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Toxicity and efficacy of selected insecticides for managing invasive fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) on maize in Indonesia

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ABSTRACT

The fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith), has become an important maize pest that invaded Indonesia in the early 2019. As a highly polyphagous pest, *S. frugiperda* larvae feed on a total of 353 different host plants belonging to 76 plant families with causing yield losses up to 100%. To overcome this pest, maize grower in some countries using insecticides. Therefore, this study was conducted during 2019-2020 at Padjadjaran University, Faculty of Agriculture and at farmer's field in the Ciledug sub-district of Cirebon, West Java, Indonesia to evaluate the efficacy of several insecticides against *S. frugiperda* in laboratory and screenhouse to confirm field efficacy against natural infestation. Nineteen insecticides belonging to different chemical group were first tested for their toxicity against the larvae under laboratory conditions and the result will be used as a baseline susceptibility data to ditermine insecticide efficacy against of *S. frugiperda* in screenhouse and natural infestations in maize fields. The results showed that among insecticides tested, the highest mortality (>80%) were noted with emamectin benzoat, chlorfenapyr, phoxim, methomyl and indoxacarb under laboratory, screenhouse and field conditions. Among all the treatments, significantly higher maize yield of 29.28 t/ha was recorded in emamectin benzoat with 33.89% increase over control, followed by phoxim (29.92 t/ha), indoxacarb (27.5 t/ha), methomyl (26.88 t/ha) and chlorfenapyr (26.38 t/ha) with a per cent increase of 24.10, 14.68, 11.49 and 9.42%, respectively over control. The lowest yield was noticed in untreated control (24.11 t/ha). Emamectin benzoate was consistently more effective than other insecticides at suppressing *S. frugiperda* populations and protecting maize plants. Furthermore, these insecticides can be used as one of the components of integrated pest management of *S. frugiperda* and delayed the development of resistance against insecticides.

Key words : Control efficacy, FAW, maize, plant damage, *Spodoptera frugiperda*, yield increase

INTRODUCTION

The fall armyworm (FAW), *Spodoptera frugiperda* (Lepidoptera : Noctuidae) is an important pest of maize crop in many parts of the word (Sisay *et al.,* 2019). CABI (2021) reported that *S. frugiperda* is native to tropical and subtropical regions of the Americas, which has invaded and spread throughout the Africa in 2016 (Goergen *et al.,* 2016). Recently, severe incidence of *S. frugiperda* was reported from Asia such as India, China, Bangladesh, Japan, Korea, Republic of Laos, Malaysia, Myanmar, Nepal, Sri Lanka, Thailand, Viet Nam, The Philippines, Cambidia, The Republic of Korea, Japan, Sudan, Egypt and Yemen (Sharanabasappa *et al.,* 2020; CABI, 2021). In the early 2019, Indonesia had confirmed the presence of *S. frugiperda* in West Sumatera. Since then, it has become one of the major invasive pests in 25 out of 34 provinces and across 9954 ha (Nonci *et al.,* 2019). In 2020, it was confirmed in Australia, Mauritania, Timor Leste, the United Arab Emirates Jordan, Syria and Papua New Guinea.

In 2021, New Caledonia and the

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Canary Islands of Spain in Europe confirmed the presence of *S. frugiperda*. More than 70 countries are now affected (FAO, 2021). The ability of the *S. frugiperda* to migrate long distances is the reasons why it is one of the most damaging crop pests in the world (Westbrook *et al.,* 2016; Day *et al.,* 2017). There are 353 reported host plants from 76 families, but maize is the most preferred (Silva *et al.,* 2017.

Several studies had been done to estimate the impact of *S. frugiperda*, in particular the crop losses that it causes. Yield reduction in maize due to damage of *S. frugiperda* larva of about 40% was reported in Honduras (Wyckhuys and O'Neil, 2006), 17 – 72% in Argentina (Murúa *et al.,* 2006), 34% in Brazil (Lima *et al.,* 2009), 39% in America (Cruz *et al.,* 2012), 22-67% in Ghana and 25-50% in Zambia (Day *et al.,* 2017), 20 – 50% was reported in Africa (Early *et al.,* 2018), 30% in Kenya (Assefa and Ayalew 2019), 11.57% in Zimbabwe (Baudron *et al.,* 2019) and 58% in in Nicaragua (Chimweta *et al.,* 2019). As of late, (FAO, 2021) announced yield loss of 20% due to *S. frugiperda* in smallholder maize fields in Sri Lanka and 100% in Nepal (CABI, 2021). Abrahams *et al.* (2017) reported that in the absence of proper control methods, *S. frugiperda* has the potential to cause maize yield losses around 21 to 53% depending on the stage of development of the plant and the suitable climatic conditions.

Because of the high potential losses caused by *S. frugiperda*, minimizing the pest losses can be the most important approach to increased productivity of maize. Integrated pest management (IPM) strategies have proved an effective tactics against insect pests like *S. frugiperda* (Day *et al.,* 2017). Different methods like cultural, biological, botanical, physical, chemical control and other methods have been practiced by many farmers around the world. The application of chemical pesticide is one of the most effective methods for *S. frugiperda* prevention at present to response the spread of the pest and minimize damage to maize fields (Cook *et al.,* 2004; Hardke *et al.,* 2011; Blanco *et al.,* 2014; Prasanna *et al.,* 2018; Gutierrez-Moreno *et al.,* 2019; Sisay *et al.,* 2019; Xiao, 2021). Koffi *et al.* (2020) reported that the application of insecticides may have contributed to the reduction *of S. frugiperda* population. Therefore, it is necessary to determine the efficacy of insecticides on *S. frugiperda* in maize crop.

There are many literatures on *S. frugiperda* control by chemical pesticides. Twenty-nine active ingredients have been recommended for *S. frugiperda*. Assefa and Ayalew (2019) reported that some insecticidal that is known to be effective against a range of insect pests was pyrethroids, carbamates, and organophosphates and several newer insecticides have been developed such as diamides, avermectins, spinosyns, and benzylureas. The objectives of this study were to evaluate selected synthetic insecticides to manage of *S. frugiperda* under laboratory, screenhouse, and field conditions to find the best insecticides which could be useful to improve its management in maize fields in Indonesia.

