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Comparative analysis of unmanned aerial vehicle and conventional spray systems for the maize fall armyworm *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera; Noctuidae) management

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Abstract: Insecticidal interventions at critical stages of maize are an important strategy for managing invasive insect pest fall armyworm (FAW) *Spodoptera frugiperda* (J.E. Smith). Conventional spraying systems cannot be used over larger areas, and the insecticide application using unmanned aerial vehicles is becoming popular among peasants. As the FAW resides inside the maize whorls, targeted insecticide application is necessary for effective management. The efficacy of (UAV) spray with different types of nozzles was compared with the conventional spray system, namely high-volume spray and Control droplet applicator. The other spray systems' droplet density, efficacy, and residues of insecticides in plants, soil and water were studied. The UAV droplet density up to 5 m swath recorded no significant variation for both nozzles. A UAV with an atomizer nozzle was as effective as a high-volume spray in reducing the FAW infestation. The residue analysis of leaf samples from the study area revealed more residues in the control droplet applicator and UAV atomizer nozzle. The per cent reduction of initial deposits in the top, middle and bottom maize leaves was least in the UAV atomizer nozzle. The insecticide residues in the study sample area were also below the detectable limit. UAV usage in maize saves time and reduces FAW damage as that of high-volume sprayers.

Keywords: atomizer nozzle; flat fan nozzle; high volume spray; control droplet applicator

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Maize (*Zea mays* L.), the 'Queen of Cereals', is among the widely cultivated and consumed crops worldwide for food, fodder, fuel, and various industrial purposes. In India, maize is grown on 90.29 lakh ha with 27.2 million t of production. Though maize can potentially increase the farmer's income, the biotic and abiotic stresses reduce the productivity of maize. Annually, insect pests destroy 20% of crop production worldwide (Pretty & Pervez Bharucha 2015). The incidence of stem borers, aphids, and armyworms significantly impairs maize yield. The fall armyworm (FAW) *Spodoptera frugiperda* (J.E. Smith) invasion from tropical and sub-tropical America to the African countries threatened maize cultivation in that region. It infests over 350 plants across 76 families (Montezano et al. 2018). In India, after the first incidence in Karnataka, it spread quickly to all the maize-growing regions because of its migrating ability and lack of native natural enemies in the introduced area (Deshmukh & Kalleshwaraswamy 2018; Suby et al. 2020).

The approximate avoidable yield loss due to fall armyworm infestation was estimated to be 2 500 kg/ha (Srinivasan et al. 2022). The window-based application of selected insecticides proved a better option for FAW management, though other methods are available (Suganthi et al. 2022). As farmlands are highly fragmented in India, indiscreet spraying leads to possible pest migration to unsprayed areas (Subramanian et al. 2021). Thus, large-scale application of insecticides is the key to effective management. Unmanned aerial vehicles (UAV) are used for spraying in developed countries (Everaerts 2008; Zhang & Kovacs 2012). While manned fixed-winged aircraft are used in thinly populated countries with large monocropping areas, an Unmanned Aerial Vehicle (UAV) is considered ideal in regions with undulated, fragmented fields and diversified cropping patterns (Qin et al. 2016). UAVs have been used to apply fertilizers, insecticides, fungicides, and other crop protection materials (Subramanian et al. 2021). The potential to cover the edges of small fields is the advantage of UAVs compared to fixed-winged aircraft or helicopters. Besides this, good mobility, adaptability at different altitudes, suitability in undulated areas, non-requirement of specialized landing platforms, reduced labour requirement, saving of time and energy, quick response time, vast area coverage, and minimum training of UAVs are some of the advantages for employing in agriculture (Shamshiri et al. 2018). On the contrary, poor penetrability into crop canopy, low droplet coverage ratio, heterogeneous droplet distribution and pesticide drift are some of the practical issues in UAVs which may limit their use in the long run (Qin et al. 2016; Mogili & Deepak 2018). Low permeability, coupled with reduced target reach, results in control failure and may have sublethal effects on the target pests, leading to resistance and resurgence problems. (Torrent et al. 2017).

