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ORIGINAL RESEARCH ARTICLE

Assessment of newer molecules for the management of fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) on maize in India

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Abstract

A field experiment was conducted to manage the maize fall armyworm (FAW), *Spodoptera frugiperda* J. E. Smith (Lepidoptera: Noctuidae) at Maize Research Centre, Agricultural Research Institute, Rajendranagar, Hyderabad during *kharif*, 2020 and *kharif*, 2021. Seven newer insecticide molecules were tested for their efficacy viz., Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC @ 0.5 ml L^{-1}, Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC @ 2 ml L^{-1}, Emamectin benzoate 5% SG @ 0.4 g L^{-1}, Spinetoram 11.7% w/w SC @ 0.5 ml L^{-1}, Chlorantraniliprole 18.5% SC @ 0.4 ml L^{-1}, Flubendiamide 480 FS @ 0.3 ml L^{-1}, Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS @ 6 ml/kg seed and a untreated check served as the control. The treatments were laid out in Complete Randomized Block Design and replicated thrice. The mean per cent infestation was less in the plots treated with Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC @ 0.5 ml L^{-1} (3.71) followed by Chlorantraniliprole 18.5% SC@ 0.4 ml L^{-1} (3.78), Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC @ 2 ml L^{-1} (4.46), Spinetoram 11.7% w/w SC @ 0.5 ml L^{-1} (4.57) and Emamectin benzoate 5% SG @ 0.4 g L^{-1} (4.62) and all the treatments were found to be statistically on par with each other. The lowest mean Leaf Injury Rating (LIR) was recorded in the treatment of Chlorantraniliprole 18.5% SC @ 0.4 ml L^{-1} (1.52) followed by Spinetoram 11.7% w/w SC @0.5 ml L^{-1} (1.52), Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC @ 0.5 ml L^{-1} (1.63). At harvest, ear damage rating was significantly low with Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC @ 0.5 ml L^{-1} (1.23) followed by Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC @ 2 ml L^{-1} (1.27), Flubendiamide 480 FS @ 0.3 ml L^{-1} (1.31), Chlorantraniliprole 18.5% SC @ 0.4 ml L^{-1} (1.40) and Spinetoram 11.7% w/w SC @ 0.5 ml L^{-1} (1.40). The grain yield was highest in Chlorantraniliprole 18.5% SC @ 0.4 ml L^{-1} with 90.19 qha^{-1} followed by Spinetoram 11.7% w/w SC @ 0.5 ml L^{-1} 88.33 qha^{-1}.

Keywords Fall army worm *(Spodoptera frugiperda)* · Novel molecules · Management

Introduction

The fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) is an invasive pest in India. It is a pest originating from the Americas and found in several other countries including Mexico, Brazil, Argentina, and the USA (Prowell et al. 2004). It causes severe economic losses in maize and other important crops like sorghum, soybean, cotton (Pogue 2002). It is also reported to cause damage in rice, grasses, and a number of weed species (Nabity et al. 2011). It is a migratory and polyphagous pest and its host preference extends to more than 350 plants comprising of different families in the Americas (Montezano et al. 2018).

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Among the listed host plants, maize and jowar are most preferred by *S. frugiperda* (Dileep Kumar et al. 2020).

Several African countries like Nigeria, Benin, and Togo were reported Fall armyworm severe incidence in 2016 (Goergen et al. 2016). In Indian subcontinent, fall army worm was first reported in 2018 near Shivamogga, Karnataka by the University of Agricultural and Horticultural Sciences, Shivamogga (Suby et al. 2020). Since then, it has spread all over the country and moved in all directions, eastwards to countries like viz. Bangladesh (December 2018), Myanmar (December 2018), Sri Lanka (January 2019), China (January 2019), Nepal, Thailand (December 2018), South Korea and Japan (July 2019). Temporal spread of fall armyworm (FAW) within India has been documented since its first report from Karnataka in May 2018. FAW spread from peninsular India to the North and Northeast during 2018 and early 2019 respectively (Suby et al. 2020). Maize is third most important staple crop in India, It is being cultivated in an area of 9.8 million ha with a production of 31.65 million tons per year and with a productivity of 3199 kg ha^{-1} (www.indiastat.com). Among the major maize producing states of India, Telangana plays a major role with an area of 0.25 million ha with a production of 1.76 million tons per year and with a productivity of 6782 kg ha^{-1} (www.indiastat.com). FAW causes 21 to 53% yield losses in maize production (Prasanna et al. 2018). Severe FAW infestation coupled with abiotic or biotic stresses causes yield loss of 80% or complete crop failures in maize and sweet corn production (Stokstad 2017; Overton et al. 2021).

Currently, the Central Insecticide Board and Registration Committee recommends the application of Chlorantraniliprole 18.5% SC, Thiamethoxam 12.6% + Lambdacyhalothrin 9.5% ZC, and Spinetoram 11.7% SC (DPPQS, 2019) to combat the menace of fall armyworm. In 2018 when fall armyworm was introduced, farmers resorted to the use of two to three sprays of different insecticides without having adequate knowledge of their efficacy and mode of action. The larvae of FAW cause severe damage to the plant by consuming foliage. Young larvae mainly feeds on epidermal leaf tissue creating holes in the leaves; and feeding on young plants through the whorl causes dead hearts. Mainly farmers complained that the currently available synthetic insecticides are not effective against FAW. Hence, they are using high doses with frequent applications of the same insecticides, which will lead to the accumulation of pesticides in the environment and speed up resistance development. In the light of facts several newer insecticide molecules have been developed in recent years with different modes of action to control the lepidopteran pests. In India, fall armyworms are yet to be exposed to these new molecules that include diamides, avermectins, spinosyns, and IGR's like benzyl ureas.With this background, the present study was conducted to evaluate newer insecticides and their efficacy against fall armyworm under field conditions in two consecutive years in two seasons (*Kharif*, 2020 and *Kharif*, 2021) to find the most effective insecticides for its management.

Materials and methods

A field experiment was conducted at Maize Research Centre, Agricultural Research Institute, Rajendranagar, Hyderabad, situated at 17^{0}31'N latitude and 78^{0}39'E longitude. Seven insecticides as treatments and one control without any insecticidal treatment were replicated thrice. The popular maize hybrid DHM 117 was chosen for the study based on the farmers preference in many states of India like Telangana, Andhra Pradesh, Bihar, Rajasthan, Madhya Pradesh, Maharashtra and West Bengal. The sowings in the field were done on 15th July 2020 and 21st June 2021 respectively, during the typical normal monsoon season for maize cultivation.