MATERIALS AND METHODS

Description of the Study Area

Research was conducted at Laboratory and screenhouse of Entomology, Faculty of Agriculture, Universitas Padjadjaran and at farmer's field in the Ciledug sub-district of Cirebon, West Java (6°30'–7°00' S and 108°40'–108°48' E) with an elevation of 6.0 meters. The soil at the experimental site was alluvial (pH 5.5 – 6.0). The experiment was carried out between June 2019 to November 2020.

Laboratory Bioassay of Synthetic Insecticides Against *S. frugiperda*

S. frugiperda larvae were collected from the unsprayed maize fields of farmer fields in Cirebon, West Java. The laboratory culture was maintained at the Department of Entomology, Faculty of Agriculture Universitas Padjadjaran at 26–28 °C, 50–60% relative humidity, and a 12:12 hr (L:D) photoperiod and was kept in the insectarium without contact with insecticides for more than 2 generations. Larvae of *S. frugiperda* were fed with maize leaves collected from 15–30-day-old maize plants, variety "Talenta". Insects were reared as described above until a sufficient population was achieved to run the experiment. The second laboratory generation larvae were used to estimate the toxicity of insecticides under laboratory and screenhouse conditions.

The leaf dipping bioassay was used to calculate the dose-mortality response of the early third instar *S. frugiperda* larvae based on IRAC method no. 018. All of insecticides tested were prepared with six serial dilution, distilled water was used as a control (each concentration was replicated four times). Tender maize leaves were cut into small pieces of approximately 4 x 4 cm. The leaf pieces were dipped individually in the insecticide solution for 5 seconds with gentle agitation to ensure the entire surface is submerged equally. This procedure was done for all five the insecticide concentrations (treatments) evaluated as well as the control treatment. Leaves were carefully drained of excess liquid and placed on fine mesh to air dry. A total 480 third-instar larvae were placed in third instar was placed onto the treated maize leaf tissue in each well, with a fine, soft brush then transferred onto the Petri dishes (twenty larva per Petri dishes), including control treatment. Mortality was calculated after 72 hr. Probit analysis was done to calculate the lethal concentrations LC_{50} and LC_{95} values for each assay of insecticide using the POLO-PC software package.

Screenhouse Study of Selected Synthetic Insecticides

The maize variety “Talenta” was planted in plastic pots (30 L) in a screenhouse following standard agronomic practices for the area. Five seeds were sown per pot and four weeks after planting (at vegetative stage) were used in the trials. Nine effective synthetic insecticides tested in the laboratory were used in the screenhouse trials (Table 1). Each synthetic insecticide was applied to the maize plants which both applied by (1) Contact method *i.e.*, spraying directly to the third instar larvae then the larvae was subsequently placed in maize plant. Insect mortality was assessed 1, 3, 6, 24, 48 and 72 hr after treatment application and plant damage was assessed at 72 hr after treatment and (2) Feeding assay method *i.e.,* the amount of synthetic insecticides required to spray was calculated and calibrated. Each synthetic insecticide solution was added to a backpack sprayer and sprayed on the maize plants in pots. Plants treated with sterile water were included as a control. Insect mortality was assessed 6, 24, 48, 72, 96 and 120 hr after treatment application and plant damage was assessed at 120 hr after treatment. Plastic cages (40 cm diameter and 1 m height) were placed covering the top of the pots right after treatments.The experiment was arranged in a completely randomized design (CRD) with four replications. One treatment consists of 10 third-instar larvae of *S. frugiperda* obtained from a laboratory colony as described above. Percentage of mortality and plant damage data were normalized by arcsine transformation and subjected to repeat measures analysis of

Table 1. List of synthetic insecticides and their active ingredients (a.i.), used in the experiment against *S. frugiperda*

Active ingredient	Mode of action*	IRAC group*
Methomyl	Acetylcholinesterase (AChE) inhibitors	1A
Phoxim		1B
Lambda-Cyhalothrin	Sodium channel modulators	3A
Permethrin		
Bifenthrin		
Imidacloprid	Nicotinic acetylcholine receptor (nAChR) competitive modulators	4A
Acetamiprid		
Thiacloprid		
Emamektin benzoate	Glutamate-gated chloride channel (GLUCL) allosteric modulators	6
Abamectin		
Chlorfenapyr	Uncouplers of oxidative phosphorylation via disruption of the proton gradient	13
Novaluron	Inhibitors of chitin biosynthesis affecting CHS1	15
Lufenuron		
Hexaflumuron		
Indoxacarb	Voltage-dependent sodium channel blockers	22A
Flubendiamide	Ryanodine receptor (RyR) modulators	28
Methoxyfenozide	Ecdysone receptor agonists	18
Monosultap	Nicotinic acetylcholine receptor (nAChR) channel blockers	14

*: IRAC Mode of Action Classification Scheme, MoA-Classification_v9.4_3March 20.pdf.

variance. The significance of the difference among the treatment means was estimated by Duncan's Multiple Range Test (DMRT) at 5% level of probability.

Field Study of Selected Synthetic Insecticides

Maize variety "Talenta" was planted at the farmer's field on a plot size of 6 m × 4 m, with a spacing of 75 cm between rows and 20 cm between plants. The agronomic aspect was carried out following standard agronomic practices for the area. Five effective synthetic insecticides tested in the screenhouse were used in the field trials. These were: Emamectin benzoate (2 mL/L); chlorfenapyr (1 mL/L); methomyl (2 mL/L); phoxim (2 mL/L); indoxacarb (2 mL/L) and control. The treatments were applied using a knapsack sprayer at seven-day intervals starting at 22 days after planting. The control plots were not sprayed. Randomized Complete Block Design (RCBD) with four replications was used for the experiment. Before and after each spraying, both number of live larvae per plant and plant damage were taken. Plant damage severity was recorded at seven-day intervals based on the rating scale (Table 2) described by Davis and Williams (1992).

