest infestation was observed with Davis score 4 (48.28 %), yet all treatments were effective in reducing FAW infestation compared to the control (Fig. 2).

Similarly, LIR values recorded ten days after spraying revealed that the lowest mean injury rating (1.98) occurred in both the 7 and 14 DAG and 10 and 20 DAG treatments. These were followed by applications at 10 % incidence (2.16), Davis score 2 (2.17), 7 DAG (2.32), 5 % incidence (2.37), 10 DAG (2.54), 14 DAG (2.56), 20 DAG (2.59) and Davis score 4 (3.17). The 7 and 14 DAG and 10 and 20 DAG treatments were statistically similar in terms of both percent infestation and LIR (Fig. 3).

At harvest, the lowest ear damage rating was also recorded for the 7 and 14 DAG treatment (2.04), followed closely by 10 and 20 DAG (2.10), 10 % incidence (2.33), Davis score 2 (2.39), 7 DAG (2.84), 20 DAG (2.85), 5 % incidence (3.02), 14 DAG (3.37), Davis score 4 (3.43) and 10 DAG (3.51) (Fig. 3).

In terms of yield performance, the highest grain yield was recorded from the 7 and 14 DAG application (81.30 q ha^{-1}), followed by 10 and 20 DAG (81.11 q ha^{-1}), 10 % incidence (71.30 q ha^{-1}), Davis score 2 (67.41 q ha^{-1}), 7 DAG (66.48 q ha^{-1}), Davis score 4 (66.48 q ha^{-1}), 10 DAG (65.74 q/ha), 5 % incidence (64.26 q/ha), 20 DAG (61.67 q/ha) and 14 DAG (60.37 q/ha). The untreated control yielded the lowest grain output (43.06 q/ha) (Fig. 4). These findings highlight the efficacy of early-stage insecticide application, particularly at V2 and V4 stages, for optimal suppression of FAW and maximizing maize productivity.

Table 1. Efficacy of insecticide spray applications for fall armyworm (*S. frugiperda*) management in maize during *Kharif* seasons of 2020, 2021 and 2022.

	Treatments	LIR		Percent infestation		Ear rating on 1-9 scale	Grain yield (qha^{-1})
		Before spraying	10 days after spraying	Before spraying	10 days after spraying		
T1	At 5 % incidence	3.46(1.99)	2.37(1.69)^{bc}	38.37(6.18)	21.15(4.61)^{bc}	3.02(1.87)^{bc}	64.26(8.05)^{cd}
T2	At 10 % incidence	3.15(1.91)	2.16(1.63)^{ab}	38.22(6.13)	14.04(3.81) ^{ab}	2.33(1.68)^{ab}	71.30(8.47)^{b}
T3	Davis score 2	3.19(1.92)	2.17(1.63)^{ab}	34.29(5.84)	15.54(4.00)^{ab}	2.39(1.70)^{ab}	67.41(8.24)^{bc}
T4	Davis score 4	3.48(1.99)	3.17(1.91)^{d}	50.83(7.16)	48.28(6.98)^{d}	3.43(1.98)^{c}	66.48(8.18)^{bc}
T5	At 7 DAG	2.97(1.86)	2.32(1.68)^{bc}	21.86(4.72)	15.88(4.03 ^{ab}	2.84(1.82)^{bc}	66.48(8.18)^{bc}
T6	At 14 DAG	3.04(1.88)	2.56(1.75)^{c}	48.79(7.01)	19.87(4.49)^{ab}	3.37(1.97)^{c}	60.37(7.80)^{d}
T7	At 7 and 14 DAG	2.84(1.83)	1.98(1.58)^{a}	28.60(5.39)	12.33(3.58)^{a}	2.04(1.59)^{a}	81.30(9.04)^{a}
T8	At 10 DAG	3.09(1.89)	2.54(1.74)^{c}	35.70(5.97)	30.63(5.55)^{c}	3.51(2.00)^{c}	65.74(8.14)^{bcd}
T9	At 20 DAG	3.20(1.92)	2.59(1.76)^{c}	43.07(6.52)	31.26(5.55)^{c}	2.85(1.83)^{bc}	61.67(7.88)^{cd}
T10	At 10 and 20 DAG	3.26(1.94)	1.98(1.57)^{a}	33.40(5.68)	13.71(3.76) ^{ab}	2.10(1.61)^{a}	81.11(9.03)^{a}
T11	Untreated control	3.56(2.01)	3.34(1.96)^{d}	52.10(6.52)	48.95(7.03)^{d}	5.02(2.35)^{d}	43.06(6.60)^{e}
	Mean	3.20	2.47	38.65	24.69	2.99	66.29
	CD 5 %	NS	0.08	NS	0.95	0.20	0.37
	CV %	-	2.27	-	9.35	5.19	2.20