Seeds were sown at a spacing of 60 cm × 20 cm, row to row and plant to plant in a plot size of 50 Sq.m (10 × 5 m^2) for each treatment which were 1.5 m apart (Fig. 1). All necessary agronomic practices, including cultural practices, fertilizers (Diammonium Phosphate, Urea and Murate of Potash) were applied by pocketing. DAP applied @125 kg ha^{-1} at the time sowing, Urea@375 kg ha^{-1} applied in three equal split doses. First dose at the time sowing (125 kg), second dose (125 kg) at 30–35 DAS (after inter cultivation), final dose (125 kg) at 60-65DAS (flowering). Murate of potash was applied @100 kg ha^{-1} in two split doses. First dose at the time of sowing (62.5 kg) and second dose applied at 60–65 DAS (37.5 kg) at flowering), irrigation and weed management were followed to ensure healthy crop. The treatments were imposed twice *i.e., Kharif*, 2020 and *Kharif*, 2021 respectively, in the consecutive years. The first spray was applied 28 days after sowing as a foliar application except for control. The second insecticidal spray was conducted 10 days after the first spray. Insecticide spray applications were carried out during the calm, warm, sunny periods of the day using a knapsack sprayer with a hollow cone nozzle and a spray volume of 500 L per ha. The insecticidal application was directed only to the whorl. A Standard Scale followed by CIMMYT and IIMR (Davis and Williams 1992; Prasanna et al. 2018), was used to record the percentage of infestation, foliar damage and ear damage. The observations were recorded on 20 plants from each treatment unit, excluding the plants in the border rows. Treatment-wise, marketable grain yield was recorded and expressed in quintals (q) per ha. The data collected was subjected to statistical analysis as Complete Randomized Block Design. Before analysis, observations of the per cent infestation, foliar damage and ear damage were square root transformed; after the analysis,

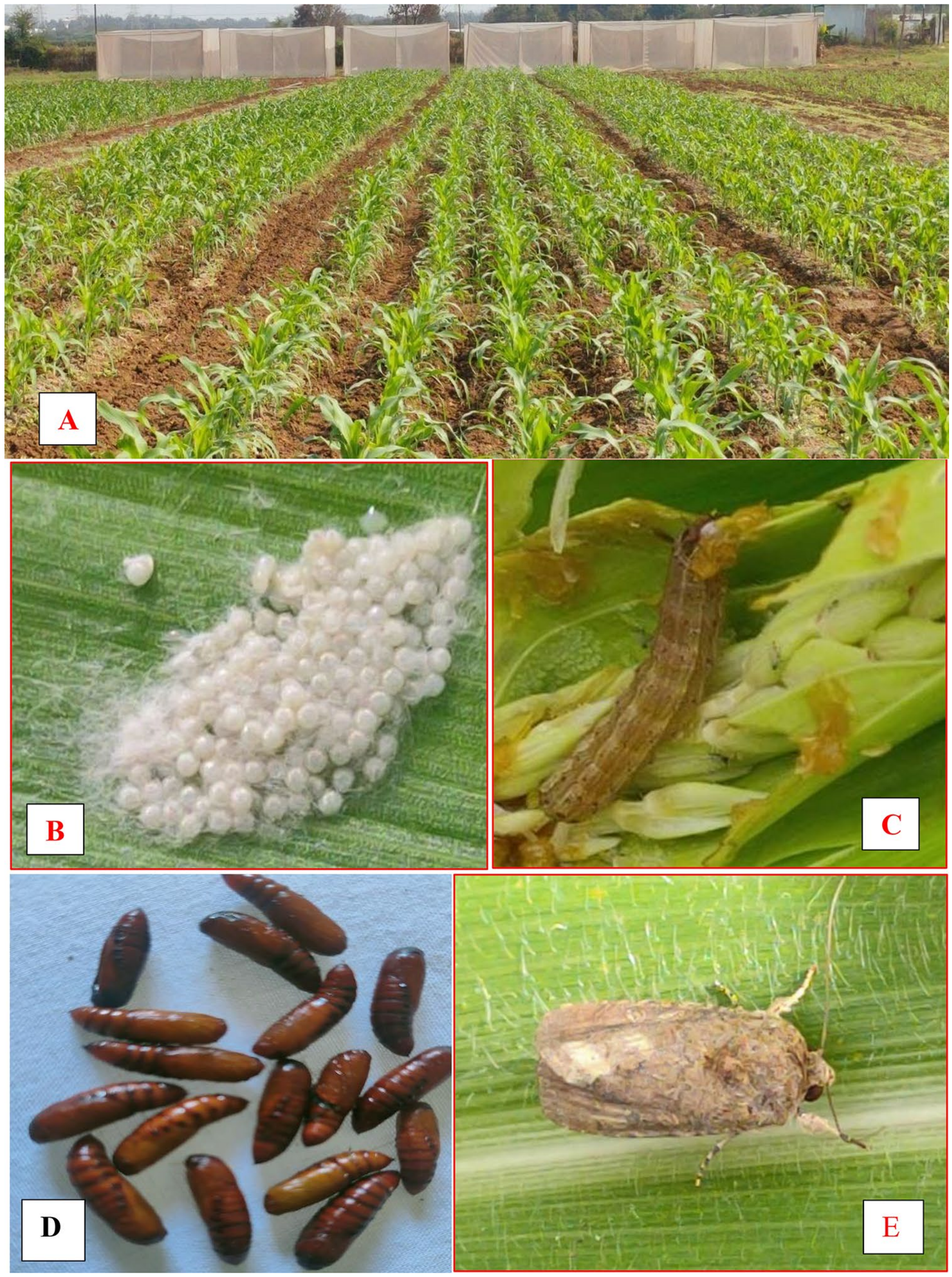

Fig. 1 Experimental field and life stages. (**A**. Experimental field view **B**. Egg mass, **C**. Larva, **D**. Pupae, **E**. Adult of the Fall Armyworm)

the original units were reconverted. The mean percentage infestation, foliar damage, ear damage and yield were analysed using Duncan's Multiple Range test DMRT ($P \leq 0.05$).