Statistical Analysis

Data were collected from ten plants which were randomly selected from each plot (U Shape) for data collection on yield characteristics during the growth of plants and at harvesting time of the crop. Data were collected on the following: larvae densities, plant damage, yield componen and yield per hectare was calculated. The percent increase in yield over control (IYOC) in various treatments was calculated by using the following formula :

$$\text{IYOC (\%)} = \frac{\text{Yield in treatment} - \text{Yield in control}}{\text{Yield in control}} \times 100\%$$

Recorded data for different characters were statistically analyzed, the mean values evaluated and analysis of variance was performed by the 'F' test. The significance of the difference among the treatment of means was estimated by Duncan's Multiple Range Test (DMRT) at 5% level of probability.

RESULTS AND DISCUSSION

Laboratory Toxicity Studies

Lethal concentrations (LC_{50} and LC_{95}) for early third-instar larvae of at 72 hr were identified (Table 3). In general, there was variation in toxicity among and within IRAC mode of action groups from methomyl (carbamat) to monosultap (Nereistoxin analogues). Emamectin benzoate was the most effective insecticide tested (LC_{50} = 177.850 ppm and LC_{95} = 745.471 ppm) and acetamiprid the least effective (LC_{50} = 12,823.293 ppm and LC_{95} = 19,568.426 ppm) against third instar larvae using maize feeding bioassay. The result

Table 2. Scale for assessment of plant damage caused by *S. Frugiperda*

Score	Type of injury
1	No visible leaf-feeding damage
2	Few pinholes on 1-2 older leaves
3	Several shot-hole injuries on a few leaves (> 5 leaves) and small circular hole damage to leaves
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
5	Elongated lesions (>2.5 cm long) on 8-10 leaves, plus a few small- to mid-sized uniform to irregular-shaped holes (basement membrane consumed) eaten from the whorl and/or furl leaves
6	Several large elongated lesions present on several whorl and furl leaves and/or several large uniform to irregular-shaped holes eaten from furl and whorl leaves
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
8	Many elongated lesions of all sizes present on most whorl and furl leaves plus many midto large-sized uniform to irregular-shaped holes eaten from the whorl and furl leaves
9	Whorl and furl leaves almost totally destroyed and plant dying as a result of extensive foliar damage

Source: Modified from Davis and Williams (1992).

indicated that emamectin benzoat was the least toxic compound and the LC_{50} values were used to calculate potency ratios (PR) of all insecticed tested. Potency ratio values of Carbamat (5.15 - fold), Organophosphates (3.11- fold), Pyrethroid Syntetic (4.04 – 11.23 - fold), Neonicotinoides (8.84 – 72.11- fold), Avermectins (1.00 – 1.32 - fold), Pyrroles (1.67 - fold), Benzoylureas (2.67 – 11.00- fold), Oxadiazines (1.11- fold), Diamides (3.97 - fold), Diacylhydrazines (5.24 - fold) and Nereistoxin (14.79- fold). The order of toxicity of all tested compounds was as follows emamectin benzoate > indoxacarb > abamectin > chlorfenapyr > nuvaluron > phoxim > flubendiamide > lambda-cyhalothrin > methoxyfenozide > hexaflumuron > permethrin> imidaclorpid > lufenuron > bifenthrin > monosultap > thiacloprid > acetamiprid (Table 3). These results were represented as reference baseline susceptibility data to ditermine insecticide efficacy against natural infestations of *S. frugiperda* in maize fields.

Screen Efficacy Studies

The efficacy of nine insecticides was evaluated at 1 DAT until 72 hours after treatment and the results are presented in Table 4. The results showed that mortality of *S. frugiperda* larvae varied significantly according to dose of insecticide used with length of time observed. Result of contact/direct applications showed that all of insecticides gave significant different compared to untreated control. At the 72^{th} hours after treatment, the highest mortality was 100% in emamectin benzoate 2 mL/L treated plots, followed by chlorfenapyr 1 mL/L, methomyl 2 mL/L and phoxim 2 mL/L. The lowest mean mortalities of *S. frugiperda* was 0.00% in untreated control followed by imidacloprid and novaluron, respectively. The results showed that among nine insecticides, emamectin benzoate, chlorfenapyr, methomyl, phoxim and indoxacarb showed higher toxicity to this pest, while imidacloprid, novaluron, lambda-cyhalothrin and chorantraniliprole the least effective in controlling the pest population.

In feeding assay method, all insecticides gave sigifficantly different compared to the untreated control. This rate of mortality is a little bit lower compared to contact/direct application. The highest mortality 100% was found in emamectin benzoate 2 mL/L, followed by chlorfenapyr 1 mL/L and phoxim 2 mL/L respectively at 120 hours after treatment. The above result indicated that the population density of *S. frugiperda* was significantly reduced after application of different insecticides. The mortalities of *S. frugiperda* larvae generally increased with increasing consentrations used. Mortalities ranged between 67 – 90% in low concentration and 88 – 100% in high concentration. Dose mortality response to insecticides is necessary to provide baseline data for future resistance monitoring. Mortalities of *S. frugiperda* was increased after 48 and 72 h. (Table 5).

The overall mean of both experiments was found that emamectin benzoate, chlorfenapyr, methomyl, phoxim and indoxacarb were more effective insecticides in suppressing the *S. frugiperda* population on maize crop and may have promise to control of *S. frugiperda* in maize. All of those insecticides were recommended to tested under field condition to determine the right time and frequency of application which helped to achieve high levels of control and the effectiveness of the products to develop an appropriate management strategy.