LIR: Leaf injury rating, **DAG**: Days after germination, **CD**: Critical difference at 5 % level of significance and **CV**: Coefficient of variance. Figures in parentheses are square root transformed values. Numbers followed by the same letter in each column are not significantly different.

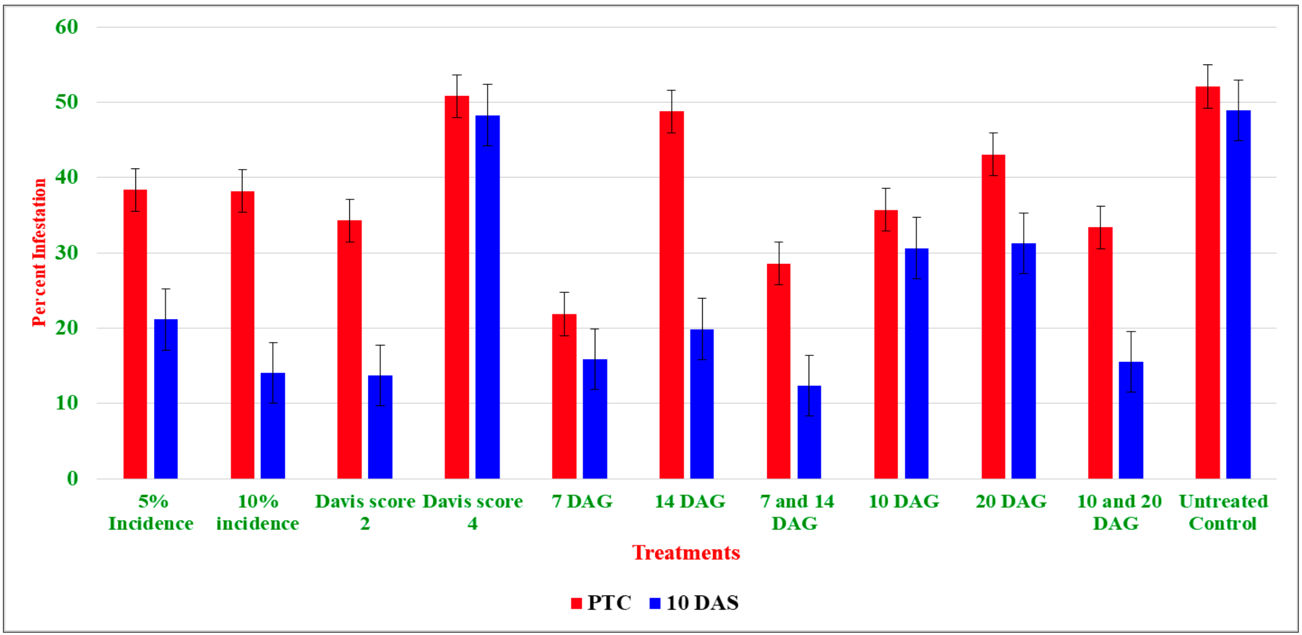

Fig. 2. Pooled assessment of insecticidal sprays on percent infestation of fall armyworm (*S. frugiperda*) in maize during 2020-2022. **PTC**: Pre-treatment count; **DAS**: Days after spraying; **DAG**: Days after germination.

