Field Efficacy of Insecticides for Management of Invasive Fall Armyworm, Spodoptera frugiperda (J. E. Smith) (Lepidoptera: Noctuidae) on Maize in India

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Field efficacy of insecticides for management of invasive fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) on maize in India

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Abstract

The invasive fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), was reported for the first time causing severe damage on maize in Karnataka, India, during May 2018. Thereafter, the pest has spread to most states of India and then spread to other Asian countries, including Thailand, Sri Lanka, Bangladesh, Myanmar, Vietnam, Laos, and China. Being a new invasive, there is no information on its susceptibility to insecticides. Hence, insecticides having different modes of action were evaluated for control of second instar larvae by the leaf-dip bioassay method, as well as under field conditions both in Jun and Sep. Emamectin benzoate 5 SG showed the highest acute toxicity, followed by chlorantraniliprole18.5 SC, and spinetoram 11.7 SC, whereas toxicities of flubendiamide 480 SC, indoxacarb 14.5 SC, lambda-cyhalothrin5 EC, and novaluron10 EC were at par by the leaf-dip bioassay. The results of field efficacy for 2 planting dates (Jun sown crop, and Sep sown crop 2018) revealed that the effective insecticides were chlorantraniliprole 18.5 SC, followed by emamectin benzoate 5 SG, spinetoram 11.7 SC, flubendiamide 480 SC, indoxacarb 14.5 SC, lambda cyhalothrin 5 EC, and novaluron 10 EC. Higher efficacy also was correlated with higher grain yield in comparison with the control. Chlorantraniliprole, emamectin benzoate, and spinetoram are suitable as one of the components of Integrated Pest Management of fall armyworm in India.

Key Words: larval population; bioassay; efficacy; yield

Resumen

El cogollero, *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae), fue reportado por primera vez causando daños severos en el maíz en Karnataka, India, durante mayo del 2018. Luego, la plaga se ha extendido a la mayoría de los Estados de la India y luego se extendió a otros países asiáticos, incluidos Tailandia, Sri Lanka, Bangladesh, Myanmar, Vietnam, Laos, y China. Al ser un nuevo invasor, no hay información sobre su susceptibilidad a insecticidas. Por lo tanto, los insecticidas que tienen diferentes modos de acción fueron evaluados para el control de las larvas del segundo estadio por el método de bioensayo por inmersión de las hojas, así como en condiciones de campo durante los meses de junio y septiembre. El benzoato de emamectina 5 SG mostró la toxicidad aguda más alta seguida por clorantraniliprol 18.5 SC y spinetoram 11.7 SC, mientras que las toxicidades de flubendiamida 480 SC, indoxacarb 14.5 SC, lambda-cyhalothrin5 EC, y novaluron10 EC estaban a la par por el bioensayo de inmersión foliar. Los resultados de la eficacia de campo para 2 fechas de siembra (cultivo sembrados en los meses de junio y septiembre del 2018) revelaron que los insecticidas efectivos fueron clorantraniliprol 18.5 SC, seguido de benzoato de emamectina 5 SG, spinetoram 11.7 SC, flubendiamida 480 SC, indoxacarb 14.5 SC, lambda cyhalothrin 5 EC y novaluron 10 EC. Se correlacionó una mayor eficacia también con un mayor rendimiento de grano en comparación con el control. El clorantraniliprol, el benzoato de emamectina y el espinetoram son adecuados como un componente para el Manejo Integrado de Plagas del cogollero en la India.

Palabras Claves: población larval; bioensayo eficacia; rendimiento

The fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), native to the Americas, is found in several countries including Mexico, Brazil, Argentina, and the USA (Prowell et al. 2004; Clark et al. 2007). It causes severe economic losses in a variety of crops such as maize, soybean, cotton (Pogue 2002; Nagoshi et al. 2007; Bueno et al. 2010) rice, other grasses, and feeds on a number of weeds (Nabity et al. 2011). Severe incidences of fall armyworm were reported from African countries such as Nigeria, Bénin, and Togo in 2016 (Goergen et al. 2016). The incursion of fall armyworm as an invasive pest into Asia was reported for the first time from India on maize during May 2018 (Sharanabasappa et al. 2018a). Since then, it has spread to different states of India on maize (Mahadevaswamy et al. 2018; Sharanabasappa et al. 2018b). The spread of this pest to other Asian countries, including Thailand, Sri Lanka, Bangladesh, Myanmar, Vietnam, Laos, and China (Guo et al. 2018; Wu et al. 2019; NATESC 2019a, b; CABI 2019) has occurred quickly. Maize is a staple crop in India, grown in an area of 8.8 million ha with a production of 22.5 million tons per yr. Among the major maize producing states, Karnataka stands first with