The performance of nine insecticides on the percent reduction of maize plants infestation as affected by *S. frugiperda* presented in Table 6. The effect of different insecticides was observed up to 72 hours after spray for contact method and 120 hours after spray for feeding assay method. It was found that the application of insecticides showed significant ($P \leq 0.01$ and $P \leq 0.05$) reduction of percent plant infestation compared to control. The mean percentage of plant damage was recorded in the range of 1.57 to 92.49. The results clearly revealed that different insecticides had a significant effect on the reduction of plant infestation and the effect was also clearly dose and methods dependent. Chlorfenapyr (1.0 mL/L), methomyl (2.0 mL/L), emamectin benzoate (2.0 mL/L), indoxacarb (2.0 mL/L), and phoxim (2.0 mL/L) recorded minimum plant damage and it was found significantly to imidacloprid, lambda-Cyhalothrin, chorantraniliprole and novaluron. In untreated control plot higher plant damage of > 96%. The results obtained

Table 3. Toxicity of Insecticides on 3rd. instar larvae of *S. frugiperda* after 72 hr exposure

Insecticides[1]	n[2]	LC_{50} (ppm)	LC_{95} (ppm)	Slope	Potency ratio
Carbamates (1A)					
Methomyl	480	916.434 (623.960 – 1346.001)	7338.545 (2581.534 – 20861.332)	1.82	5.15
Organophosphates (1B)					
Phoxim	480	553.4388 (306.7751 – 998.4334)	19184.2188 (1547.414 – 237838.26)	0.77	3.11
Pyrethroid Syntetic (3A)					
Lambda-Cyhalothrin	480	705.9755 (412.4836 – 1208.2903)	1245.795 (836.937 – 1961.737)	4.54	3.97
Permethrin	480	1165.6962 (981.2100 – 1384.8693)	2847.2289 (1975.1544 – 4104.3439)	4.23	6.55
Bifenthrin	480	1997.9159 (820.2242 – 4866.5569)	55219.6504 (3567.5352 – 854710.5026)	1.14	11.23
Neonicotinoides (4A)					
Imidacloprid	480	1571.4095 (2587.2712 – 12928.5448)	2587.2712 (2587.2712 – 12928.5848)	2.89	8.84
Acetamiprid	480	12823.293 (11379.982 – 14449.658)	19568.426 (16730.992 – 22887.065)	1.98	72.11
Thiacloprid	280	5416.9307 (1027.1416 – 28567.7628)	20202.817 (12529.306 – 32575.931)	3.22	30.46
Avermectins (6)					
Emamektin benzoat	480	177.850 (38.074 – 159.178)	745.471 (344.835 – 1611.573)	1.68	1.00
Abamectin	480	234.0640 (186.1666 – 294.2846)	753.5381 (480.4836 -1125.9829)	3.29	1.32
Pyrroles (13)					
Chlorfenapyr	480	297.7126 (90.9218 – 309.3596)	4484.7050 (1354.6307 – 14847.2786)	1.15	1.67
Benzoylureas (15)					
Novaluron	480	464.543 (247.843 – 870.714)	2874.662 (1132.062 – 7299.672)	2.08	2.61
Lufenuron	480	1956.729 (1113.893 – 3437.306)	14831.290 (3500.751 – 62834.275)	1.87	11
Hexaflumuron	480	1062.2779 (530.1347 – 2128.5807)	40464.891 (1332.177 – 1229121.428)	1.46	5.97
Oxadiazines (22A)					
Indoxacarb	480	197.0362 (105.6095 – 9914.1517)	946.2409 (434.7301 – 2059.6039)	1.36	1.11
Diamides (28)					
Flubendiamide	480	717.761 (562.748 – 915.472)	2566.092 (1607.692 – 4095.829)	2.97	4.04
Diacylhydrazines (18)					
Methoxyfenozide	480	932.3747 (722.1812 – 1203.7457)	3288.1933 (1887.4434 – 5728.4978)	2.99	5.24
Nereistoxin analogues (14)					
Monosultap	480	2631.4246 (1809.361 -39827.6712)	10454.4547 (4129.6566 – 26466.0318)	2.74	14.79
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[1]: IRAC Mode of Action Classification Scheme, MoA-Classification_v9.4_3March20.pdf; [2]: Number of insects tested.

Table 4. Effect of several insecticides against mortality of *S. frugiperda* and control efficiency (CE%) applied by contact methods