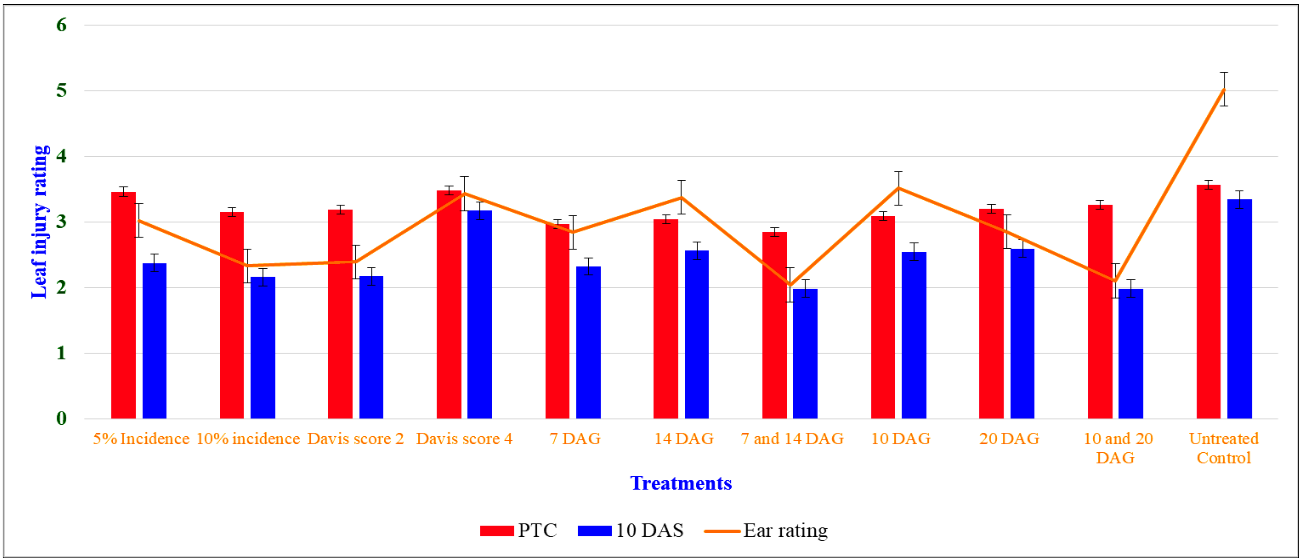

Fig. 3. Pooled analysis of insecticidal spray efficacy on leaf injury rating (**LIR**) due to fall armyworm (*S. frugiperda*) in maize (2020-2022). **PTC**: Pre-treatment count; **DAS**: Days after spraying; **DAG**: Days after germination.

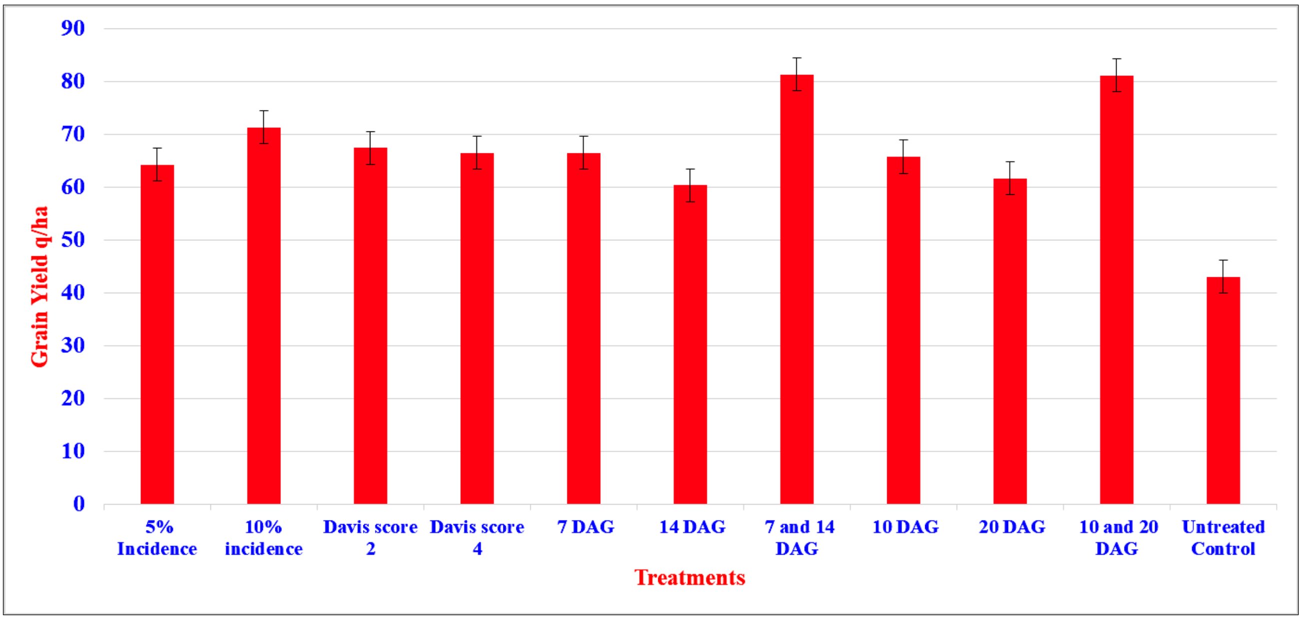

Fig. 4. Mean grain yield of maize under insecticide applications at different growth stages (2020–2022). DAG: Days after germination.