The use of UAVs for agricultural operations is gaining momentum in India after the nod by Union Agriculture Ministry and Central Insecticides Board and Registration Committee for about 477 registered pesticides (https://timesofindia.indiatimes.com/business/india-business/govt-approves-477-pesticides-for-being-sprayed-by-drones/articleshow/90942684.cms). Though many private players operate in India, published data on the efficacy of insecticides in UAV applications is very scanty, and drone operators mostly use less than the recommended quantity of insecticide active ingredient. This may lead to reduced efficacy, increased pesticide usage, pest resistance, and health and environmental risks (Wang et al. 2020). UAV spray systems require low spray fluid and higher insecticide concentrations than high-volume spray systems. The little droplets of < 50 μm size will be removed by drift, while oversized droplets (> 400 μm) will not penetrate the crop canopy uniformly. Hence, medium-sized droplets are desired for pesticide application (50–300 μm) for effective penetration and reduced drift (Hewitt 2008), which can be managed using appropriate nozzles. The present research compared the efficacy of UAVs fitted with atomizers and flat fan nozzles with conventional spray systems, namely high-volume sprayers and control droplet applicators, to manage the fall armyworm in maize. In addition, the spray droplet distribution was analyzed by studying the pesticide deposition in soil and water in different parts of maize plants.

MATERIAL AND METHODS

Field experiments

Field experiments were conducted in two locations during 2020–2022 at Perumbalanur, Tiruvannamalai, Tamil Nadu, India (11.14374 N; 79.12802 E) (Location I) and Tamil Nadu Agricultural University

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(TNAU) research farm, Coimbatore, Tamil Nadu, India (11.07396 N; 76.561272 E) (Location II). The commercial maize hybrid Kaveri 6681® (Ms Kaveri seeds, Secunderabad, Telangana) was sown in 0.6 ha at 75 × 20 cm spacing in location I. The field was divided into blocks to evaluate the different spray techniques (Table 1). Each field was left with a buffer space of 1.5 m around the borders to avoid spray drift. In location II, the University hybrid CoHM 8 was sown in 0.6 ha at 75 × 20 cm spacing. Experimental fields were divided into four blocks with a buffer space of 80 m^2 left between treatments to avoid drift effects. Tamil Nadu Agricultural University (TNAU) recommended agronomic practices be followed in both locations (TNAU Agritech Portal 2021). The insecticides recommended in TNAU fall armyworm integrated pest management modules were applied at critical maize growth periods (Suganthi et al. 2022). For the window, I [15–20 days after sewing (DAS)], emamectin benzoate 5% SG @ 10 g/ha (EM1®, Ms Dhanuka Agritech Ltd.) and window II (35–40 DAS) chlorantraniliprole 18.5% soulble granule (SC) @ 30 g/ha (Coragen®, Ms FMC India Ltd., India) were applied to evaluate the efficacy of different spray systems.

Sprayers and operating parameters

The different spray systems, namely UAV with atomizer nozzle, UAV with flat fan nozzle, high volume sprayer (battery-operated knapsack sprayer), and control droplet applicator (CDA), were evaluated in both locations. The quadcopter comprises an airframe, propulsion system, and command and control system. The spraying system comprises a 16 L tank, 12 direc current (DC) diaphragm pressure pump, transparent water hoses, four nozzles and an electronic control valve.

The configuration of the UAV is as follows:

Type of Drone: Engine-operated drone/UAV
Number of rotors: 4
Pitch circle diameter: 1.35 m
Forward speed: 3 m/s
Payload capacity: 10 L
Height of spray: 1 m from the crop canopy
Wind speed: 6 km/h
Types of nozzle fitted: Flat fan and Centrifugal atomizer

UAV spray efficacy was compared with a high-volume knapsack sprayer (battery operated, 16 L & 12 DC output) and Control Droplet Applicator (CDA) of one-litre capacity.

Application of insecticides through different spray techniques

The spray application area was measured using GPS connected with a UAV. The insecticide active ingredient required for the treatment area was measured using a weighing scale and mixed with a known quantity of water for spray (UAV). After thoroughly mixing with an estimated amount of water poured into the spraying machine, the remaining water required for the treatment area was added (Table 2) and thoroughly mixed. Insecticide spraying was carried out during the early morning hours when the wind speed was < 2.5 km to minimize the drift. UAV pilots monitored the flight speed and height (Figure 1).

Similarly, the insecticide required for a high volume sprayer and control droplet applicator was quantified for the treatment area with the help of hand-held GPS

Table 1. Experiment field details

Experiment area	Spray technique	Thiruvannamalai farmers field (location I)			Tamil Nadu Agricultural University research field (location II)			Spray fluid/ha (L)
		field parameters (m)	buffer zone* (m^2)	total area (m^2)	field parameters (m)	buffer zone# (m^2)	total area (m^2)	
Block A	unmanned aerial vehicle with atomizer nozzle	28.5 × 27.5	96.00	783.75	40 × 20	80.00	800	60
Block B	unmanned aerial vehicle with flat fan nozzle	29.0 × 25.5	95.25	739.50	40 × 20	80.00	800	60
Block C	battery-operated knapsack sprayer	25.5 × 28.0	94.50	714.00	40 × 20	80.00	800	500
Block D	control droplet applicator	20.5 × 18.5	94.50	379.25	40 × 20	80.00	800	5
Block E	untreated control	18.5 × 16.5	–	305.25	40 × 20	20.00	800	–