Treatments	Larval mortality (%±SE) at...............HAT											
	1	CE (%)	3	CE (%)	6	CE (%)	24	CE (%)	48	CE (%)	72	CE (%)
Imidacloprid (2 mL/L)	0 ± 0.00^{a}	0	10 ± 2.11^{b}	10	20 ± 25.8^{bc}	20	31 ±3.48^{b}	31	44 ± 2.67^{b}	44	44 ± 2.67^{b}	44
Imidacloprid (1 mL/L)	0 ± 0.00^{a}	0	0 ± 0.00^{a}	0	1 ± 1.00^{a}	1	4 ± 2.21^{a}	4	36 ± 3.71^{b}	36	36 ± 3.71^{b}	36
Emamectin benzoate (2 mL/L)	0 ± 0.00^{a}	0	0 ± 0.00^{a}	0	56 ± 3.06^{ef}	56	100 ± 0.00^{i}	100	100 ± 0.00^{g}	100	100 ± 0.00^{g}	100
Emamectin benzoate (1 mL/L)	0 ± 0.00^{a}	0	0 ± 0.00^{a}	0	24 ± 2.21^{bc}	24	100 ± 0.00^{i}	100	100 ± 0.00^{g}	100	100 ± 0.00^{g}	100
Lambda-Cyhalothrin (1.5 mL/L)	62 ± 2.49^{d}	62	62 ± 2.49^{g}	62	70 ± 2.11f^{g}	70	86 ± 1.63^{efgh}	86	90 ± 0.00^{efg}	90	94 ± 1.63^{fg}	94
Lambda-Cyhalothrin (0.75 mL/L)	30 ± 4.71^{b}	30	40 ± 2.11^{f}	40	46 ± 4.00^{de}	46	66 ± 2.67^{cd}	66	67 ± 2.60^{c}	67	77 ± 3.35^{c}	77
Indoxacarb (2 mL/L)	8 ± 2.00^{a}	8	11 ± 1.80^{bc}	11	48 ± 5.12^{e}	48	89 ± 4.07^{ghi}	89	94 ± 3.40fg	94	99 ± 1.00g	99
Indoxacarb (1 mL/L)	6 ± 2.67^{a}	6	8 ± 2.91^{ab}	8	26 ± 3.71^{bc}	26	68 ± 2.91^{cd}	68	77 ± 4.23^{cd}	77	83 ± 5.17^{def}	83
Chorantraniliprole (6 mL/L)	0 ± 0.00^{a}	0	0 ± 0.00a	0	18 ± 3.59^{b}	18	88 ± 3.89^{ghi}	88	92 ± 2.49^{fg}	92	92 ± 2.49efg	92
Chorantraniliprole (3 mL/L)	0 ± 0.00^{a}	0	0 ± 0.00^{a}	0	0 ± 0.00^{a}	0	2 ± 3.40^{b}	2	32 ± 2.49^{b}	32	32 ± 2.49^{b}	32
Chlorfenapyr (1 mL/L)	35 ± 4.77^{c}	35	82 ± 4.16^{h}	82	95 ± 1.67^{h}	95	100 ± 0.00^{i}	100	100 ± 0.00^{g}	100	100 ± 0.00^{g}	100
Chlorfenapyr (0.5 mL/L)	23 ± 2.13^{b}	23	30 ± 2.58^{e}	30	33 ± 4.23^{cd}	33	73 ± 5.17^{cde}	73	79 ± 3.79^{cde}	79	81 ± 4.07^{de}	81
Methomyl (2 mL/L)	6 ± 1.63^{a}	6	26 ± 3.40^{de}	26	84 ± 3.40^{gh}	84	98 ± 1.33^{hi}	98	100 ± 0.00^{g}	100	100 ± 0.00^{g}	100
Methomyl (1 mL/L)	6 ± 1.63^{a}	6	20 ± 2.11^{cd}	20	73 ± 1.53^{g}	73	75 ± 2.24^{def}	75	79 ± 1.80^{cde}	79	84 ± 1.63def	84
Phoxim (2 mL/L)	0 ± 0.00^{a}	0	0 ± 0.00^{a}	0	70 ± 3.85^{fg}	70	94 ± 2.81^{ghi}	94	100 ± 0.00^{g}	100	100 ± 0.00^{g}	100
Phoxim (1 mL/L)	0 ± 0.00^{a}	0	0 ± 0.00^{a}	0	44 ± 3.06^{de}	44	61 ± 3.14^{c}	61	67 ± 3.00^{c}	67	67 ± 3.00^{c}	67
Novaluron (4.0 mL/L)	0 ± 0.00^{a}	0	20 ± 2.11^{cd}	0	33 ± 2.60^{cd}	33	64 ± 2.30^{efg}	64	71 ± 2.33^{efg}	71	71± 2.33^{efg}	71
Novaluron (2.0 mL/L)	0 ± 0.00^{a}	0	0 ± 0.00^{a}	0	2 ± 1.33^{a}	2	52 ± 1.27^{efg}	52	65 ± 3.07^{def}	65	65± 3.07def	65
Control	0 ± 0.00^{a}	-	0 ± 0.00^{a}	-	0 ± 0.00^{a}	-	0 ± 0.00^{a}	-	0 ± 0.00^{a}	-	0 ± 0.00^{a}	-

Means followed by the same letter in the column are not significantly different according to Duncan's Multiple Range Test at α = 0.05.

Table 5. Effect of several insecticides against mortality of *S. frugiperda* and control efficiency (CE%) applied by feeding assay mehods

Treatments	Larval mortality (%±SE) at...............HAT											
	1	CE (%)	3	CE (%)	6	CE (%)	24	CE (%)	48	CE (%)	72	CE (%)
Imidacloprid (2 mL/L)	0 ± 0.00a	0	46 ± 3.71^{bcd}	46	83 ± 3.67^{efg}	83	90 ± 3.33^{fghi}	90	90 ± 3.33^{fgh}	90	90 ± 3.33^{fgh}	90
Imidacloprid (1 mL/L)	0 ± 0.00^{a}	0	38 ± 2.49^{bc}	38	70 ± 2.98^{cd}	70	70 ± 2.98^{bcd}	70	70 ± 2.98^{bc}	70	70 ± 2. 98^{bc}	70
Emamectin benzoate (2 mL/L)	100 ± 0.00^{i}	100	100 ± 0.00^{h}	100	100 ± 0.00^{i}	100	100 ± 0.00^{i}	100	100 ± 0.00^{h}	100	100 ± 0.00^{h}	100
Emamectin benzoate (1 mL/L)	70 ± 2.11^{gh}	70	87.5 ± 2.98^{gh}	87.5	90 ± 2.98^{efgh}	90	90 ± 2.98^{fghi}	90	90 ± 2.98^{fgh}	90	90 ± 2.98^{fgh}	90
Lambda-Cyhalothrin (1.5 mL/L)	15 ± 3.81^{cd}	15	80 ± 2.63^{fg}	80	84 ± 3.19^{efgh}	84	88 ± 2.92^{efgh}	88	88 ± 2.92^{defg}	88	88 ± 2.92^{defg}	88
Lambda-Cyhalothrin (0.75 mL/L)	5 ± 1.67^{abc}	5	60 ± 2.58^{de}	60	64 ± 2.21^{bc}	64	72 ± 1.33^{cd}	72	78 ± 2.91^{bcde}	78	78 ± 2.91^{bcde}	78
Indoxacarb (2 mL/L)	31 ± 4.33^{ef}	31	79 ± 4.58^{fg}	79	93 ± 2.13^{ghi}	93	94 ± 2.21^{ghi}	94	94 ± 2.21^{gh}	94	94 ± 2.21^{gh}	94
Indoxacarb (1 mL/L)	20 ± 2.00^{de}	20	52 ± 5.72^{cd}	52	64 ± 4.07^{bc}	64	68 ± 4.00^{bc}	68	68 ± 4.00^{b}	68	68 ± 4.00^{b}	68
Chorantraniliprole (6 mL/L)	14 ± 2.67^{bcd}	14	76 ± 3.40^{fg}	76	96 ± 1.63^{hi}	96	98 ± 1.33^{hi}	98	98 ± 1.33^{gh}	98	98 ± 1.33^{gh}	98
Chorantraniliprole (3 mL/L)	0 ± 0.00^{a}	0	54 ± 3.40^{d}	54	84 ± 3.06^{efgh}	84	90 ± 2.98^{fghi}	90	92 ± 2.49^{gh}	92	92 ± 2.49^{gh}	92
Chlorfenapyr (1 mL/L)	78 ± 3.59^{gh}	78	100 ± 0.00^{h}	100	100 ± 0.00^{i}	100	100 ± 0.00^{i}	100	100 ± 0.00^{h}	100	100 ± 0.00^{h}	100
Chlorfenapyr (0.5 mL/L)	37 ± 2.13^{f}	37	71 ± 1.80^{ef}	71	76 ± 3.06^{cde}	76	77 ± 3.00^{cde}	77	77 ± 3.00^{bcd}	77	77 ± 3.00^{bcd}	77
Methomyl (2 mL/L)	12 ± 3.27^{bcd}	12	84 ± 3.40^{fg}	84	88 ± 2.49^{efghi}	88	89 ± 1.80^{fghi}	89	89 ± 1.80^{efgh}	89	89 ± 1.80^{efgh}	89
Methomyl (1 mL/L)	5 ± 1.67^{abc}	5	75 ± 2.24^{efg}	75	77 ± 2.13^{de}	77	80 ± 2.58^{def}	80	80 ± 2.58^{cdef}	80	80 ± 2.58f	80
Phoxim (2 mL/L)	89 ± 2.77^{hi}	89	100 ± 0.00^{h}	100	100 ± 0.00^{i}	100	100 ± 0.00^{i}	100	100 ± 0.00^{h}	100	100 ± 0.00^{h}	100
Phoxim (1 mL/L)	70 ± 2.58^{g}	70	85 ± 4.28^{fgh}	85	93 ± 3.00^{ghi}	93	94 ± 2.67^{ghi}	94	94 ± 2.67^{gh}	94	94 ± 2.67^{gh}	94
Novaluron (4.0 mL/L)	3 ± 2.13^{ab}	3	49 ± 4.58^{cd}	49	80 ± 3.65^{def}	80	86 ± 2.21^{efg}	86	88 ± 2.49^{defg}	88	88 ± 2.49^{defg}	88
Novaluron (2.0 mL/L)	0 ± 0.00^{a}	0	32 ± 2.49^{b}	32	55 ± 2.24^{b}	55	59 ± 2.77^{b}	59	67 ± 2.13^{b}	67	67 ± 2.13^{b}	67
Control	0 ± 0.00^{a}	-	0 ± 0.00^{a}	-	0 ± 0.00^{a}	-	0 ± 0.00^{a}	-	0 ± 0.00^{a}	-	0 ± 0.00^{a}	-