Discussion

The current study highlights the critical role of precise timing and frequency of insecticide application in effectively managing *S. frugiperda* in maize cultivation under Indian agro-climatic conditions. The data revealed that a strategic two-round application of chlorantraniliprole 18.5 % SC-once during the early whorl stage (VE-V5) and again at the onset of the late whorl stage (V6-V12) was sufficient to suppress larval infestation, reduce foliar and ear damage and optimize grain yield. This approach aligns with earlier reports highlighting the vulnerability of maize to FAW during whorl stages, which are known to be the most economically damaging growth phases (28, 29).

Our findings emphasize that insecticide application beyond the VT stage offer diminishing returns regarding larval suppression and damage mitigation. This can be attributed to physiological changes in maize foliage post-tasselling, such as increased toughness and reduced nitrogen content, which impair the establishment and survival of neonates (30, 31). As a result, the attractiveness and suitability of older maize plants for oviposition and early larval development decline significantly.

Furthermore, while all tested insecticides, including synthetic and biopesticidal formulations, reduced larval feeding damage, synthetic products like Emastar 112 EC exhibited superior efficacy in limiting foliar injury and protecting grain yield. These results corroborate previous findings in which synthetic insecticides consistently outperformed neem-based and botanical products (25, 32). However, the relatively slower action of biopesticides and products like Eradicoat contributed to marginally higher damage levels, particularly in untreated or inadequately treated plots (33). Interestingly, although additional insecticide applications between VT and R3 stages were associated with reduced cob damage, the benefits in terms of yield gains were not markedly significant. This suggests that targeting vegetative stage feeding is more critical for preserving yield potential, consistent with the observations noted that feeding damage at early vegetative stages could lead to yield losses ranging from 15 % to 73 % (11, 34).

From an economic standpoint, the study demonstrates that two well-timed insecticide sprays are sufficient to ensure a substantial yield advantage (1.5-fold or greater) over untreated controls (35). This is particularly relevant for resource-constrained farming communities, as excessive or mis-timed pesticide applications can lead to increased production costs. Additionally, such practices pose ecological risks by disrupting beneficial arthropod populations and causing environmental contamination. Furthermore, a single application of potent synthetic insecticides like Emastar 112 EC during the VE–V5 stage delivered satisfactory protection and profitability, offering a cost-effective alternative for smallholder farmers. In contrast, biopesticides, despite requiring multiple applications due to their slow mode of action, remain an environmentally safer option and hold promise for sustainable pest management when integrated into broader IPM frameworks (36).

Finally, the study underscores the importance of aligning pest control strategies with pest biology and crop phenology to achieve maximum efficacy and profitability. Over-reliance on repeated insecticide applications is economically unsustainable and ecologically detrimental and the evidence supports a shift toward judicious, stage-specific applications tailored to the FAW lifecycle.

Conclusion

The findings of this study confirm that chlorantraniliprole 18.5 % w/w SC is highly effective in managing *S. frugiperda* infestations in maize, particularly when applied strategically at the early (VE-V5) and late whorl (V6-VT) stages. These stages represent the most critical periods for intervention, as infestations beyond the VT stage have negligible impact on yield and do not warrant further insecticide application. Farmers adopting newer chemistries such as chlorantraniliprole require only two well-timed sprays to achieve effective pest suppression and optimal grain yield. In contrast, those using biopesticides or conventional insecticides may require additional applications to achieve similar levels of protection and profitability. Implementing this targeted approach not only enhances pest control efficiency but also minimizes insecticide usage, thereby reducing production costs, environmental contamination and risks to human health. These results provide a practical, sustainable framework for integrated FAW management in maize cultivation in tropical agroecosystems.

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Authors' contributions

VSK was responsible for experimentation and data curation, as well as writing the original draft and contributing to review and editing. US contributed to the original draft and participated in review and editing. MB, NKMV, RM, SD and BD were involved in the review and editing of the manuscript. RBA contributed to review and editing, while SPL was involved in methodology development and also participated in review and editing. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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