*Buffer zone around the treatment; #Buffer zone in between the treatments

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Table 2. Insecticides applied at different growth stages in different sprayers

Sprayer	Thiruvannamalai farmer field (Location I)				TNAU research farm (Location II)			
		insecticide quantity (g)				insecticide quantity (g)		
	treatment area (m^2)	Window I Emamectin benzoate 5% SG	Window II Chlorant-raniliprole 18.5% SC	spray fluid (L)	treatment area (m^2)	Window I Emamectin benzoate 5% SG	Window II Chlorant-raniliprole 18.5% SC	spray fluid (L)
Unmanned aerial vehicle with atomizer nozzle	783.75	0.78	2.34	2.35	800	0.80	2.4	2.4
Unmanned aerial vehicle with flat fan nozzle	739.50	0.73	2.21	2.20	800	0.80	2.4	2.4
High volume spray	714.00	0.71	2.14	35.50	800	0.80	2.4	40.0
Control droplet applicator	379.25	0.38	1.13	0.20	800	0.80	2.4	0.40

SG – soulble granule; SC – soulble concentrate

(Model Garmin e Trax 32X). The spray fluid requirement per hectare was 500 L. The quantity of spray solution was worked out for the estimated area. The treatment area, active ingredients, and spray fluid volume are given in Tables 1 and 2. Spraying was resorted to when the infestation reached grade 3 in different treatments, while the second spray was decided based on the intensity of FAW infestation (Srinivasan et al. 2022). At location I, the first spraying was initiated on November 7, 2020, followed by a second spray on November 28, 2020. At location II, the first spraying was done on March 9, 2021, and the second spray was done 17 days later.

Efficacy of different sprayers

The FAW damage score was recorded using different spray techniques to evaluate the biological efficacy. The FAW infestation was scored per the