Means followed by the same letter in the column are not significantly different according to Duncan's Multiple Range Test at α = 0.05.

Table 6. Effect of several insecticides against plant damage caused by *S. frugiperda*

Treatments	Plant damage (%+SE)		Percent reduction over control	
	Contact method	Feeding assay method	Contact method	Feeding assay method
Imidacloprid (2 mL/L)	35.56 ± 1.05[h]	20.00 ± 1.82[efgh]	59.29	75.312
Imidacloprid (1 mL/L)	91.11 ± 0.60[j]	55.56 ± 1.83[k]	1.57	38.31
Emamectin benzoate (2 mL/L)	15.56 ± 1.09[ef]	17.78 ± 1.08[defg]	80.07	77.62
Emamectin benzoate (1 mL/L)	20.00 ± 1.20[fg]	20.00 ± 1.67[efgh]	75.46	75.31
Lambda-Cyhalothrin (1.5 mL/L)	7.41 ± 0.81[abcd]	8.25 ± 0.81[ab]	88.54	87.53
Lambda-Cyhalothrin (0.75 mL/L)	19.42 ± 0.84[fg]	21.85 ± 0.65[ghi]	76.06	73.38
Indoxacarb (2 mL/L)	6.08 ± 0.70[abc]	14.60 ± 1.32[cde]	89.92	80.93
Indoxacarb (1 mL/L)	12.70 ± 0.52[de]	19.89 ± 1.15[efgh]	83.04	75.42
Chorantraniliprole (6 mL/L)	13.33 ± 1.32[de]	13.33 ± 0.57[bcd]	82.39	82.25
Chorantraniliprole (3 mL/L)	46.86 ± 0.97[i]	68.86 ± 0.931[kl]	47.55	24.48
Chlorfenapyr (1 mL/L)	3.60 ± 0.35[a]	4.87 ± 0.42[a]	92.49	91.05
Chlorfenapyr (0.5 mL/L)	10.58 ± 0.42[bcde]	16.14 ± 1.04[cdef]	85.24	79.32849
Methomyl (2 mL/L)	4.97 ± 0.21[ab]	12.75 ± 0.58[bcd]	91.07	82.85533
Methomyl (1 mL/L)	14.07 ± 1.39[ef]	21.80 ± 0.67[fghi]	81.62	73.44002
Phoxim (2 mL/L)	11.11 ± 0.97[cde]	11.11 ± 0.88[bc]	84.69	84.56153
Phoxim (1 mL/L)	24.44 ± 3.78[g]	24.44 ± 1.15[hi]	70.85	70.69345
Novaluron (4.0 mL/L)	10.19 ± 0.20[bcde]	26.50 ± 1.48[i]	85.65	68.5503
Novaluron (2.0 mL/L)	24.29 ± 0.38[g]	40.50 ± 2.28[j]	71.00	53.98517
Control	96.24 ± 1.31[j]	96.12 ± 1.31[m]	-	-

Means followed by the same letter in the column are not significantly different according to Duncan's Multiple Range Test at α = 0.05.

in the screenhouse study demonstrated that a significant reduction in plant damage to maize compared to the control, which is attributed to the reduced number of larvae in treated plants.