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an area of 1.22 million ha and a production of 3.31 million tons (Anonymous 2017). The recent invasion of fall armyworm threatens the food security of India. The invasive fall armyworm populations showed genetic similarity to the fall armyworm from South Africa, and the area of origin is consistent with the Western Hemisphere (Nagoshi et al. 2019). Insecticides are used widely as a tool in fall armyworm management both in the Americas (Tomquelski & Martins 2007; Hardke et al. 2011; Gutierrez-Moreno et al. 2019) and in Africa (Prasanna et al. 2018; Sisay et al. 2019). Therefore, it is necessary to determine the field efficacy of insecticides on fall armyworm to integrate with Integrated Pest Management practices. At present, the Central Insecticide Board and Registration Committee recommends the use of chlorantraniliprole 18.5 SC, thiamethoxam 12.6% + lambda cyhalothrin 9.5 % ZC, and spinetoram 11.7 SC (DPPQS 2019) for fall armyworm management. In the yr of fall armyworm introduction, farmers have resorted to 2 to 3 sprays of different insecticides without the knowledge of their efficacy. The fall armyworm larva feeds by remaining most of its life in the whorl of maize, thus reducing its contact with insecticides (FAO 2018). Multiple sprays of insecticides may lead to the quick development of resistance as has occurred in other areas (Gutierrez-Moreno et al. 2019). Dose-mortality response to insecticides is necessary to provide baseline data for future resistance monitoring (Cook et al. 2004). Several newer insecticides have been developed in recent yr having different modes of action for control of lepidopteran pests, to which the fall armyworm in India has yet to be exposed. These include diamides, avermectins, spinosyns, and benzylureas. Monitoring of the resistance is a vital component of insecticide resistance management, which aims to identify the initial resistant individuals as well as cross-resistance, if any, among the population (Brent 1986; Dennehy et al. 1990). The objective of this study is therefore to evaluate selected synthetic insecticides to manage of fall armyworm under both laboratory to generate baseline data and field conditions in 2 planting dates to find the best insecticides for its management.

Materials and Methods

INSECTICIDES

Commercial insecticide formulations used in field efficacy test and bioassays were: (1) lambda-cyhalothrin (Karate 5EC, Syngenta Private India Ltd, Pune, Maharashtra, India); (2) indoxacarb (Kento14.5 SC, Hyderabad Chemical Private Ltd., Hyderabad, Telangana, India); (3) spinetoram (Delegate 11.7 SC, Dow Agro Science Private Ltd., Mumbai, Maharashtra, India); (4) chlorantraniliprole (Coragen 18.5 SC, Dupont Private India Ltd., Gurgaon, Haryana, India); (5) emamectin benzoate (Fitrest 5 SG, Bayer crop Science Private Ltd., Thane, Maharashtra, India); (6) flubendiamide (Fame 480 SC, Bayer Crop Science Private Ltd., Thane, Maharashtra, India), and (7) novaluron (Rimon 10 EC, Indofil Industries Ltd., Mumbai, Maharashtra, India).