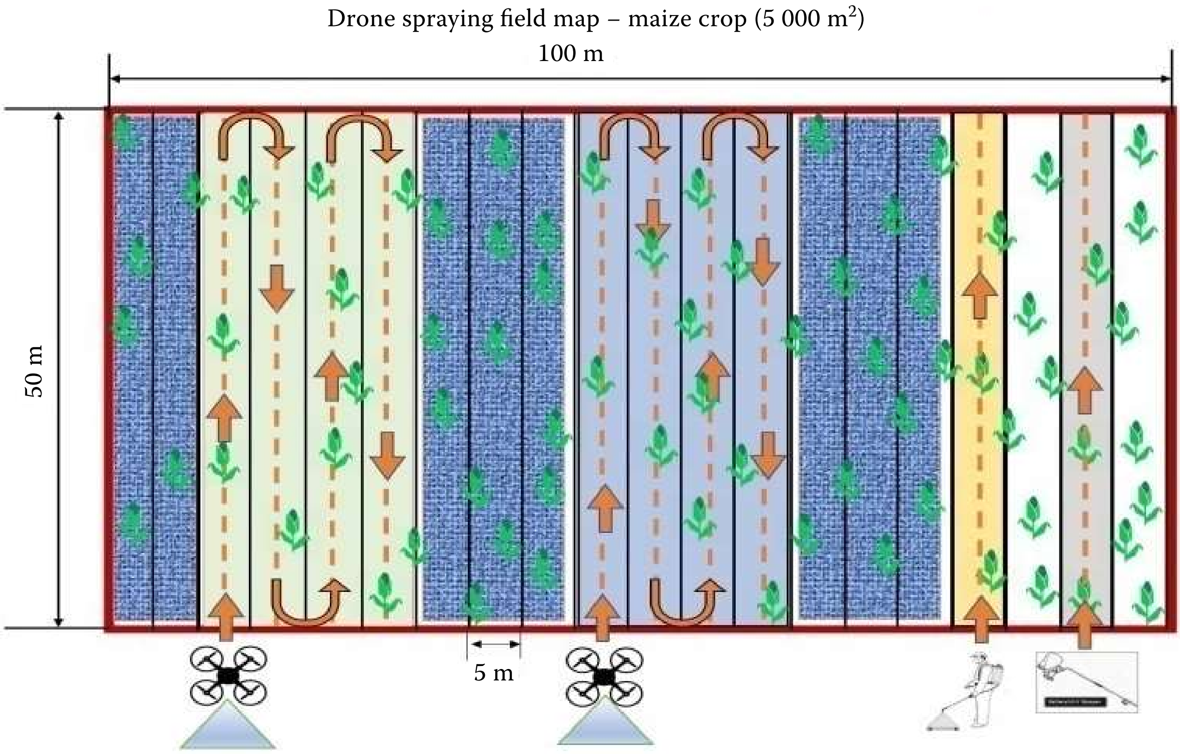

Figure 1. Different types of spray techniques application

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TNAU damage scale (Srinivasan et al. 2022). From each block, five spots, namely four corners and one centre, were selected, leaving the extreme corners of the block, and ten plants from each spot were tagged for observation, totalling 50 tagged plants for observation besides recording 50 randomly selected plants (untagged) to avoid observer bias. The scoring was done one day before treatment (pretreatment), followed by 5, 10, and 15 days after each spraying (DAS). The poled mean of 5, 10, and 15 DAS scores was arrived. The formula used for the calculation is as follows.

Spray droplet distribution measurement

The swath of the UAV is an essential parameter in deciding the spray fluid's volume and coverage. The spray samples were collected at 1 m, 3 m, and 5 m away from the centre of the spray area and analyzed for the volume median diameter (VMD) and droplet density (Nos. / cm^2) of the atomizer and flat fan nozzle (Figure 2).

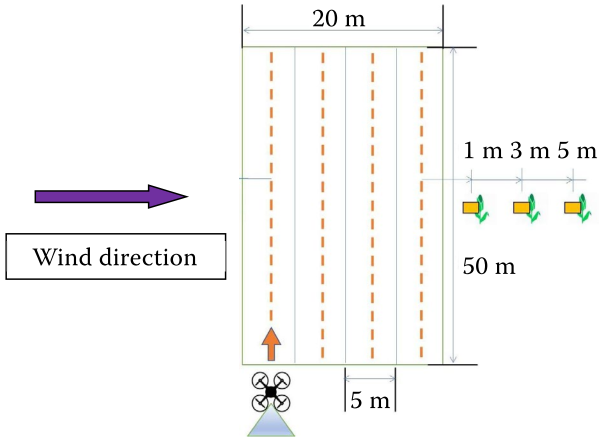

Figure 2. Sample collection for residue analysis from the experimental plots

Residue analysis

Sample collection from the field. The maize leaf samples were collected from the randomly selected five spots in each spray technique at location I after the first spray and the second spray. To study the vertical deposition, in location II, the maize leaf samples were collected from the top (60 cm), bottom (10 cm), and middle canopy (30 cm) from ground level in plots receiving different treatments after the first spray. Soil samples were collected from the sprayed plots at four corners and the centre following standard protocol. Water samples were collected from the surface water source near the spray area, earmarked for sampling in a windward direction. In all the spraying systems, leaf, soil, and water samples were collected within two hours after spraying and transported in ice-cool boxes to the laboratory for analysis.

Extraction and clean up of plant, soil, and water samples. The residue extraction from the maize leaves followed the procedure described by Suganthi et al. 2022. The extraction of residues from the soils collected from the different spraying technique areas was done following the standard protocol (Suganthi et al. 2017). The methodology described by Sharma, 2013 was followed to analyze the water samples collected from both locations after applying insecticides through different spray gadgets.

Chemicals and reagents. The critical inputs for residue analysis, namely certified reference materials of chlorantraniliprole and emamectin benzoate (> 90% purity), MS grade acetonitrile, and formic acid, were purchased from M/s Sigma Aldrich, India. M/s Merck India Ltd, India supplied magnesium sulphate and anhydrous sodium chloride (AR grade). Primary, secondary amine (PSA) and Graphical Carbon Block (GCB) were procured from M/s Agilent Technologies India Private Ltd. Ultra-pure water required for analysis and instrumentation was obtained from Q3 Merck Millipore unit installed in the laboratory. Stock solutions of pesticides (400 ppm) were prepared using acetonitrile and stored at –20 °C. The intermediate stock solution was diluted to prepare a working standard mix. The formulations of chlorantraniliprole (18.5% SC) and emamectin benzoate [5% souslble concentrate (SG)] were purchased from local pesticide outlets.

Instrument and operating parameters. Initial deposits were analyzed using Waters Alliance 2695 Liquid chromatography Separations Module fitted with Xterra analytical column C18, 5 μm (4.8 × 250 mm) (Waters, Milford, MA, USA) and coupled with Acquity TQD Mass spectrometry with electrospray ionization interface in positive mode. Waters Masslynx software (version 4.1) was employed for instrument control and data acquisition. An isocratic flow of mobile phase consisting of acetonitrile: water with 0.1% formic acid (50:50, *v*/*v*) @ 0.5 mL/min was followed, facilitating the elution of both the analytes within 10.0 min. For MS/MS, the optimum parameters were namely 3.5 KV voltage, 150 °C ion source temperature, and 500 °C

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desolvation temperature. The cone and desolvation gas flow were set at 50 and 1 100 L/h, respectively. Working standard solutions were directly infused into the mass spectrometer to identify the parent and daughter ions, and the chromatograms were recorded in full scan mode.