Field Efficacy Studies

Under field conditions, densities of *S. frugiperda* larvae were significantly reduced by all the insecticides treatments compared to the control. The results are summarized in Table 7. One days before treatment the means of larvae per plant ranged from 0.53 to 1.68 in the treatments, and there were no statistical differences among the treatments, which indicated homogeneous distribution of pest in the experimental plots. One d after the first spray, significantly least number of larvae (P < 0.05) was recorded with chlorfenapyr (0.20 larvae per plant), emamectin benzoate (0.38 larvae per plant), indoxacarb (0.55 larvae per plant), phoxim (0.93 larvae per plant), and methomyl (1.20 larva per plant). The highest efficacy (P < 0.05) the chemical control of *S. frugiperda* was observed at 4 - 7 times after applications or 44 to 65 days after planting. Mortality of *S. frugiperda* was consistently controlled by all insecticide applications with different modes of action. Emamectin benzoate, chlorfenapyr, phoxim, methomyl and indoxacarb were highly effective with percent efficacy of 100%, respectively and no significant difference was observed between them. The results of this study suggest that emamectin benzoate, chlorfenapyr, phoxim, methomyl and indoxacarb may have potential in reducing population of *S. frugiperda* in maize fields.

Plant damage are summarized in Table 8. Both vegetative and reproductive structures of the plants are consumed by the larvae. The level of plant damage due to *S. frugiperda* varied depend on the treatments. The decrease in plant damage matches with a decrease in the *S. frugiperda* population density in the same treatments. Plant damage was not significantly different during the first assessment data period at 21 DAT and 23 DAT (*i.e.*, before and after treatments were applied). The highest plant damage was found at 44 DAT or after treatments had been applied forth (P < 0.05) which is 72.78% in control treatment and the lowest was 0.00% at Indoxacarb 3 mL/L. The results show that a higher larvae population density is associated with a higher plant damage intensity. The largest reduction in plant damage was achieved with the 6 and 7weeks spray period with percent efficacy up to 100%. All the treatments were significantly

Table 7. Efficacy of insecticides on larvae of *S. frugiperda* in maize

Treatments	Population density (±SE) of *S. frugiperda* at ....DAT							
	21	23	30	37	44	51	58	65
Emamectin Benzoate (2 mL/L)	0.88 ± 0.33	0.38 ± 0.42^{cd}	0.05 ± 0.06^{b}	0.08 ±0.26^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}
Chlorfenapyr (1 mL/L)	0.95 ± 0.17	0.20 ± 0.16^{d}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.03 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}
Methomyl (2 mL/L)	0.60 ± 0.08	0.93 ± 0.54^{bc}	0.20 ±0.86^{b}	0.03 ± 0.05^{b}	0.03 ± 0.05^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}
Phoxim (2 mL/L)	1.68 ± 1.67	1.20 ± 0.47^{b}	0.10 ± 0.79^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}
Indoxacarb (2 mL/L)	0.53 ± 0.15	0.55 ± 0.31^{cd}	0.08 ±0.26^{b}	0.03 ± 0.05^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ±0.00^{b}	0.00 ± 0.00^{b}
Control	0.80 ± 0.26	1.88 ± 0.45^{a}	2.63 ± 0.47^{a}	2.68 ± 0.35^{a}	2.35 ± 0.81^{a}	1.70 ± 0.53^{a}	1.70 ± 0.43^{a}	0.30 ±0.17^{a}

Means followed by the same letter in the column are not significantly different according to Duncan's Multiple Range Test at $\alpha = 0.05$.

Table 8. Efficacy of insecticides against plant damage caused by *S. frugiperda* in maize.

Treatments	Plant damage (%±SE) at........DAT							
	21	23	30	37	44	51	58	65
Emamectin Benzoate (2 mL/L)	26.84 ± 6.38	30.00 ± 3.51	16.39 ± 3.99 ^{b}	3.89^{b} ± 1.92	2.22 ± 2.40^{b}	0.83^{b} ± 1.06	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}
Chlorfenapyr (1 mL/L)	28.06 ± 4.19	35.56 ± 3.27	16.95 ± 2.47 ^{b}	0.56^{b} ± 0.64	1.39^{b} ± 2.10	0.28^{b} ± 0.56	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}
Methomyl (2 mL/L)	26.95 ± 3.32	29.17 ± 6.38	20.28 ± 5.55 ^{b}	0.83^{b} ± 1.06	1.67^{b}± 2.13	0.28^{b} ± 0.56	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}
Phoxim (2 mL/L)	28.33 ± 3.69	34.45 ± 6.72	20.00 ± 9.03 ^{b}	0.00 ± 0.00^{b}	0.83^{b}± 1.67	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}
Indoxacarb (2 mL/L)	32.22 ± 4.35	35.00 ± 2.13	30.00 ± 21.66 ^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ± 0.00^{b}	0.00 ±0.00^{b}	0.00 ±0.00^{b}
Control	30.55 ± 6.12	35.00 ± 2.57	54.45 ± 1.29 ^{a}	64.44 ± 3.40^{a}	72.78 ± 8.42^{a}	56.67^{a} ± 11.76	27.22^{a} ±13.44	9.72^{a} ± 6.51

Means followed by the same letter in the column are not significantly different according to Duncan's Multiple Range Test at $\alpha = 0.05$.

superior over untreated control. The response of yield attributing parameters *viz.*, cob length, cob diameter and 100-grain weight of maize were presented in Table 9. Application of insecticide no influenced of the cob length (19.44 – 19.66 cm) and 100-grain weight with the average 26.27 – 28.20 g. Significant differences were recorded on diameter of cob due to insecticidal treatments. The maximum (4.55 cm) of diameter of cob was recorded from emamectin benzoate, which was followed by chlofenapyr (4.51 cm), phoxim and methomyl (4.43 cm) and indoxacarb (4.35 cm) while the minimum (4.25 cm) diameter of cob was obtained from control.

Statistical analysis shows the application of various types of insecticides has a significant effect on the maize yields per hectare. There was significant increase in weight cob of maize in all insecticide treated plots compared with control plot. The yields were closely related to a higher of *S. frugiperda* population density and plant damage. The highest yield (29.28 t/ha) was recorded from emamectin benzoat followed by phoxin (29.92 t/ha), indoxacarb (27.5 t/ha), methomyl (26.88 t/ha) and chlorfenapyr (26.38 t/ha), while the lowest (24.11 t/ha) yield was recorded from control. It is obvious that, different results were detected among insecticides treatments and increased yield per hectar up to 9.42 - 33.89% (Table 10).