LABORATORY BIOASSAYS

Fall armyworm larvae were collected in Jul to Aug 2018 from the unsprayed maize fields of Zonal Agricultural and Horticultural Research Station, Shivamogga, Karnataka, India (13.9740000°N, 75.5753333°E), farmer fields near Muttodu (13.9726667°N, 75.5833333°E), and Kudarekonda village (14.1260000°N, 75.5496667°E). The laboratory culture was maintained at the Department of Entomology, College of Agriculture, Shivamogga, at 23.9 to 29.4 °C, 80% relative humidity, and a 12:12 h (L:D) photoperiod; the first generation population was used for this study. A leaf-dip bioassay method (Tukaram et al. 2014) with small modifications was employed to establish the median lethal concentration (LC_{50} value) for different insecticides. A fresh, uniform sized maize leaf bit (3 cm length × 2 cm width) (hybrid 'Pioneer 3550') from 20-d-old seedlings was immersed in aqueous insecticide solution for 10 s while agitating gently in distilled water for the control. The treated leaf bits were air dried and were transferred individually to plastic vials (5 cm × 5 cm) and secured. Twenty second early instar larvae were released on each leaf bit. Three replications per concentration were performed. The mortality was assessed after 24 h of exposure. Larvae were considered dead if they failed to make a movement on prodding. The mortality data were corrected by the Abbott's formula (Abbott 1925) and subjected to Probit analysis using the statistical program SPSS version 16.0 software (IBM SPSS, Armonk, New York, USA) to obtain the LC_{50}, fiducial limits (95%), slopes, and Chi-square values. Overlapping of the 95% confidence limits was the criterion to judge if there were significant differences among the insecticides used. When the 95% confidence limits for 2 insecticides overlap, they are not significantly different, otherwise they are significantly different. Relative potency ratios to estimate the potency of the active ingredients were calculated as the LC_{50} of the least toxic compound divided by the LC_{50} of the most toxic compound (Gutierrez-Moreno et al. 2019).

FIELD STUDIES

Seven insecticides and the control without any treatment were replicated 3 times. The maize hybrid Pioneer 3550 was planted at the Kudarekonda field on 27 Jun and 20 Sep 2018. The seed was sown at row to row and plant to plant with a spacing of 45 × 20 cm in a plot size of 10 × 5 m^2 for each treatment. All the crop-raising practices including cultural practices, fertigation, and weed management were followed to maintain healthy crops, and no insecticides other than those included in the trial were applied. The treatments were imposed 2 times during each planting date. The first spray was given at 15 d after sowing as foliar application except for the control, whereas the second application was done at 15 d after the first spray. Insecticide applications were carried out during calm, warm, sunny periods using a high volume knapsack sprayer fitted with a hollow cone nozzle and using 400 L per ha (first spray) and 500 L per ha (second spray) In the first spray, the insecticides were sprayed on both leaves and whorls, whereas in the second application the spray fluid was directed only to the whorl by modifying the hollow cone nozzle. A visual observation of the number of live larvae per plant was recorded 1 d before and 3, 7, 10, and 14 d after each treatment on 20 plants from each experimental unit; the plants in the border rows were excluded. Treatment-wise, marketable grain yield was recorded, and was pooled and expressed in kg per ha. The data collected was subjected to statistical analysis as Randomized Complete Block Design after suitable transformations. Observations of the number of larvae per plant were analyzed after $\sqrt{X+0.5}$; after the analysis, the original units were reconverted. Mean separation of the number of larvae and yield was performed using Duncan's Multiple Range test DMRT ($P \leq 0.05$).

Results

TOXICITY OF INSECTICIDES FOR MANAGEMENT OF FALL ARMYWORM UNDER LABORATORY CONDITIONS

The LC_{50} values ranged from 0.0051 to 0.610 ppm (Table 1). The LC_{50}s for flubendiamide, indoxacarb, lambda cyhalothrin, and novaluron were not significantly different (95% confidence limit overlap), whereas the LC_{50}s for the remaining insecticides are significantly differ-

Table 1. Dose-mortality responses of fall armyworm larvae to different insecticides in leaf dip assays at 24 h after exposure.

Insecticides	IRAC MoA Group	*n*	LC_{50} (ppm)	Fiducial limits 95%	Slope ± SE	χ^2	LC_{95} (ppm)	Potency ratios
emamectin benzoate	Avermectin, glutamate gated chloride channel allosteric modulator	480	0.0051a	0.0032–0.0073	0.8 ± 0.1	2.84	0.552	119
chlorantraniliprole	Diamide, ryanodine receptor modulator	420	0.0159b	0.0096–0.0229	0.9 ± 0.1	4.39	1.156	38
spinetoram	Spinosyn, nAChR modulator	360	0.0411c	0.0287–0.0542	1.3 ± 0.1	0.68	0.773	15
flubendiamide	Diamide, ryanodine receptor modulator	420	0.1150d	0.0822–0.1538	1.1 ± 0.1	0.22	3.589	5
indoxacarb	Oxadiazine, voltage gated chloride channel blocker	480	0.29d	0.1450–0.4350	0.6 ± 0.1	2.62	103.800	2
lambdacyhalothrin	Pyrethroid, sodium channel modulator	420	0.60d	0.30–0.95	0.7 ± 0.1	4.29	127.800	1
novaluron	Benzoylurea, chitin synthesis inhibitor	480	0.610d	0.40–0.90	0.7 ± .09	3.10	1.610	–