Data analysis

Significant differences between the treatments were calculated using analysis of variance (ANOVA), and means were separated by least significant difference (LSD) at 95% using SPSS (version 21.0) package. The percentage and damage scores were subjected to appropriate transformations before performing a mean comparison. For residue analysis, the chromatogram data were used to calculate residue concentration. The residue quantification process was performed by applying the following equation with inputs from the chromatogram.

$$Residues\ (\text{mg/g}) = \frac{As}{Astd} \times \frac{Wstd}{Ws} \quad (1)$$

where: *As* – sample peak area; *Astd* – standard peak area; *Wstd* – weight of standard (μg/mL); *Ws* – weight of the sample (g/mL)

RESULTS

Spray droplet distribution

The spray swath decides the quantum of spray fluid required to cover a unit area. The present investigation studied the efficacy of atomizer and flat fan nozzles mounted on UAV against *S. frugiperda* at different swath widths. Volume Mean Diameter (VMD) is the mid-way drop size that is reached when the accumulated volume of smaller drops accounts for 50% of the sprayed liquid leaving the nozzle. The atomizer nozzle recorded a VMD of 258, 223, and 219 μm from 1 m, 3 m, and 5 m swath (F = 6.36), whereas the VMD for the flat fan nozzle were 267, 220, and 213 μm (F = 12.27) (Table 3).

Efficacy of different spray techniques against fall armyworm infestation

The fall armyworm scores in the different treatments were on par with each other before imposing treatments in location I (Figure 3). In emamectin benzoate 5% SG treated plots, the pooled mean score (average of 5,10 and 15 days after spraying) after the first spray was the lowest in high volume spraying (1.50) and was on par with drone atomizer spraying (1.59), while the control registered a mean score of 2.85 (F = 38.46). The high-volume spraying recorded a significantly higher reduction in FAW damage (51.09%), followed by drone atomizer-sprayed fields (41.40%). The insecticide chlorantraniliprole 18.5% SC was used in the second window spraying, and a similar trend of FAW reduction was recorded (F = 29.57). The per cent reduction in FAW infestation was maximum in High volume spraying (51.09%), which was closely followed by drone atomizer (41.40%). A similar trend in the reduction of infestation was observed in untagged plants (F = 22.62).

At location II (Coimbatore), the FAW damage in different treatments in tagged plants before imposing treatments ranged between 3.38 and 3.60, with no significant difference. The maximum per cent reduction in score levels in the tagged and untagged plants was more in high-volume spraying, followed by drone atomizer sprayed fields (Figure 4) (F = 24.60 & 13.50). A maximum of 60.73% reduction was observed in high-volume spraying followed by drone atomizer (51.66%). The high-volume spray was again significantly superior in the second spray as it recorded the

Table 3. Spray droplet distribution pattern of unmanned aerial vehicles in maize ecosystem

Sample No.	Distance from the centre	Unmanned aerial vehicles (UAV) with atomizer nozzle		UAV with flat fan nozzle	
		Volume median diameter (VMD)	Droplet density per cm^2	VMD	Droplet density per cm^2
1	1 m	258 ± 8.5^a	57 ± 7.8	267 ± 9.8^a	54 ± 7.6
2	3 m	223 ± 8.0^b	55 ± 8.1	220 ± 6.8^b	48 ± 7.2
3	5 m	219 ± 8.5^b	52 ± 7.7	213 ± 5.5^b	42 ± 7.6
	F-value	6.36	0.11	12.27	0.75
	LSD (P < 0.05)	0.0081	NS	0.0004	NS

Cumulative mean of ten replications; SE – standard error; mean values followed by the same superscript alphabet (s) in the columns do not differ significantly by least significant difference (LSD) (P < 0.05)