From the finding of this study, it was found that emamectin benzoate, chlorfenapyr, methomyl, phoxim and indoxacarb were the most effective treatment against *S. frugiperda* in maize considering all the parameters studied *viz.*, reduction of populations densities, plant infestation, reduction of plant infestation, cob yield (t/ha) and percent increase of yield *etc.* Similar to our results, previous studies reported that emamectn benzoat and chorfenapyr effective in reduced infestation of *S. frugiperda* (Hardke *et al.,* 2011; Sharanabasappa *et al.,* 2020). Malo *et al.* (2004) reported that phoxim effective against *S. frugiperda* larvae. Belay *et al.* (2012) reported that more than 80% mortality was observed in chlorantraniliprole, flubendamide, spinosad, indoxacarb, and fenvalerate treatments 96 hr after application. Emamectin benzoate and beta cypermethrin have been widely used for the control of the *S. frugiperda* in Africa. Cruz *et al.* (2012) was reported that over 90% of larval mortality through the use of new insecticide chlorantraniliprole, flubendiamide, and was found to perform better than traditional insecticide lambda-cyhalothrin and novaluron (Hardke *et al.,* 2015; Zhao *et al.,* 2020). The result of the experiment have clearly shown that *S. frugiperda* can be controlled through the application of insecticides. Those insecticides have been used effectively for control of this pest in the Americas, the United States, Mexico, Canada and several countries in Africa (Sisay *et al.,* 2019) and Nepal (Bhusal and Chapagain, 2020).

The maize yields was closely related to a higher of *S. frugiperda* population density and plant damage. Chimweta *et al.* (2019) have

Table 10. Maize yield and % increased over control in field efficacy treatments

Treatments	Cob yields/ ha^{-1}	% Increased yield over control
Emamectin Benzoate (2 mL/L)	32.28^{a}	33.89
Chlorfenapyr (1 mL/L)	26.38^{bc}	9.42
Methomyl (2 mL/L)	26.88^{bc}	11.49
Phoxim (2 mL/L)	29.92^{ab}	24.1
Indoxacarb (2 mL/L)	27.65^{bc}	14.68
Control	24.11^{c}	-

Means followed by the same letter in the column are not significantly different according to Duncan's Multiple Range Test at α = 0.05.

Table 9. Yield component of maize at different treatment

Treatments	Cob length (cm)	Cob diameter (cm)	100-grain weight (g)
Emamectin Benzoate (2 mL/L)	19.44	4.55^{a}	27.83
Chlorfenapyr (1 mL/L)	19.48	4.51^{a}	26.27
Methomyl (2 mL/L)	19.66	4.43^{ab}	28.2
Phoxim (2 mL/L)	19.58	4.43^{ab}	27.56
Indoxacarb (2 mL/L)	19.49	4.35^{bc}	28.01
Control	19.14	4.25^{c}	23.17

Means followed by the same letter in the column are not significantly different according to Duncan's Multiple Range Test at α = 0.05.

reported leaf, silk and tassel damage levels ranging between 25 and 50% and grain yield decrease of 58%. Cruz and Turpin (1983) reported that a 15% yield reduction from 98% of plants infested and 35% from 100% infested. Baudron *et al.* (2019) reported that yield loss up to 12% at 60% plants infested. The reduction in yield was due to the feeding of the cob and kernels by the larger larvae that are present in the whorls of older plants (Abrahams *et al.,* 2017; Capinera 2017). Therefore, higher intensity of *S. frugiperda* attack is associated with a lower production of maize cobs at harvest time.

This study provides valuable information about the efficacy of insecticides with relatively novel modes of action to manage *S. frugiperda*. In Florida, *S. frugiperda* is one of the most important sweetcorn pests, and synthetic insecticides are applied against *S. frugiperda* to protect both the vegetative stages and reproductive stage of corn (Capinera, 2017). Gutierrez-Moreno *et al.* (2019) reported that maize farmers needed to spray up to 12 time to control *S. frugiperda.* The intensive application of chemical insecticides to control *S. frugiperda* was up to 3 - 5 sprays per season (Blanco *et al.,* 2014; Burtet *et al.,* 2017). Therefore, number of insecticides spraying depending of seriously infested fields. However, insecticides should be applied no later than 25 days after planting for keeping the plants free of larvae during the vegetative period and the number of sprays needed reduced during the silking period. The young plant (vegetative stage) leaf tissue is suitable for growth and survival, on more mature plants the leaf tissue is unsuitable, and the larvae tend to settle and feed in the ear zone, and particularly on the silk tissues. The present results are in agreement with Malo and Hare (2020), detecting of *S. frugiperda* infestations before they cause economic damage is the key to their management. On maize, if 5% of seedlings are cut or 20% of whorls of small plants (during the first 30 days) are infested with *S. frugiperda*, it is recommended to apply an effective control measure to prevent further damage. Present findings are in agreement with the reports of Wu *et al.* (2020) who reported that maize can be damaged at any stage, especially young leaves and growing points. It is also the most preferred oviposition plants for adults, the hatching rate and survival rate on maize are significantly higher than on other plants. Larvae of *S. frugiperda* usually attack at the early stage of maize it caused heavily damaged and yield reductions (Xu *et al.,* 2019).

CONCLUSION

The results of the present research revealed that all of insecticed tested were showed good results in terms of population densities, damage reduction, and yield increase. The results showed that among insecticides tested, the highest mortality (>80%) were noted with emmamectin benzoat, chlorfenapyr, phoxim, methomyl and indoxacarb under laboratory, screenhouse and field conditions. Among all the treatments, significantly higher maize yield of 29.28 t/ha was recorded in emmamectin benzoat with 33.89% increase over control, followed by phoxim (29.92 t/ha), indoxacarb (27.5 t/ha), methomyl (26.88 t/ha) and chlorfenapyr (26.38 t/ha) with a per cent increase of 24.10, 14.68, 11.49 and 9.42% over control. The lowest yield was noticed in untreated control (24.11 t/ha). Emmamectin benzoate was consistently more effective than other insecticides at suppressing *S. frugiperda* populations and protecting maize plants. Furthermore, these insecticides can be used as one of the components of integrated pest management of *S. frugiperda* in Indonesia.

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