Potency ratio = LC_{50} of the least toxic compound/LC_{50} of the most toxic compound.
LC_{50} values followed by the same letter do not show significant differences based upon non-overlapping fiducial limits 95%.

ent from each another. Values of the slope of less than 1 were found in emamectin benzoate, chlorantraniliprole, indoxacarb, lambda-cyhalothrin, and novaluron. Values of the slope slightly above 1 were found for spinetoram and flubendamide (Table 1). The insecticides emamectin benzoate, chlorantraniliprole, and spinetoram were the most toxic, with a value of 119, 38, and 15-fold potency ratios, respectively, followed by flubendiamide, indoxacarb, lambda-cyhalothrin, and novaluron with potency ratios of 5, 2, 1, and 1-fold, respectively.

FIELD EFFICACY OF INSECTICIDES FOR MANAGEMENT OF FALL ARMYWORM ON DIFFERENT DATES OF PLANTING

Jun Planting

All the insecticides significantly reduced the fall armyworm larvae ($P \leq 0.05$, Duncan Multiple Range Test) in all replications compared to the control at 3, 7, and 10 d after treatment in the first and second applications (Table 2). The first application was done 15 d after planting, and 1 d before treatment the means of larvae per plant ranged from 1.83 to 2.33 in the treatments, and there were no statistical differences among the treatments. Three d after the first spray, significantly least number of larvae was recorded with chlorantraniliprole (0.10 larvae per plant), emamectin benzoate (0.10 larvae per plant), spinetoram (0.13 larvae per plant), flubendiamide (0.13 larva per plant), and lambda-cyhalothrin (0.17 larvae per plant), and were statistically on par with each other. The next best treatments were indoxacarb (0. 20 larvae per plant) and novaluron (0. 23 larvae per plant), but on par with lambda-cyhalothrin.

At 7 and 10 d after first spray, there was an increase in infestation in all the treatments ($P \leq 0.05$), but significantly less than the control. At 7 d after first spray, the lowest number of larvae per plant was recorded with chlorantraniliprole (0.13 larvae per plant), spinetoram (0.13 larvae per plant), emamectin benzoate (0.17 larva per plant), and flubendiamide (0.23 larva per plant), followed by indoxacarb (0.27 larvae per plant), lambda-cyhalothrin (0.47 larvae per plant), and novaluron (0.80 larvae per plant). Novaluron treatment recorded 0.80 larva per plant, and it was inferior to chlorantraniliprole, emamectin benzoate, spinetoram, and flubendiamide in reducing the number of larvae per plant. A similar trend was evident after 10 d after treatment. At 14 d after the first spray, all the mean numbers of larvae in insecticide treatments were non-significant from the control.

At 3 and 7 d after the second spray, a significantly low number of larvae were recorded with all the insecticide treatments in comparison with the control ($P \leq 0.05$). At 7 d after treatment, fall armyworm larvae were reduced in all insecticide treatments in comparison with the control. At 10 d after the second spray, the lowest number of larvae per plant was recorded in chlorantraniliprole (0.20 larvae per plant), fludendamide (0.30 larvae per plant), emamectin benzoate (0.33 larvae per plant), and spinetoram (0.40 larvae per plant), which were statistically similar ($P \leq 0.05$). At 14 d after the second spray, all the insecticide treatments and the control were non-significant (Table 2).

Yield

Chlorantraniliprole recorded the higher grain yield of 6,650 kg per ha, which was similar to emamectin benzoate (6,517 kg per ha), spinetoram (6,467 kg per ha). The next best treatments were flubendiamide, lambda cyhalothrin, indoxacarb, and novaluron, which recorded yields of 5,833, 5,675, 5,673, and 5,353 kg per ha, respectively. The untreated control recorded the lowest yield (3,246 kg per ha) (Fig. 1).

Table 2. Efficacy of different insecticides against fall armyworm on maize under field conditions in Jun planted crop 2018.