Scale for screening of maize genotypes based on foliar damage

Score	Damage symptoms/ Description	Response
1	No visible leaf feeding damage	Highly resistant
2	Few pinholes on 1–2 older leaves	Resistant
3	Several shot-hole injuries on a few leaves	Resistant
4	Several shot-hole injuries on several leaves (6–8 leaves) or small lesions/ pinholes, small circular lesions, and a few small elongated (rectangular-shaped) lesions of up to 1.3 cm in length present on whorl and furl leaves	Moderately Resistant

Score	Damage symptoms/ Description	Response
5	Elongated lesions (> 2.5 cm long) on 8–10 leaves, plus a few small- to midsized uniform to irregular-shaped holes (basement membrane consumed) eaten from the whorl and/or furl leaves	Moderately Resistant
6	Several large elongated lesions present on several whorl and furl leaves and/ or several largeuniform to irregular-shaped holes eaten from furl and whorl leaves	Susceptible
7	Many elongated lesions of all sizes present on several whorl and furl leaves plus several large uniform to irregular-shaped holes eaten from the whorl and furl leaves	Susceptible
8	Many elongated lesions of all sizes present on most whorl and furl leaves plus many mid- to large-sized uniform to irregular-shaped holes eaten from the whorl and furl leaves	Highly Susceptible
9	Whorl and furl leaves almost totally destroyed and plant dying as a result of extensive foliar damage	Highly Susceptible

Source: Davis and Williams (1992), Prasanna et al. (2018)

Scale for ear damage caused by FAW where FAW is already present on plants

Score	Damage symptoms/ Description	Response
1	No damage to the ear	Resistant
2	Damage to a few kernels (< 5) or less than 5% damage to an ear	Resistant
3	Damage to a few kernels (6–15) or less than 10% damage to an ear	Resistant
4	Damage to 16–30 kernels or less than 15% damage to an ear	Moderately Resistant
5	Damage to 31–50 kernels or less than 25% damage to an ear	Moderately Resistant
6	Damage to 51–75 kernels or more than 35% but less than 50% damage to an ear	Susceptible
7	Damage to 76–100 kernels or more than 50% but less than 60% damage to an ear	Susceptible
8	Damage to > 100 kernels or more than 60% but less than 100% damage to an ear	Highly Susceptible
9	Almost 100% damage to an ear	Highly Susceptible

Source: Davis and Williams (1992), Prasanna et al. (2018)

Results

Kharif, 2020

All the insecticides were found to be effective compared to the control with respect to mean percentage infestation and leaf injury rating (LIR) at 10 days after treatment in the first and second insecticidal applications (Table 1). One day before treatment the mean per cent infestation ranged from 45.03 to 55.17 in the different treatments and the leaf injury rating ranged from 2.97 to 3.43. There was no significant difference among the treatments except seed treatment with Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS@ 6 ml per kg seed. Seed treatment with Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS @ 6 ml per kg seed was found to be effective up to 28 days after sowing (DAS).

Ten days after the first spray, mean per cent infestation was significantly least with Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS (14.97) followed by Emamectin benzoate 5% SG (23.43), Flubendiamide 480 FS (26.73), Chlorantraniliprole 18.5% SC (27.43), Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC (29.93), Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (30.53), Spinetoram 11.7% w/w SC (32.47). At ten days after the second spray, a significantly lower mean per cent infestation was recorded across all the insecticide treatments in comparison to the control ($P \leq 0.05$). The lowest mean percentage of infestation was recorded in Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (3.83) < Chlorantraniliprole 18.5% SC (4.10) < Novaluron + Emamectin benzoate (4.30) < Emamectin benzoate 5% SG (5.60) < Spinetoram 11.7% w/w SC (5.70).

Ten days after the first spray, significantly least mean LIR was recorded with Flubendiamide 480 FS (2.00) < Chlorantraniliprole 9.3% + Lambdacyhalothrin4.6% ZC

Table 1 Efficacy of newer molecules for the management of Fall Armyworm in Maize during *Kharif*-2020

T.No	Insecticide	Dose	Per cent infestation			Leaf Injury Rating on 1–9 scale			Ear damage rating on 1–9 scale	Grain yield (qha^{-1})
			PTC	10 DAS	10 DASS	PTC	10 DAS	10 DASS		
T1	Chlorantraniliprole 9.3% + Lambda-cyhalothrin 4.6% ZC	0.5 ml/l	53.57 $(7.35)^{b}$	30.53 $(5.55)^{bc}$	3.83 $(2.08)^{a}$	3.00 $(1.87)^{b}$	2.00 $(1.58)^{a}$	1.63 $(1.46)^{abc}$	1.22 $(1.31)^{a}$	84.44 $(9.22)^{b}$
T2	Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC	2 ml/l	55.17 $(7.46)^{b}$	29.93 $(5.51)^{bc}$	4.30 $(2.19)^{a}$	2.97 $(1.85)^{b}$	2.10 $(1.61)^{a}$	2.00 $(1.58)^{cd}$	1.23 $(1.31)^{a}$	82.22 $(9.09)^{b}$
T3	Emamectin benzoate 5% SG	0.4 g/l	45.03 $(6.71)^{b}$	23.43 $(4.87)^{b}$	5.60 (2.47)ab	3.30 $(1.95)^{b}$	2.37 $(1.69)^{a}$	2.10 $(1.61)^{d}$	1.77 $(1.50)^{d}$	81.48 $(9.05)^{b}$
T4	Spinetoram 11.7% w/w SC	0.5 ml/l	49.63 $(7.07)^{b}$	32.47 $(5.74)^{c}$	5.70 $(2.47)^{ab}$	3.43 $(1.98)^{b}$	2.17 $(1.63)^{a}$	1.60 $(1.45)^{ab}$	1.57 $(1.44)^{cd}$	86.30 $(9.32)^{ab}$
T5	Chlorantraniliprole 18.5% SC	0.4 ml/l	46.97 $(6.87)^{b}$	27.43 $(5.24)^{bc}$	4.10 (2.14)a	3.10 $(1.89)^{b}$	2.07 $(1.60)^{a}$	1.43 $(1.39)^{a}$	1.23 $(1.32)^{ab}$	91.48 $(9.59)^{a}$
T6	Flubendiamide480 FS	0.3 ml/l	48.27 $(6.96)^{b}$	26.73 $(5.20)^{bc}$	8.13 $(2.93)^{b}$	3.00 $(1.86)^{b}$	2.00 $(1.58)^{a}$	1.90 $(1.55)^{bcd}$	1.31 $(1.35)^{abc}$	81.48 $(9.05)^{b}$
T7	Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS	6 ml /kg seed	0.00 $(0.71)^{a}$	14.97 $(3.93)^{a}$	26.83 $(5.20)^{c}$	0.00 $(0.71)^{a}$	2.30 $(1.67)^{a}$	4.10 $(2.14)^{e}$	1.50 $(1.41)^{bcd}$	47.41 $(6.92)^{c}$
T8	Untreated Control	Water Spray	51.07 $(7.18)^{b}$	60.43 $(7.80)^{d}$	65.57 $(8.13)^{d}$	3.07 $(1.89)^{b}$	4.23 $(2.18)^{b}$	5.80 $(2.51)^{f}$	2.30 $(1.67)^{e}$	37.78 $(6.18)^{d}$
	Mean		**43.71**	**30.74**	**15.51**	**2.73**	**2.40**	**2.57**	**1.52**	**74.07**
	SED		**0.40**	**0.36**	**0.28**	**0.11**	**0.07**	**0.06**	**0.04**	**0.15**
	CD 5%		**0.85**	**0.77**	**0.60**	**0.24**	**0.15**	**0.12**	**0.09**	**0.33**
	CV%		**6.30**	**6.59**	**8.05**	**6.36**	**4.00**	**3.24**	**3.06**	**1.79**

