INTRODUCTION

Maize (*Zea mays* L.), the "Queen of cereals" is a staple crop in India, grown in an area of 8.8 million ha with a production of 22.5 million tons per year (Sharanabasappa *et al.* 2020). The crop is cultivated in an area of 3.55 lakh ha in the state with an annual production of 25.3 lakh tonnes and productivity of 7.1 tonnes/ha (INDIASTAT, 2021). The crop is affected by more than 30 insect pests in field as well as storage (Mathur, 1992) and with the recent introduction of the invasive fall armyworm *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) there is a growing concern among maize growers of the country (Lackisha Navin *et al.*, 2021). It was recorded as a polyphagous invasive pest in Africa during 2016 (Goergen *et al.*, 2016) which expanded to show its presence in Asia, in 2018. The pest was first observed in Shivamogga, Karnataka during May, 2018 and in quick succession in different parts of the country *viz.*, Tamil Nadu, Andhra Pradesh, Telangana, Maharashtra, Madhya Pradesh, Odisha, Bihar, West Bengal, Gujarat, Chhatisgarh and Kerala at alarming levels in farmer's field (IIMR-2020). The fall armyworm is having a wider host range of more than 353 hosts causing widespread threat in the Americas (Montezano *et al.* 2018). Yield losses in maize due to fall armyworm infestation goes up to 32% in the United States (Wiseman and Isenhour, 1993) and 45-60% in Nicaragua (Hruska and Glandstone, 1988).

The infestation by maize starts at a very early stage *viz.*, 14-21 days causing extensive defoliation in maize whorls, besides feeding upon tassels and cobs at later stages of the crop (Lamsal *et al.* 2020). The first three instars cause damage by scrapping, while late instar larval stages tend to reside and feed inside the central whorls or funnel leaves (Tefera *et al.* 2019) causing severe injury to the whorls. The central whorl is often filled with moist frass and excreta, and the developing larvae plug the whorl region with frass and feeds inside in a protective environment leading to control failures occasionally (Nidhi *et al.*, 2019).An attempt was made to evaluate newer molecules with differential mode of action for effectively tackling the invasive pest and to integrate the same in the IPM programmes.

Emamectin benzoate belongs to the avermectin family, derived as a natural fermentation product from the soil microorganism, *Streptomyces avermitilis* (Stavrakaki, 2022). It is a broad-spectrum, macrocyclic lactone insecticide effective against agricultural and forestry pests and possess less toxic effects to predators, parasitoids and honeybees) (Jansson *et al.* 1996). It is a chloride channel activator, stimulates the γ-aminobutyric acid receptor (GABA-R) and glutamate-gated chloride channels (GluCls), resulting in increased membrane chloride ion permeability and disrupts nerve signals in target insect pests (Wu *et al.* 2016). Spinetoram, is a biological product derived from the soil actinomycete, *Saccharopolyspora polyspinosa*. the insecticide affects nicotinic acetyl choline receptors and γamino butyric acid receptors in the post synaptic membranes. It has a broad spectrum insecticidal activity and widely used for the management of lepidopteran pests (Zhang *et al.* 2018). Chlorantraniliprole was the first commercialised diamide belonging to the anthranilic diamide group and has been proved effective against a range of lepidopteran insect pests (Satpathy *et al.* 2020). The insecticide activates ryanodine receptors by stimulating calcium release from muscle cells causing impaired regulation, paralysis and death of the target insect species (William *et al.* 2020). Flubendiamide belongs to the phthalic acid diamide and has been proven effective against a wide range of lepidopterans including *Helicoverpa*, *Spodoptera*, etc. Flubendiamide stimulates calium pump activity leading to a decreased internal calcium concentration (Masaki *et al.* 2006). This results in disruption of muscle function, leading to cessation of feeding paralysis, regurgitation and ultimate death of the insect. Chlorantraniliprole + lambda cyhalothrin has a dual mode of action against lepidopteran pests and is available as a ready mix formulation (Osae *et al.* 2022). Lufenuron belongs to the the class of benxoylurea and acts as chitin synthesis inhibitors to a wide range of insects, leading to abnormal moulting from neonate to adult stages. It is widely used against several army worm species belonging to Lepidoptera (Gelbic *et al.* 2011). The present investigations were carried out to compare the efficacy of novel insecticides against maize fall armyworm.