Insecticides	Dosage (g ai per ha)	Number of larvae per plant*								
		First spray					Second spray			
		1 DBT	3 DAT	7 DAT	10 DAT	14 DAT	3 DAT	7 DAT	10 DAT	14 DAT
chlorantraniliprole 18.5 SC	37.0	1.83a	0.10d	0.13d	0.67d	0.80a	0.17c	0.17d	0.20d	0.20e
emamectin benzoate 5 SG	12.5	2.10a	0.10d	0.17d	0.80cd	1.03a	0.17c	0.27cd	0.33d	0.27de
spinetoram 11.7 SC	29.2	1.97a	0.13cd	0.13d	0.87bcd	1.10a	0.27c	0.27cd	0.40cd	0.37bcd
flubendiamide 480 SC	99.8	2.03a	0.13cd	0.23cd	0.70d	1.13a	0.30c	0.33cd	0.30d	0.43abc
lambdacyhalothrin 5 EC	25.0	2.33a	0.17bcd	0.43c	1.07bc	1.07a	0.27c	0.53cd	0.60bc	0.47ab
indoxacarb 14.5 SC	36.2	2.23a	0.20bc	0.27c	1.10bc	1.20a	0.37c	0.33bc	0.37cd	0.30cde
novaluron 10 EC	50.0	2.07a	0.23b	0.80b	1.20b	1.23a	0.80b	0.70 b	0.83b	0.47ab
control	–	2.17a	1.93a	2.00a	1.87a	1.67a	1.60 a	1.33a	1.40a	0.57a

*Mean of 20 plants per treatment.
DBT = d before treatment; DAT = d after treatment.
In column, means followed by common letters are not significantly different at ($P \leq 0.05$) by Duncan's Multiple Range test DMRT.

Sep Planting

One d before treatment, the larval numbers per plant ranged from 2.30 to 2.70 in all treatments, and were non-significant ($P \leq 0.05$). Three, 7, 10, and 14 d post-first spray, significantly low numbers of larvae, i.e., 0.27 to 1.17 larvae per plant, 0.20 to 1.13, 0.17 to 0.77, and 0.13 to 0.57 larvae per plant, respectively, were recorded among all the treatments ($P \leq 0.05$). Novaluron showed the highest number of larvae for all the tested insecticides, and it was significantly different from the rest of insecticide treatments at 10 and 14 d after treatment. In the second spray, all insecticide treatments consistently showed fewer larvae than the control and novaluron treatments (Table 3) at 3, 7, and 10 d after treatment. Fourteen d after treatment, there was a decrease in the larval population in all treatments, perhaps due to the crop about to reach the tasseling stage (d).

Yield

Chlorantraniliprole recorded the higher grain yield with 6,233 kg per ha, which was significantly similar to emamectin benzoate (6,180 kg per ha), spinetoram (5,867 kg per ha), and flubendiamide (5,467 kg per ha) (Fig. 2). The next most efficient treatments were lambda-cyhalothrin, indoxacarb, and novaluron. The control showed a reduction of 3,557 kg in comparison with the best insecticide treatment (chlorantraniliprole). In the Sep planted crop, the most effective insecticides were chlorantraniliprole and emamectin benzoate, followed by spinetoram, flubendiamide, lambda-cyhalothrin, and indoxacarb. Novaluron was the least effective compound to manage fall armyworm at the tested concentrations.

Discussion

INSECTICIDE SUSCEPTIBILITY

Toxicity studies showed that the LC_{50} values of emamectin benzoate, chlorantraniliprole, and spinetoram were found to be very low compared with flubendamide, indoxacarb, lambda-cyhalothrin, and novaluron. However, it is difficult to compare susceptibility of our results to other studies given the different methods of bioassays to monitor susceptibility in fall armyworm. For instance, Gutierrez-Moreno et al. (2019) studied the field-evolved resistance of the fall armyworm to different insecticides using topical applications, and recorded the mortality 72 h post-treatment. The baseline of the susceptible population, for equivalent compounds other than the ones used in this research, indicated that the most toxic compound was emamectin benzoate followed by chlorantraniliprole, spinetoram, flubendiamide, triflumuron (a benzoylurea), and pyrethroids. In other residual bioassays, Belay et al. (2012) studied the effect of different insecticides for management of fall armyworm larvae using a direct spray over third instar larvae. More than 80% mortality was observed in chlorantraniliprole, flubendamide, spinosad, indoxacarb, and fenvalerate treatments 96 h after application. Yet another study by overlay diet-assay showed reduced LC_{50} values including chlorfenapyr (1.2 ppm), emamectin benzoate (0.0029 ppm), fipronil (2.4 ppm), and tebufenozide (0.95 ppm) (Argentine et al. 2002). In diet-incorporated assays, the LC_{50} values of chlorantranilprole (0.068 µg mL^{-1}) and spinetoram (0.066 µg mL^{-1}) were significantly lower than the LC_{50} of indoxacarb (0.392 µg mL^{-1}) and flubendiamide (0.930 µg mL^{-1}) (Hardke et al. 2011). Despite that the method of bioassay used by Hardke et al. (2011) was dif-