Values in parenthesis are square root transformed values

Numbers followed by same letter in each column are not significantly different

DAS Days after Spraying, *DASS* Days after Second Spray

(2.00) < Chlorantraniliprole18.5% SC (2.07) < Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC (2.10) < Spinetoram 11.7% w/w SC (2.17) < Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS (2.30) < Emamectin benzoate 5% SG (2.37). while, statistically all the treatments were on par with each other.

Ten days after the second spray, a significantly low mean leaf injury rating was recorded with all the insecticide treatments in comparison with the control ($P \leq 0.05$). The lowest mean LIR was recorded in Chlorantraniliprole 18.5% SC (1.43) < Spinetoram 11.7% w/w SC (1.60) < Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (1.63) < Flubendiamide 480 FS (1.90) < Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC (2.00) < Emamectin benzoate 5% SG (2.10).

At harvest, the lowest ear damage rating was recorded with Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (1.22) < Chlorantraniliprole 18.5% SC (1.23) < Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC (1.23) < Flubendiamide 480 FS (1.31) < Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS (1.50) < Spinetoram 11.7% w/w SC (1.57) < Emamectin benzoate 5% SG (1.77). All these chemicals were found to be effective over control.

Chlorantraniliprole 18.5% SC recorded the highest grain yield with 91.48 q ha^{-1} followed by Spinetoram 11.7% w/w SC (86.30 q ha^{-1}), Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (84.44 q ha^{-1}), Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC (82.22 q ha^{-1}), Emamectin benzoate 5% SG (81.48 q ha^{-1}). Flubendiamide 480 FS (81.48 q ha^{-1}). The control recorded the lowest grain yield 37.78 q ha^{-1}, while seed treatment recorded 47.41 q ha^{-1}, showing superior over the control (Fig. 2).

Kharif 2021

During *Kharif* 2021, all the insecticides were also found to be effective with respect to mean per cent infestation and LIR at 10 days after treatment in the first and second insecticidal applications (Table 2). The first spray was done 28 days after sowing and one day before, the pre-treatment count of mean per cent infestation was ranged from 47.24 to 56.81 per cent in different treatments. Similarly, the LIR ranged from 3.00 to 3.43 among the treatments. There was no significant difference among the treatments except seed treatment with Cyantraniliprole 600 FS @ 2.4 ml per kg seed, which was found to be effective at 28DAS.

Ten days after the first spray, the least mean per cent infestation was recorded with Spinetoram 11.7% w/w SC (23.16), Chlorantraniliprole 18.5% SC (23.71), Emamectin benzoate 5% SG (23.78) (Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC) (23.99) followed by (Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC) (25.27), Cyantraniliprole 600 FS (27.02) and Flubendiamide 480 FS (28.68). At ten days after the second spray, the lowest mean per cent infestation was recorded with all the insecticide treatments in comparison with the control ($P \leq 0.05$). The lowest mean per cent infestation was recorded in Spinetoram, 11.7% w/w SC (3.43), Chlorantraniliprole 18.5% SC (3.46), (Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC) (3.59), Emamectin benzoate 5% SG(3.63) and were found to be statistically on par with each other. The next best treatments were (Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC) (4.62) and Flubendiamide 480 FS (9.20) were found to be effective over control against fall armyworm.

Ten days after the first spray, the LIR was recorded with Spinetoram 11.7% w/w SC (2.10) < Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (2.10) < Chlorantraniliprole 18.5% SC (2.17) < Emamectin benzoate 5% SG (2.37) < Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC (2.47) < Flubendiamide 480 FS (2.50). At 10 days after the second spray, the lowest mean LIR was recorded with all the insecticide treatments in comparison with the control ($P \leq 0.05$). The lowest mean leaf injury rating was recorded with Spinetoram, 11.7% w/w SC (1.43) < Chlorantraniliprole 18.5% SC (1.60) < Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (1.63) < Flubendiamide 480 FS (1.90) < Emamectin benzoate 5% SG (2.00) < Novaluron