MATERIAL AND METHODS

An experiment with eight treatments and three replications was taken up in the Department of Millets, Tamil Nadu Agricultural University, Coimbatore during two seasons *viz., kharif,* 2021 and *kharif,* 2022. The maize hybrid, Co(H)M 8 was planted at a recommended spacing of 75 x 20 cm. Plots of 4.5 x 3.0 m size were laid out for imposing different treatments. The insecticidal treatments were imposed, using a battery operated knapsack sprayer using 500 lit spray fluid per hectare preferably during early morning hours when the wind speed was considerably low. Observations on fall armyworm infestation was recorded by randomly sampling 20 plants per plot and the individual plants were scored on 1-9 scale of Davis and Williams (1992). The per cent infestation was worked out based on the number of plants showing fresh whorl infestation

$$\text{Per cent infestation} = \frac{\text{No. of plants showing fresh infestation}}{20} \text{ x } 100$$

Two rounds of spraying were imposed in the trial plots; the first when the Davis score in all the treatments exceeded 4.0 and the second spraying fifteen days later. Observations on per cent infestation and score have been recorded just prior to spraying and at 10 days after each spraying. The 1-9 Davis and Williams Scale (1992) followed for recording scores is furnished in Table 1. Besides recording whorl injury, the cob injury was also recorded at the time of harvest following a similar 1-9 scale of ear and kernel damage rating (Table 2) proposed by Williams *et al.* (2006). At the time of harvest, the individual plot yield was recorded and extrapolated to grain yield per ha. Based on the current price of the insecticides used for the experiment the Benefit: Cost (BC) ratio was also worked out. The data on per cent damage and FAW score were subjected to appropriate transformations and analysed through one way ANOVA.

RESULTS AND DISCUSSION

The pretreatment infestation ranged between 66.7 and 71.7 per cent in different treatments. The pooled mean of two years revealed that after the first round of spraying, the least infestation was recorded in plots treated with chlorantraniliprole 9.3% + Lambda cyhalothrin 4.6% ZC (16.7%) followed by flubendiamide (20.0%) and spinetoram (20.0%) as against 86.7 per cent in control plots (Table 3). The score also reflected a similar trend with chlorantraniliprole 9.3% + lambda cyhalothrin 4.6% ZC registering the least score (1.4) followed by flubendiamide (1.5) and spinetoram (1.5) as against 5.8 in control plots. After second round of spraying too, chlorantraniliprole 9.3% + lambda cyhalothrin 4.6% ZC exhibited the least infestation (10.0%) with a score of 1.4 and was on par with emamectin benzoate (10.0% infestation; 1.2 score). Chlorantraniliprole-lambda-cyhalothrin combination was found more effective than emamectin benzoate in reducing the infestation by the tomato pinworm, *Tuta absoluta* (Fanigliulo, 2012). It should be noted that, the combination product, chlorantraniliprole 9.3% + Lambda cyhalothrin 4.6% ZC was found to be toxic to the egg parasitoid, *Telenomus podisi*, an effective one against the soybean pentatomid, *Euschistus heros* (Fabricius), wherein the insecticide chlorantraniliprole was less toxic to the aforesaid parasitoid (Silva *et al.* 2018). Chlorantraniliprole + Lambda cyhalothrin has been found to significantly reduce the population of fall armyworm at 200-240 ml/ha recommendation (Osae *et al.* 2022). The combination insecticide has also been proved effective against the brinjal fruit and shoot borer, *Leucinodes orbonalis* (Sen *et al.* 2017) under field conditions and the tomato pin worm, *Tuta absoluta* under laboratory conditions (Braham *et al.* 2017). Emamectin benzoate 5% SG, spinetoram 11.7%SC, chlorantraniliprole 18.5%SC and flubendiamide 480%SC registered fall army worm infestation in the range of 10.0 to 15.0 per cent while the scores were also on par with each other (1.2 – 1.4) in all these treatments with the control exhibiting 78.3 per cent infestation and a score of 5.4. The efficacy of chlorantraniliprole, emamectin benzoate, spinetoram and flubendiamide were proved by Deshmukh *et al.* (2020) in both laboratory bioassay and field evaluation studies under Indian conditions. Chlorantraniliprole was one of the insecticides that resulted in more than 40 per cent mortality of larval population at 28 days after treatment in studies conducted by Hardke *et al.* (2011). Mian *et al.* (2022) observed the efficacy of chlorantraniliprole and emamectin benzoate in terms of reduction in larval population which was the reason behind reduced levels of infestation in the aforesaid treatments in trials conducted at Pakistan. Emammectin benzoate 5%SG possess selective efficacy against lepidopteran pests due to its contact action and translaminar activity (Fanigliulo and Sacchetti, 2008). Emamectin benzoate has also been proved effective against *Helicoverpa armigera* in tomato (Fanigliulo and Sacchetti, 2008), diamond back moth infesting cabbage (Zhao *et al.* 2006), cotton boll worm (Ahmad *et al.,* 2019), etc. Out of the seven insecticides evaluated against maize fall armyworm under laboratory conditions, spinetoram exhibited poor performance when compared to broflanilide and abamectin (Idrees *et al.* 2022). With respect to cob infestation, all the treatments except lufenuron exhibited a significant reduction (30.0 – 45.0 %) while lufenuron exhibited a cob infestation of 53.3 per cent as against 61.7 per cent in untreated control. However, the cob infestation score did not exceed 2.7 in all the treatments while the control registered a cob score of 2.8. The maximum yield was recorded in emamectin benzoate 5%SG and flubendiamide 480%SC treated plots (5880 kg/ha and 5855 kg/ha, respectively. This was followed by spinetoram 11.7%SC and chlorantraniliprole 18.5%SC treated plots wherein the yields were 5542 kg/ha and 5658 kg/ha, respectively as against 3989 kg/ha in the untreated control. Vinothkumar et al. (2023) observed that, spinetoram registered significantly higher yields followed by chlorantraniliprole while registering lesser larval population and minimum levels of infestation. The Central Insecticide Board and Registration Committee also recommends the use of chlorantraniliprole 18.5 SC, emamectin benzoate 5%SG, spinetoram 11.7 SC, combination insecticides such as novaluron 5.25 % + emamectin benzoate 0.9 % SC for fall armyworm management (DPPQS, 2023).