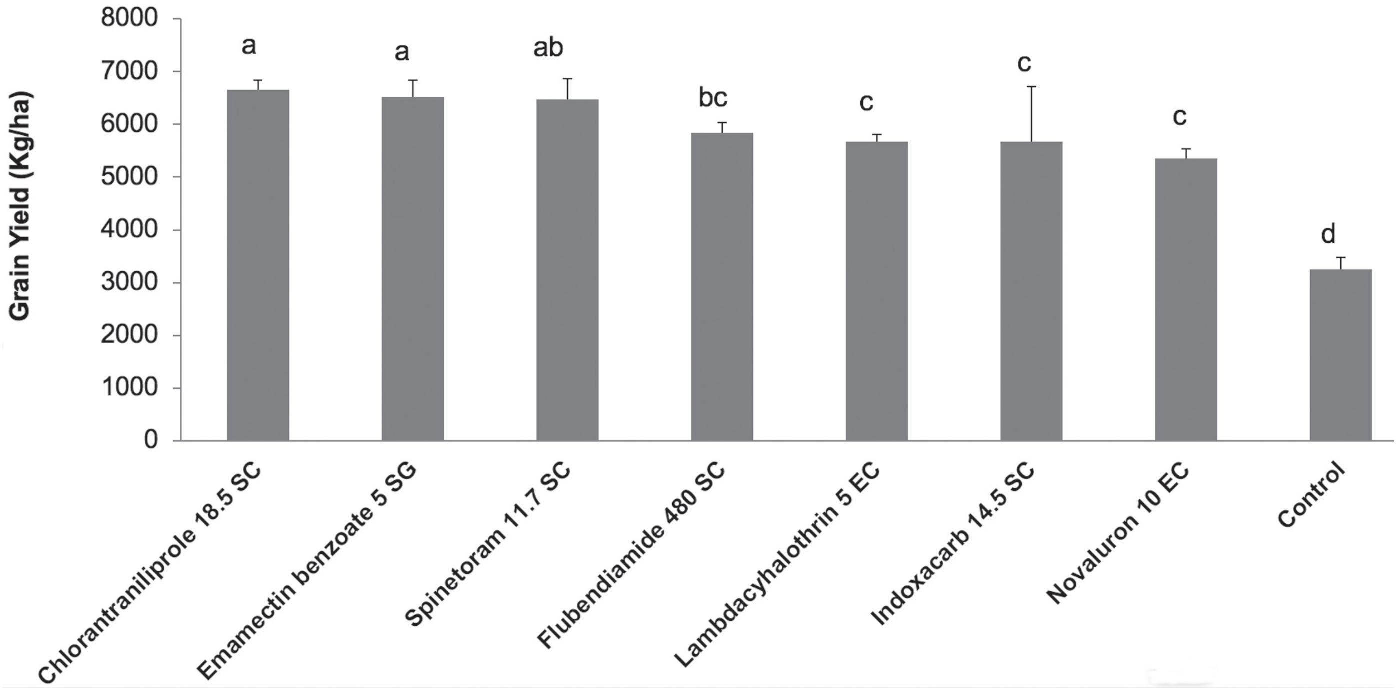

Fig. 1. Corn yield in field efficacy treatments in Jun planted crop in 2018.

ferent from our method, the active ingredients for spinetoram and chlorantraniliprole exhibited similar levels of toxicity. Higher values of the slopes and (LC_{95}) were found with indoxacarb and lambda-cyhalothrin in our results (Table 1). These results represent initial efforts to develop baseline susceptibility data for the insecticides that are currently used for control of fall armyworm. These toxicity values help in monitoring of changes in susceptibility to these new insecticides as their use becomes widespread on maize in the southern states of India. However, a standard bioassay method for fall armyworm is important to assess the susceptibility.