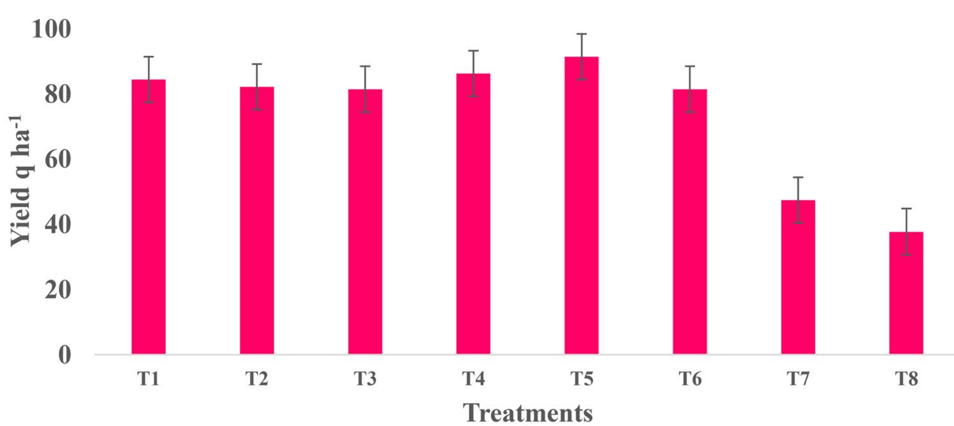

Fig. 2 Grain yield of Maize during *Kharif* 2020. T1: Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC; T2: Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC; T3: Emamectin benzoate 5% SG; T4: Spinetoram 11.7% w/w SC; T5: Chlorantraniliprole 18.5% SC; T6: Flubendiamide480 FS; T7: Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS; T8: Untreated Control

Table 2 Efficacy of newer molecules for the management of Fall Armyworm in Maize during *Kharif*-2021

T.No.	Insecticide	Dose	Per cent infestation			Leaf Injury Rating on 1–9 scale			Ear damage rating on 1–9 scale	Grain yield (q ha^{-1})
			PTC	10 DAS	10 DASS	PTC	10 DAS	10 DASS		
T1	Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC	0.5 ml/l	47.24 (6.91)^{b}	23.99 (4.94)^{a}	3.59 (2.02)^{a}	3.30 (1.95)^{b}	2.10 (1.61)^{a}	1.63 (1.46)^{ab}	1.24 (1.32)^{a}	89.38 (9.48)^{a}
T2	Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC	2 ml/l	51.69 (7.22)^{bc}	25.27 (5.07)^{ab}	4.62 (2.26)^{a}	3.07 (1.88)^{b}	2.47 (1.72)^{a}	2.10 (1.61)^{c}	1.31 (1.35)^{a}	74.32 (8.65)^{b}
T3	Emamectin benzoate 5% SG	0.4 g/l	52.81 (7.28)^{bc}	23.78 (4.92)^{a}	3.63 (2.03)^{a}	3.40 (1.97)^{b}	2.37 (1.69)^{a}	2.00 (1.58)^{bc}	1.77 (1.50)^{b}	77.53 (8.83)^{b}
T4	Spinetoram 11.7% w/w SC	0.5 ml/l	51.75 (7.23)^{bc}	23.16 (4.86)^{a}	3.43 (1.98)^{a}	3.33 (1.96)^{b}	2.10 (1.61)^{a}	1.43 (1.39)^{a}	1.23 (1.32)^{a}	90.37 (9.53)^{a}
T5	Chlorantraniliprole 18.5% SC	0.4 ml/l	56.81 (7.57)^{bc}	23.71 (4.92)^{a}	3.46 (1.99)^{a}	3.43 (1.98)^{b}	2.17 (1.63)^{a}	1.60 (1.45)^{a}	1.57 (1.44)^{b}	88.89 (9.45)^{a}
T6	Flubendiamide480 FS	0.3 ml/l	52.29 (7.27)^{bc}	28.68 (5.40)^{b}	9.20 (3.10)^{b}	3.00 (1.86)^{b}	2.50 (1.73)^{a}	1.90 (1.55)^{bc}	1.31 (1.34)^{a}	63.46 (7.99)^{c}
T7	Cyantraniliprole 600 FS	2.4 ml/kg seed	2.80 (1.80)^{a}	27.02 (5.25)^{ab}	31.43 (5.65)^{c}	1.10 (1.16)^{a}	3.27 (1.94)^{b}	4.10 (2.14)^{d}	2.33 (1.68)^{c}	44.44 (6.70)^{d}
T8	Untreated Control	Water Spray	52.07 (7.23)^{bc}	55.37 (7.47)^{c}	65.57 (8.13)^{d}	3.07 (1.89)^{b}	4.23 (2.18)^{c}	5.80 (2.51)^{e}	2.52 (1.74)^{c}	32.10 (5.69)^{e}
	Mean		45.93	28.87	15.62	2.96	2.65	2.57	1.66	70.06
	SED		**0.28**	**0.19**	**0.14**	**0.21**	**0.07**	**0.06**	**0.04**	**0.25**
	CD 5%		**0.60**	**0.40**	**0.29**	**0.44**	**0.15**	**0.12**	**0.08**	**0.54**
	CV%		**4.28**	**3.47**	**4.05**	**11.29**	**3.98**	**3.24**	**2.69**	**3.06**

Values in parenthesis are square root transformed values

Numbers followed by same letter in each column are not significantly different

DAS Days after Spraying, *DASS* Days after Second Spray

5.25% + Emamectin benzoate 0.9% w/w SC (2.10). Compared to control, all of these were found to be effective for fall armyworm control.

At harvest, the lowest ear damage rating was recorded with Spinetoram 11.7% w/w SC (1.23), Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (1.24) followed by Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC(1.31), Flubendiamide 480 FS (1.31), Chlorantraniliprole 18.5% SC (1.57) and Emamectin benzoate 5% SG (1.77). All these were found to be effective against fall armyworm.

Spinetoram 11.7% w/w SC recorded the highest grain yield with 90.37 q ha^{-1} followed by Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (89.38 q ha^{-1}), Chlorantraniliprole 18.5% SC (88.89 q ha^{-1}), Emamectin benzoate 5% SG (77.53 q ha^{-1}) and Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC (74.32 q ha^{-1}). The control recorded the least grain yield, 32.10 q ha^{-1}, while seed treatment recorded 44.44 q ha^{-1}, indicating seed treatment is superior to control (Fig. 3).

Pooled analysis (*Kharif*-2020 and *Kharif*-2021)

In the pooled analysis, all the insecticides were found to be effective over control with respect to mean per cent infestation and LIR at 10 days after treatment in the first and second spray applications (Table 3). One day before spraying the pre-treatment per cent infestation ranged from 48.92 to 53.43 among the treatments and the LIR ranged from 3.00 to 3.38. Statistically, there were no differences among the treatments except seed treatment with Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS@ 6 ml per kg seed was found to be effective upto 28 DAS.