The Benfit: Cost ratio (B:C) was worked out based on the yield obtained in different treatments keeping the cost of maize grains @ Rs. 2400/quintal. It was observed that, the maximum BC ratio was realised with emamectin benzoate5%SG (2.31) followed by chlorantraniliprole 18.5%SC (2.16), flubendiamide 480%SC (2.10) and spinetortam 11.7%SC (2.09) in that order while the untreated control registered a BC ratio of 1.55.

CONCLUSION

Evaluation of newer insecticides against fall armyworm revealed that, chlorantraniliprole 9.3% + lambda cyhalothrin 4.6% ZC registered lesser infestation after first round of spraying. Emamectin benzoate 5%SG, Spinetoram 11.7%SC, Chlorantraniliprole 18.5%SC, Flubendiamide 480%SC and Chlorantraniliprole 9.3% + Lambda cyhalothrin 4.6% ZC were on par in their efficacy in reducing the fall armyworm infestation after second round of spraying, though emamectin benzoate and flubendiamide treated plots registered comparatively higher yields. With respect to B:C ratio, emamectin benzoate and chlorantraniliprole 18.5%SC registered comparatively higher BC ratio. Thus, the above insecticides at the recommended doses can be used in maize ecosystems to effectively tackle the fall armyworm menace.

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Ethics statement

No specific permits were required for the described field studies because no human or animal subjects were involved in this research.

Originality and plagiarism

The authors assure that the contents are written by us and were not plagiarised.

Consent for publication

All the authors agreed to publish the content.

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There were no conflict of interest in the publication of this content

Data availability

All the data of this manuscript are included in the MS. No separate external data source is required. If anything is required from the MS, certainly, this will be extended by communicating with the corresponding author through corresponding official mail

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Writing- reviewing &editing – TS, PSS, TE

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Table 1. Whorl leaf feeding rating scale for FAW by Davis *et al.*, (1992)

Rating Scale	1-9 scale description
1	No damage or few pinholes
2	Few short holes (also known as shot holes) on several leaves
3	Shot holes on several leaves
4	Several leaves with shot holes and a few long lesions
5	Several holes with long lesions
6	Several leaves with lesions < 2.5 cm
7	Long lesions common on one half of the leaves
8	Long lesions common on one half to two thirds of leaves
9	Most leaves with long lesions