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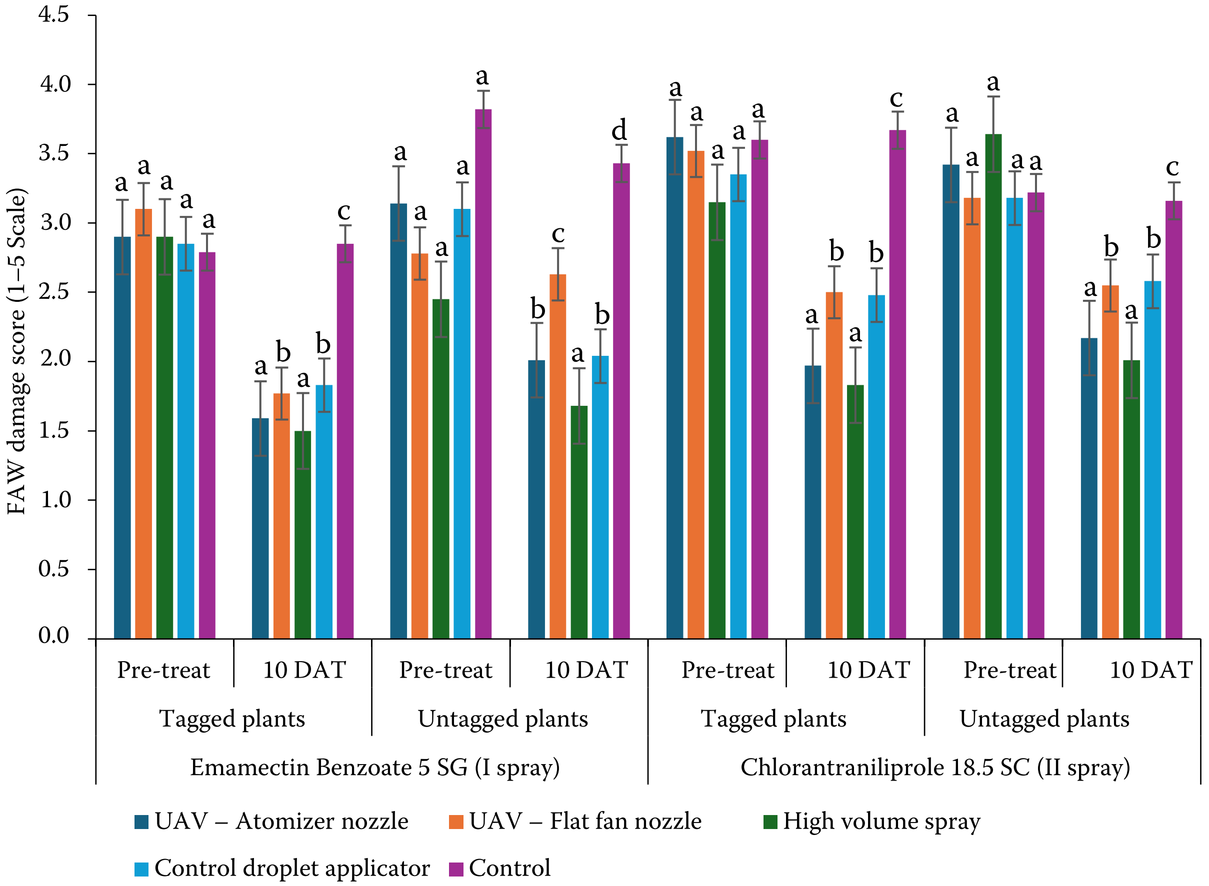

Figure. 3. Efficacy of different spraying systems against fall armyworm *Spodoptera frugiperda* at location I. Bars are means of fifty plants (four replication) at each location, and bars followed by the same letter(s) are not significantly different by least significant difference (LSD) ($P < 0.05$) (DAT – days after treatment; UAV – unmanned aerial vehicle); SG – soulble granule; SC – soulble concentrate

lowest damage score (1.42; 59.31% reduction) in the tagged plants ($F = 56.35$), whereas in untagged plants, the high-volume spraying (1.10; 55.82% reduction), as well as drone atomizer (1.15; 53.82%), were almost equal in reducing the FAW damage ($F = 35.26$).

Spray particle deposition in different systems

The UAV atomizer and control droplet applicator spray recorded higher emamectin benzoate 5% SG residues (0.80 and 1.23 µg/g) ($F = 23.68$) (Figure 5). The chlorantraniliprole 18.5% SC resi-

Table 4. Initial deposits of chlorantraniliprole 18.5% soulble concentrate (SC) in unmanned aerial vehicles (UAV) – sprayed maize plots