Ten days after the first spray, the least mean per cent infestation was recorded with Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS (14.97) < Emamectin benzoate 5% SG (23.61) < Chlorantraniliprole 18.5% SC (25.57) < Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (27.26) < Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC (27.60) < Flubendiamide 480 FS (27.71) < Spinetoram 11.7% w/w SC (27.81). At 10 days after the second spray, a low mean per cent infestation was recorded with all the insecticide treatments in comparison with the control ($P \leq 0.05$). The lowest mean per cent infestation was recorded in Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (3.71) < Chlorantraniliprole 18.5% SC (3.78) < Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC (4.46) < Spinetoram 11.7% w/w SC (4.57) < Emamectin benzoate 5% SG (4.62) < Flubendiamide 480 FS (8.67) < Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS (26.83). All these were found to be effective in fall armyworm control (Fig. 4).

Ten days after the first spray, significantly low LIR was recorded with Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (2.05) < Chlorantraniliprole 18.5% SC (2.13) < Spinetoram 11.7% w/w SC (2.13) < Flubendiamide480 FS (2.25) < Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC < (2.27) < Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS (2.30) < Emamectin benzoate 5% SG (2.37). All these insecticides were statistically on par with each other (Fig. 5).

At ten days after the second spray, the lowest mean LIR was recorded in Chlorantraniliprole, 18.5% SC (1.52) < Spinetoram 11.7% w/w SC (1.52) < Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (1.63) < Flubendiamide 480 FS (1.90) < Emamectin benzoate 5% SG (2.05) < (Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC) (2.05). All these were found to be effective in control of fall armyworm.

At harvest lowest ear damage rating was recorded with Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC) (1.23) < Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC) (1.27) < Flubendiamide 480 FS (1.31) < Chlorantraniliprole 18.5% SC (1.40) < Spinetoram 11.7% w/w SC (1.40) < Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS(1.50) < Emamectin benzoate 5% SG (1.77). All these were found to be effective against fall armyworm.

Chlorantraniliprole 18.5% SC recorded the higher grain yield with 90.19 qha^{-1} < Spinetoram 11.7% w/w SC (88.33 qha^{-1}) < Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC (86.91 qha^{-1}) < Emamectin benzoate 5% SG (79.51 qha^{-1}) < Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC (78.27 qha^{-1}) < Flubendiamide 480 FS (72.47 qha^{-1}).

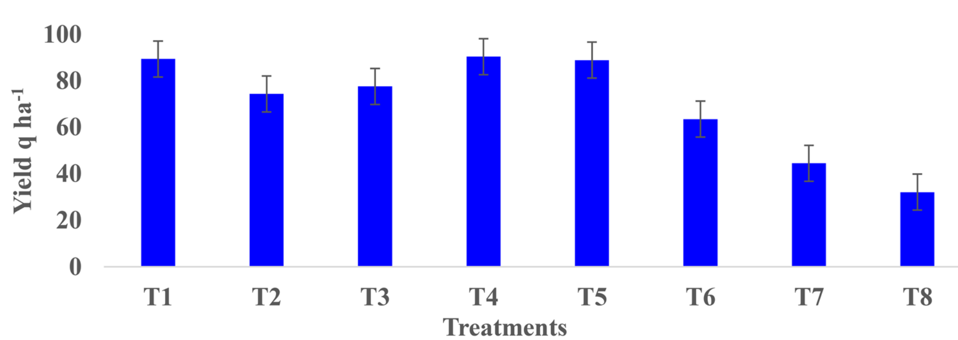

Fig. 3 Grain yield of Maize during *Kharif* 2021. T1: Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC; T2: Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC; T3: Emamectin benzoate 5% SG; T4: Spinetoram 11.7% w/w SC; T5: Chlorantraniliprole 18.5% SC; T6: Flubendiamide 480 FS; T7: Cyantraniliprole 600 FS; T8: Untreated Control

Table 3 Pooled efficacy of newer molecules for the management of Fall Armyworm in Maize (*Kharif*2020 &*Kharif*2021)

T.No.	Insecticide	Dose	Per cent infestation			Leaf Injury Rating on 1–9 scale			Ear damage rating on 1–9 scale	Grain yield (q ha^{-1})
			PTC	10 DAS	10 DASS	PTC	10 DAS	10 DASS		
T1	Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC	0.5 ml/l	50.40 $(7.13)^{b}$	27.26 $(5.27)^{b}$	3.71 $(2.05)^{a}$	3.15 $(1.91)^{b}$	2.05 $(1.60)^{a}$	1.63 $(1.46)^{ab}$	1.23 $(1.31)^{a}$	86.91 $(9.35)^{a}$
T2	Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC	2 ml/l	53.43 $(7.34)^{b}$	27.60 $(5.30)^{b}$	4.46 $(2.22)^{a}$	3.02 $(1.87)^{b}$	2.27 $(1.66)^{a}$	2.05 $(1.60)^{c}$	1.27 $(1.33)^{ab}$	78.27 $(8.87)^{b}$
T3	Emamectin benzoate 5% SG	0.4 g/l	48.92 $(7.00)^{b}$	23.61 $(4.90)^{b}$	4.62 $(2.26)^{a}$	3.35 $(1.96)^{b}$	2.37 $(1.69)^{a}$	2.05 $(1.60)^{c}$	1.77 $(1.50)^{d}$	79.51 $(8.94)^{b}$
T4	Spinetoram 11.7% w/w SC	0.5 ml/l	50.69 $(7.15)^{b}$	27.81 $(5.31)^{b}$	4.57 $(2.25)^{a}$	3.38 $(1.97)^{c}$	2.13 $(1.62)^{a}$	1.52 $(1.42)^{a}$	1.40 $(1.38)^{bc}$	88.33 $(9.42)^{a}$
T5	Chlorantraniliprole 18.5% SC	0.4 ml/l	51.89 $(7.23)^{b}$	25.57 $(5.09)^{b}$	3.78 $(2.07)^{a}$	3.27 $(1.94)^{b}$	2.13 $(1.62)^{a}$	1.52 $(1.42)^{a}$	1.40 $(1.38)^{bc}$	90.19 $(9.52)^{a}$
T6	Flubendiamide480 FS	0.3 ml/l	50.28 $(7.12)^{b}$	27.71 $(5.31)^{b}$	8.67 $(3.02)^{b}$	3.00 $(1.86)^{b}$	2.25 $(1.66)^{a}$	1.90 $(1.55)^{bc}$	1.31 $(1.35)^{abc}$	72.47 $(8.54)^{b}$
T7	Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS	6 ml/kg seed	0.00 $(0.71)^{a}$	14.97 $(3.93)^{a}$	26.83 $(5.20)^{c}$	0.00 $(0.71)^{a}$	2.30 $(1.67)^{a}$	4.10 $(2.14)^{d}$	1.50 $(1.41)^{c}$	47.41 $(6.92)^{c}$
T8	Untreated Control	Water Spray	51.57 $(7.21)^{b}$	57.90 $(7.64)^{c}$	65.57 $(8.13)^{d}$	3.07 $(1.89)^{b}$	4.23 $(2.18)^{b}$	5.80 $(2.51)^{e}$	2.41 $(1.71)^{e}$	34.94 $(5.95)^{d}$
	Mean		44.65	29.05	15.27	2.74	2.47	2.57	1.53	72.25
	SED		**0.28**	**0.19**	**0.25**	**0.10**	**0.06**	**0.05**	**0.03**	**0.14**
	CD 5%		**0.59**	**0.41**	**0.54**	**0.22**	**0.12**	**0.11**	**0.06**	**0.34**
	CV%		**4.35**	**3.58**	**7.37**	**5.89**	**3.32**	**3.00**	**1.99**	**1.90**