Table 2. Ear and kernel damage rating scale by Williams *et al.* (2006)

Rating Scale	1-9 scale description
1	No damage to any ears
2	Tip (<30 mm) damage to 1-3 ears
3	Tip damage to 4–6 ears
4	Tip damage to 7 or more ears and damage below ear tips to 1–3 kernels of 1–3 ears
5	Tip damage to 7 or more ears and damage to 1–3 kernels below tips of 4–6 ears
6	Ear tip damage to 7–10 ears and damage to 1–4 kernels below tips of 7–10 ears
7	Ear tip damage to 7–10 ears and 4–6 kernels destroyed on 4–6 ears
8	Ear tip damage to all ears and 4–6 kernels below tips destroyed on 7–8 ears
9	Ear tip damage to all ears and 5 or more kernels destroyed below tips of 9–10 ears

Table 3. Evaluation of newer molecules for the management of maize fall armyworm (Pooled mean of two years viz., *kharif* 2021 &*kharif* 2022)

Treatments	Dose (g or ml/lit)	Pre-treatment count		10 DAS I Spray		10 DAS II Spray		Cob damage		Plot yield (kg/ha)	BC ratio*
		% infestation #	Score $	% infestation #	Score $	% infestation #	Score $	% infestation #	Score $		
Chlorantraniliprole 9.3% + Lambda cyhalothrin 4.6% ZC	0.5	71.7 (57.9)	4.0 (2.1)	16.7a (24.1)	1.4a (1.4)	18.3bc (18.4)	1.4a (1.4)	45.0c (42.1)	2.3bc (1.7)	5563b	2.09
Novaluron 5.25% + Emamectin benzoate 0.9% SC	2.0	68.3 (55.7)	4.1 (2.1)	21.7ab (27.8)	1.7b (1.5)	25.0c (30.0)	2.1b (1.6)	35.0ab (36.3)	2.0ab (1.6)	5289c	2.01
Emamectin benzoate 5% SG	0.4	71.7 (57.9)	3.8 (2.1)	25.0bc (30.0)	1.7b (1.5)	10.0a (18.4)	1.2a (1.3)	40.0bc (39.2)	2.0ab (1.6)	5880a	2.31
Spinetoram 11.7%SC	0.5	68.3 (55.7)	4.2 (2.2)	20.0ab (26.6)	1.5ab (1.4)	11.7ab (20.0)	1.2a (1.3)	35.0ab (36.3)	2.0ab (1.6)	5542b	2.09
Chlorantraniliprole 18.5%SC	0.4	66.7 (54.8)	4.0 (2.1)	31.7c (34.3)	2.0c (1.6)	15.0ab (22.8)	1.3a (1.3)	30.0a (33.2)	1.8a (1.5)	5658b	2.16
Flubendiamide 480%SC	0.3	70.0 (56.8)	3.9 (2.1)	20.0ab (26.6)	1.5ab (1.4)	15.0ab (22.8)	1.4a (1.4)	30.0a (33.2)	1.8a (1.5)	5855a	2.10
Lufenuron	0.6	68.3 (55.7)	4.2 (2.2)	45.0d (42.1)	2.4d (1.7)	45.0d (42.1)	4.4c (2.2)	61.7d (51.8)	2.8c (1.8)	4862d	1.91
Untreated control	–	70.0 (56.8)	4.3 (2.2)	86.7e (68.6)	5.8e (2.5)	78.3e (62.2)	5.4d (2.4)	53.3d (46.9)	2.7c (1.8)	3989e	1.55
SEd		-	-	**2.30**	**0.04**	**3.04**	**0.06**	**2.12**	**0.08**	–	–
CD (p< 0.05)		NS	NS	**4.94**	**0.08**	**6.52**	**0.14**	**4.56**	**0.17**	–	–

#Values in paranthesis are arcsine transformed values

$ Values in paranthesis are square root transformed values

*Cost of maize grains fixed at Rs. 2400/quintal to work out B:C ratio

Values in a column followed by a common letter are not significantly different by LSD (P<0.05)

Fig 1. Population of natural enemies in different treatments (Pooled mean of two years viz., *kharif* 2021 &*kharif* 2022)