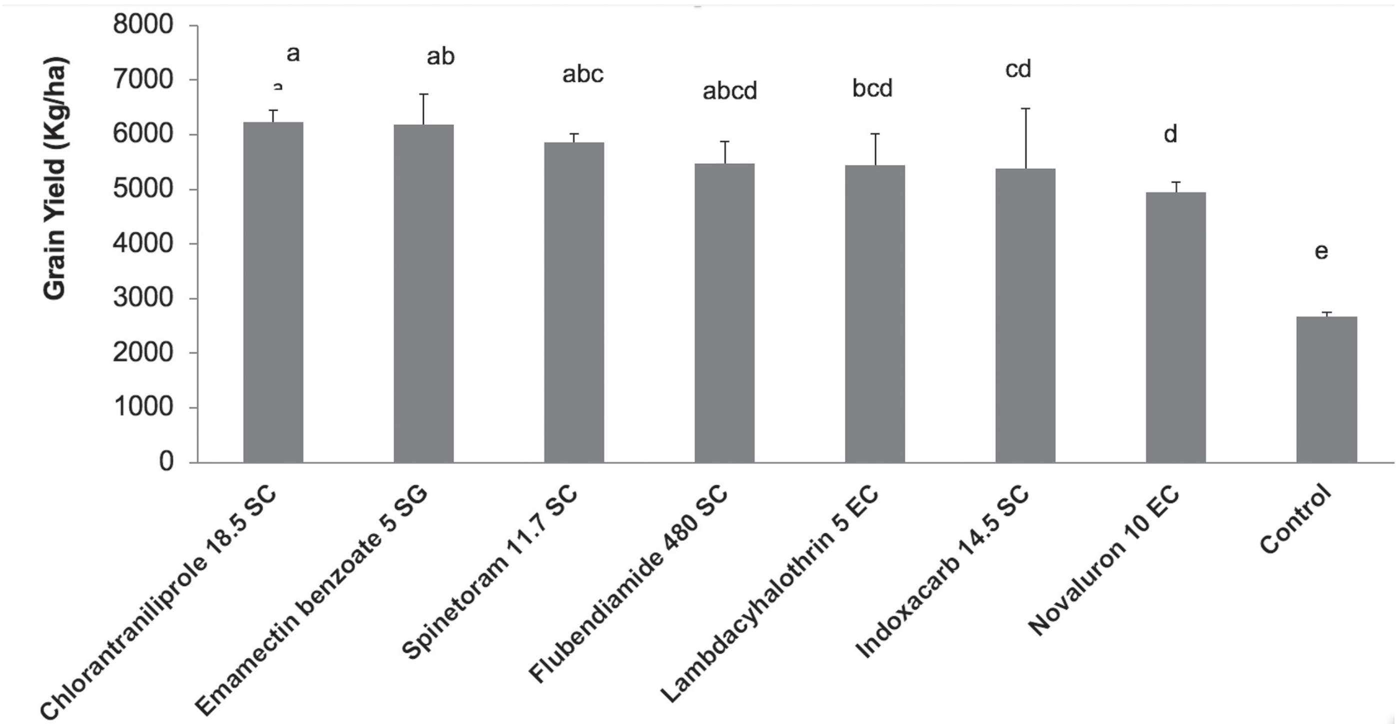

Fig. 2. Corn yield in field efficacy treatments in Sep planted crop in 2018.

Table 3. Efficacy of different insecticides against fall armyworm on maize under field conditions in Sep planted crop 2018.