Values in parenthesis are square root transformed values

Numbers followed by same letter in each column are not significantly different

DAS Days after Spraying, *DASS* Days after Second Spray

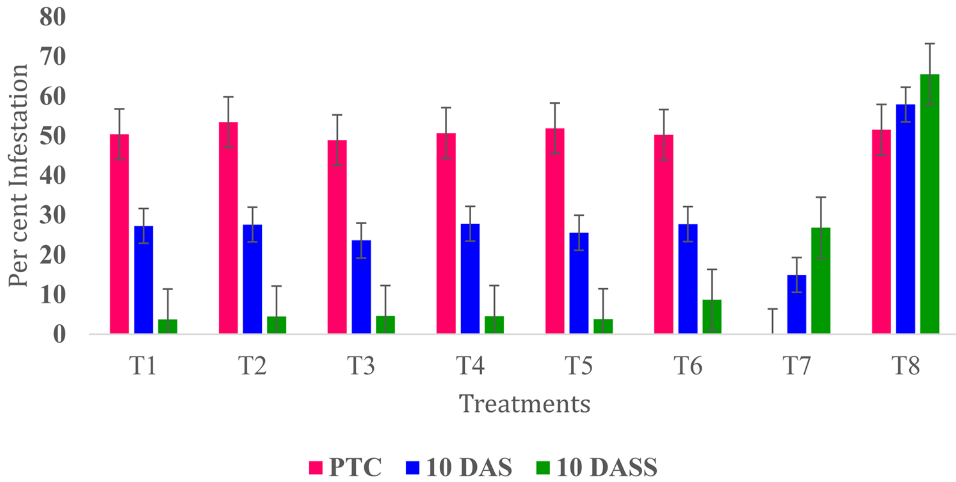

Fig. 4 Pooled evaluation of newer molecules against per cent infestation of Fall Armyworm in Maize (2020–2021). T1: Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC; T2: Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC; T3: Emamectin benzoate 5% SG; T4: Spinetoram 11.7% w/w SC; T5: Chlorantraniliprole 18.5% SC; T6: Flubendiamide480 FS; T7: Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS; T8: Untreated Control; PTC: Pre Treatment Count; 10 DAS: 10 days after Spraying; 10 DASS: 10 Days after second Spraying

The control recorded the lowest grain yield of 34.94 qha^{-1}, while seed treatment recorded 47.41 qha^{-1} (Fig. 6).

Discussion

Insecticides selected in the present study belong to different groups with different modes of action. Chlorantraniliprole, Cyantraniliprole and Flubendiamide belong to the diamide group targeting the unregulated release of internal calcium ions, which results in calcium depletion and muscle paralysis resulting in insect death. Spinetoram belongs to the spinosyns group attacking GABA and N Acetylcholine receptors, resulting in neurotoxicity. The combination product Chlorantraniliprole + lambdacyhalothrin results in complementary modes of action delivering rapid knockdown can inhibit conduction in insect nerve axons and is therefore toxic to insects; Emamectin benzoate is an Avermectin which inhibits muscle contraction, causing a continuous flow of chlorine ions in the GABA and H-Glutamate receptor sites; Novaluron is a chemical belonging to the class of insect growth regulators (IGR). IGRs slowly kill the insects over a few days by

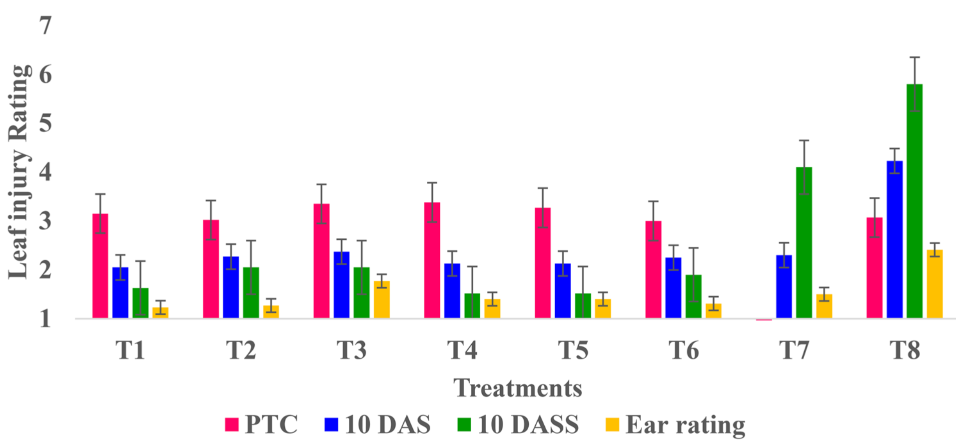

Fig. 5 Pooled evaluation of newer molecules against LIR of Fall Armyworm in Maize (2020–2021). T1: Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC; T2: Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC; T3: Emamectin benzoate 5% SG; T4: Spinetoram 11.7% w/w SC; T5: Chlorantraniliprole 18.5% SC; T6: Flubendiamide480 FS; T7: Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS; T8: Untreated Control; PTC: Pre Treatment Count; 10 DAS: 10 Days After Spraying; 10 DASS: 10 Days After Second Spraying