Sample Location	High-volume spray (HVS) (µg/g)	Control droplet applicator (µg/g)	Reduction of initial deposit over HVS (%)	UAV – atomizer nozzle (µg/g)	Reduction of initial deposit over HVS (%)	UAV – flat fan nozzle (µg/g)	Reduction of initial deposit over HVS (%)
Top leaves	59.55 ± 9.87[a]	21.87 ± 4.39[a]	63.27	47.19 ± 2.79[a]	20.75	39.61 ± 1.01[a]	33.48
Middle leaves	45.79 ± 3.37[ab]	19.37 ± 2.33[a]	57.69	36.81 ± 9.66[a]	19.60	33.30 ± 1.61[b]	27.27
Bottom leaves	34.96 ± 4.43[b]	5.77 ± 0.28[b]	83.49	22.92 ± 2.89[b]	34.45	18.97 ± 0.53[c]	45.73
F-value	2.76	8.54		4.70		69.43	
LSD ($P < 0.05$)	0.0902	0.0025		0.0028		< 0.0001	

Cumulative mean of five samples; SE – standard error; Mean values followed by the same superscript alphabet (s) in the columns do not differ significantly by least significant difference (LSD) ($P < 0.05$)

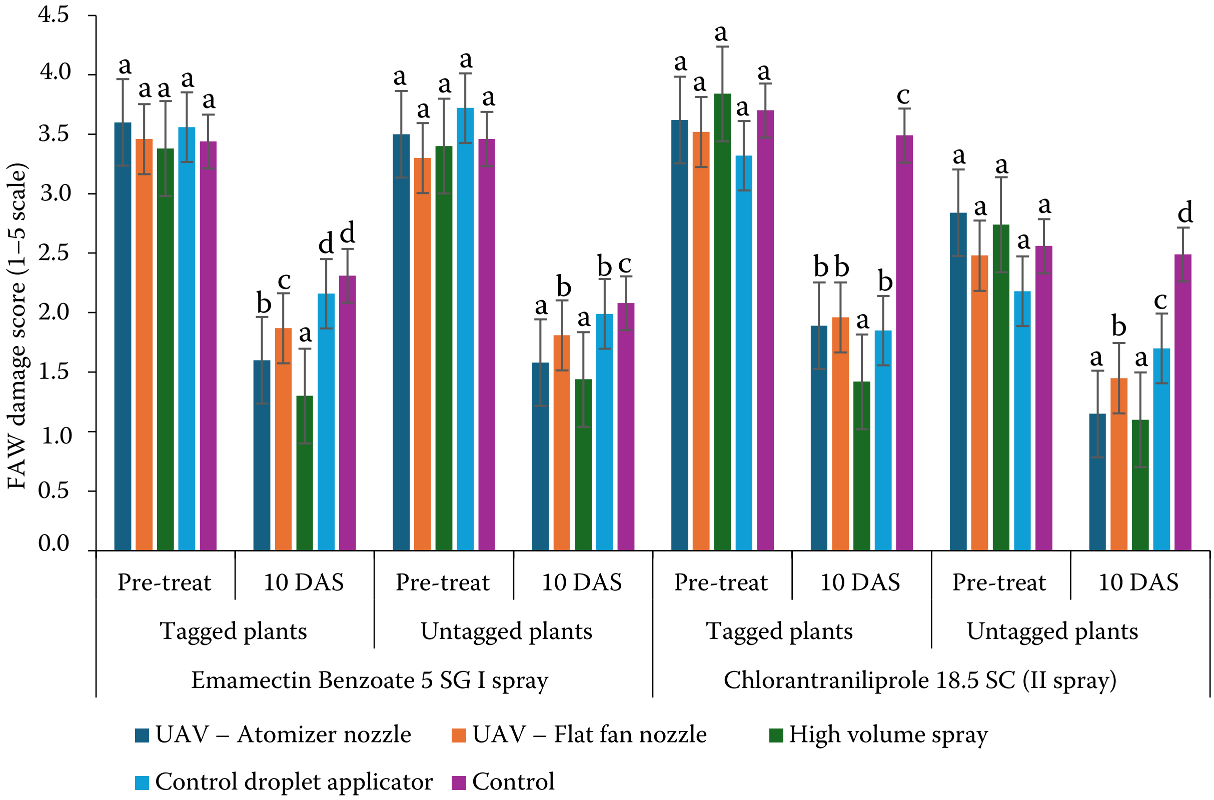

Figure. 4. Efficacy of different spraying systems against fall armyworm *Spodoptera frugiperda* at location II. Bars are means of fifty plants (four replication) at each location, and bars followed by the same letter(s) are not significantly different by least significant difference (LSD) (P < 0.05) (DAT – days after freatment; UAV – unmanned aerial vehicle); SG – soulble granule; SC – soulble concentrate

dues were more in high volume sprayer (54.66 µg/g) (F = 983.13) (Figure 6). The deposition of chlorantraniliprole 18.5% SC was maximum (59.55 µg/g) in high-volume spraying, followed by UAV atomizer (47.19 µg/g), UAV flat fan (39.61 µg/g) and ultra-low volume sprayer (21.87 µg/g) (Table 4). It was also noticed that the initial deposits were more in the top leaves, followed by the middle and bottom leaves.