Insecticides	Dosage (g ai per ha)	Number of larvae per plant*								
		First spray	Second spray							
		1 DBT	3 DAT	7 DAT	10 DAT	14 DAT	3 DAT	7 DAT	10 DAT	14 DAT
Chlorantraniliprole 18.5 SC	37.0	2.40a	0.13b	0.27c	0.37c	0.57c	0.27f	0.20e	0.20d	0.13c
Emamectin benzoate 5 SG	12.5	2.47a	0.17b	0.33bc	0.43c	0.50c	0.33ef	0.30de	0.20d	0.17c
Spinetoram 11.7 SC	29.2	2.50a	0.20b	0.37bc	0.50c	0.57c	0.40def	0.33de	0.17d	0.17c
Flubendiamide 480 SC	99.8	2.57a	0.23b	0.47bc	0.60c	0.80c	0.50cde	0.53cd	0.60c	0.40b
Lambdacyhalothrin 5 EC	25.0	2.70a	0.23b	0.40bc	0.47c	0.67c	0.63c	0.47cde	0.47bc	0.47b
Indoxacarb 14.5 SC	36.2	2.57a	0.27b	0.30c	0.53c	0.80c	0.60cd	0.63c	0.60bc	0.53b
Novaluron 10 EC	50.0	2.47a	0.33b	0.87b	1.20b	1.33b	1.17b	1.13b	0.77b	0.57b
Control	–	2.30a	2.53a	2.73a	3.07a	2.77a	2.37a	1.63a	1.10a	0.83a

*Mean of 20 plants per treatment.
DBT = d before treatment; DAT = d after treatment.
In column, means followed by common letters are not significantly different at ($P \leq 0.05$) by Duncan's Multiple Range test DMRT.

FIELD EFFICACY STUDIES

In the present study, the data for 2 different dates of planting showed that at 3 and 7 d after treatment for the 2 sprays, fall armyworm larva densities were significantly lower among treatments chlorantraniliprole, emamectin benzoate, spinetoram, flubendamide, and lambda-cyhalothrin, compared with the control. The Sep sown crop also recorded lower numbers of larval population in the treatments chlorantraniliprole, emamectin benzoate, spinetoram, flubendiamide, and lambda-cyhalothrin than in the untreated plot at 3 and 7 d after treatment than in the untreated plot. Among the insecticides, novaluron, an insect growth regulator, recorded high larval population at 10 d after spray. Therefore, under these different dates of planting and pest pressure, we observed that synthetic insecticides provided a period of plant protection of 10 d. However, continuous egg laying and larval infestations made it difficult to extend management beyond this period. Daves et al. (2009) screened 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) that effectively reduced infestation up to 13 d after treatment. Hardke et al (2011) 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) in sorghum 7 d after treatment. Lambda-cyhalothrin provided only 40% reduction in insecticide treated whorls. Foliage collected from treated fields and used under laboratory conditions indicated longer control by chlorantraniliprole (14 d, 85.9% of mortality). However, at 7 d after treatment, flubendiamide resulted in mortality of only 53.1%, and lambda-cyhalothrin resulted in 28.1% mortality. In our study, we cannot rule out that fall armyworm larvae may have some reduced susceptibility to pyrethroids. Further refining of the method of bioassay and comparing results with a susceptible colony will confirm if reduced susceptibility is present in fall armyworm from India as has occurred in other regions (Gutierrez-Moreno et al. 2019).

Treatments of insecticides resulted in lower larval infestation and higher crop yields for both planting seasons. One critical factor in corn protection from fall armyworm larva damage was excellent insecticide coverage of the whorl of the plant. During both crop production seasons, 2 applications only provided enough protection for fall armyworm, and subsequently resulted in higher yields compared with the untreated field. However, we are cautious about giving a precise number of applications because scouting should be the principal tool to decide on the interventional chemical treatments.

We have screened different insecticides for control of fall armyworm in Shivamogga, Karnataka. This data will be very helpful to compare populations from other regions and those with a susceptible population. The recent invasion of fall armyworm has forced the farmers to deploy a massive pesticide spraying program on maize and sorghum fields as an emergency response in southern India to manage fall armyworm damage. Due to heavy fall armyworm damage, some farmers have applied different types of unregistered synthetic insecticides. This study provides valuable information about the efficacy of insecticides with relatively novel modes of action to manage fall armyworm. In addition, under the 2 different planting date system, these compounds provide good protection for the fall armyworm infestation, and that resulted in significant yield. These chemicals should be used as a last resort in fall armyworm management. An Integrated Pest Management approach is needed for effective management of fall armyworm; other factors of mortality that includes natural enemies, use of botanical compounds, pheromones to detect adults, plant deterrent compounds, and cultural practices should be integrated in a comprehensive Integrated Pest Management system for management of fall armyworm.

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