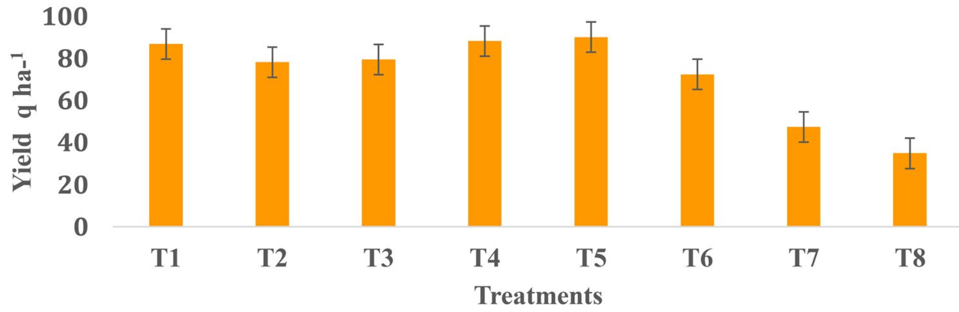

Fig. 6 Mean grain yield of Maize during 2020 and 2021. T1: Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC; T2: Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC; T3: Emamectin benzoate 5% SG; T4: Spinetoram 11.7% w/w SC; T5: Chlorantraniliprole 18.5% SC; T6: Flubendiamide480 FS; T7: Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS; T8: Untreated Control

disrupting the normal growth and development of immature insects (https://www.irac-online.org/mode-of-action/).

In the present study, the newer molecules used for the management of FAW were quite effective with respect to mean per cent infestation and LIR at ten days after treatment in the first and second spray applications. Seed treatment chemicals like Cyantraniliprole 19.8% + Thiamethoxam 19.8% w/w FS and Cyantraniliprole 600 FS were found effective up to 28 DAS indicating their novel mode of action, activation of insect ryanodine receptors resulting in depletion of intracellular calcium stores followed by muscle paralysis and death. Seed dressing chemicals are quick in action as they are quickly taken up by the roots and move upward in the plant through the xylem. Quick and novel modes of action of these chemicals were responsible for bringing down the FAW infestation in the early stage of the crop. While the same seed treatment chemicals are least effective at 48 DAS because of their low residual toxicity.

Similarly, Emamectin benzoate 5% SG was recorded least per cent infestation ten days after the first spray indicating the highest efficacy by providing residual activity against pests that ingest the substance when feeding. But, at ten days after the second spray, Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC was found to be effective followed by Chlorantraniliprole 18.5% SC, Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC, Spinetoram 11.7% w/w SC and Emamectin benzoate 5% SG indicating all these chemicals more or less act on muscle regulation, central nervous system after contact and the pests are rendered immobile and eventually die.

Chemical insecticides were used heavily to manage FAW (Yu et al. 2003), and in the early 1980's methyl parathion, carbaryl and cypermethrin were the main insecticides to manage FAW in most of the countries in the Americas (Pitre 1986). Studies on the efficacy of chemicals on fall armyworm are very limited in India. The results of the present study are in tune with the earlier studies of Sharanabasappa et al. (2020) who reported that Emamectin benzoate 5 SG, Chlorantraniliprole18.5 SC and Spinetoram 11.7 SC resulted in the highest acute toxicity against *S. frugiperda* in Maize under field as well as laboratory bioassay studies. Similarly, Daves et al. 2009, reported that insecticides viz*.,* Intrepid 2F (Methoxyfenozide, 28.34 g ai per ac), Lannate 2.4LV (Methomyl, 102.05 g ai per ac), Sevin XLR Plus 4F (Carbaryl, 226.79 g ai per ac), and Tracer 4SC (Spinosad, 14.19 g ai per ac) were effective up to 13 days after treatment. However, a similar study conducted by Hardke et al. 2011 in sorghum found that chlorantraniliprole (0.101 kg ai per ha), flubendiamide (0.098 kg ai per ha), and novaluron (0.088 kg ai per ha) provided an effective reduction in infestation (2.5, 5.0, and 2.5%, respectively) up to 7 days after treatment only.

Conclusion

The present study concludes that among the insecticides, Chlorantraniliprole 9.3% + Lambdacyhalothrin 4.6% ZC @ 0.5 ml L^{-1} followed by Chlorantraniliprole 18.5% SC@ 0.4 ml L^{-1}, Novaluron 5.25% + Emamectin benzoate 0.9% w/w SC @ 2 ml L^{-1} Spinetoram 11.7% w/w SC @ 0.5 ml L^{-1}, Emamectin benzoate 5% SG @ 0.4 g L^{-1} are effective in fall armyworm management. FAW larva's peculiar behaviour of burrowing deep in the whorls and causing infestation has significantly constrained its management. Application at a crucial time with whorl-directed spray fluid has given better results in the research. The insecticidal treatments resulted in less per cent infestation, low LIR, less cob damage and higher crop yields during both the monsoon seasons. During consecutive monsoon seasons, two rounds of chemical applications provided enough protection for fall armyworm, resulting in higher yields than the untreated control.

Although these chemicals provide reasonable protection against fall armyworm infestation, they should be used as a last resort in fall armyworm management. Multiple sprays of insecticides may lead to the quick development of resistance, as in other areas (Gutiérrez-Moreno et al. 2019). Hence, an Integrated Pest Management approach is needed for effective fall armyworm management, including cultural practices, pheromones and botanical compounds etc.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42690-024-01279-5.

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Data availability The data sets generated during and/or analysed during the current study are available in the (Mendeley data) repository, (https://doi.org/10.17632/bn8tsh8x6w.1) link: https://data.mendeley.com/datasets/bn8tsh8x6w/draft?a=2e931e77-e18d-4b2a-98c9-163afe78dfd8.

Declarations

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of interest The authors declare that they have no conflict of interest.

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