Insecticide residues in soil and water

The emamectin benzoate deposits in soil and water were below the detectable limit (BDL) in all the evaluated spraying systems (Table 5). The initial deposits of chlorantraniliprole 18.5% SC were BDL in soil and water for high volume and control droplet spray. The initial deposits in water were above the acceptable level for the UAV atomizer and UAV flat fan nozzle (2.81 and 0.30 µg/L).

Table 5. Residues of insecticides in soil and water in maize fields sprayed with Unmanned aerial vehicles (UAV)

Samples	Insecticide	High volume sprayer (µg/g)	Controlled droplet applicator (µg/g)	UAV – Flat fan nozzle (µg/g)/(µg/L)	UAV – Atomizer nozzle (µg/g)/(µg/L)
Soil	Chlorantraniliprole 18.5% SC	BDL	BDL	BDL	BDL
	Emamectin benzoate 5% SG	BDL	BDL	BDL	BDL
Water	Chlorantraniliprole 18.5% SC	BDL	BDL	0.30	2.81
	Emamectin benzoate 5% SG	BDL	BDL	BDL	BDL

Values are the mean of three replications; level of quantification for water: 0.0005 µg/L or 0.0005 ppb; level of quantification for soil: 0.020 µg/g; BDL – below detectable limit

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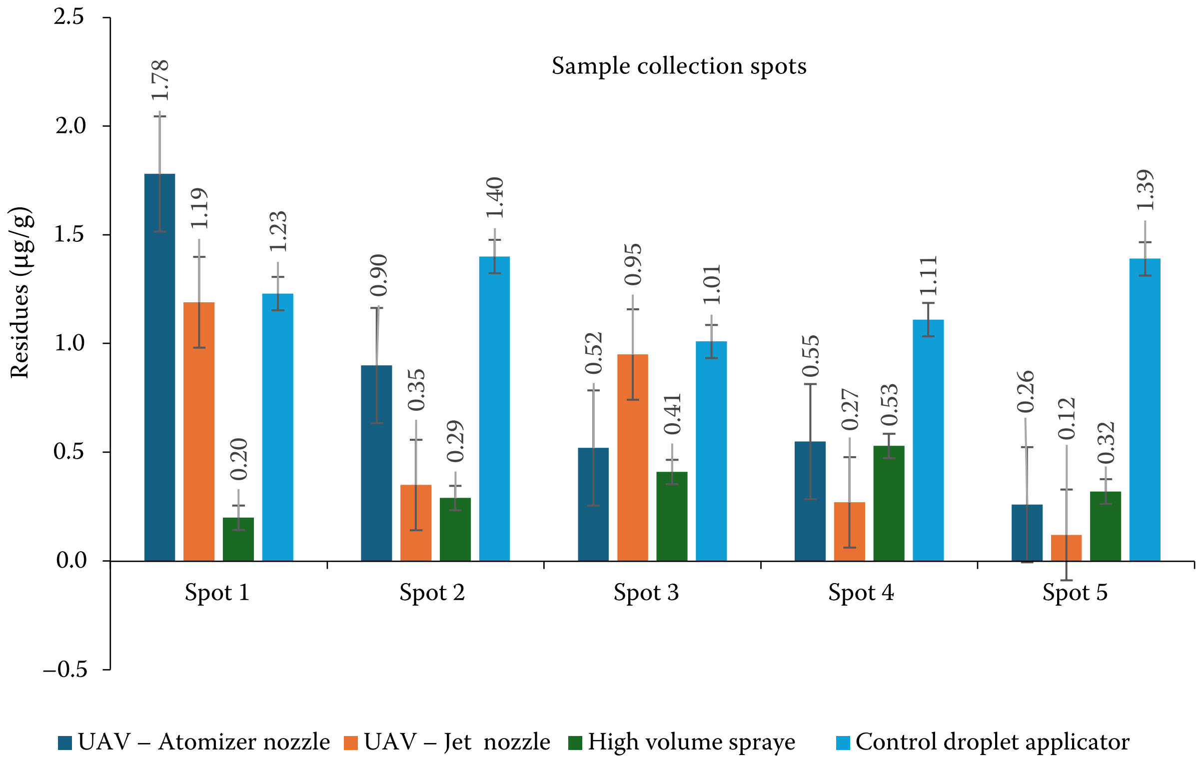

Figure 5. Emamectin benzoate 5% soulble granule (SG) residues in maize leaves under different spraying systems (UAV – unmanned aerial vehicle)

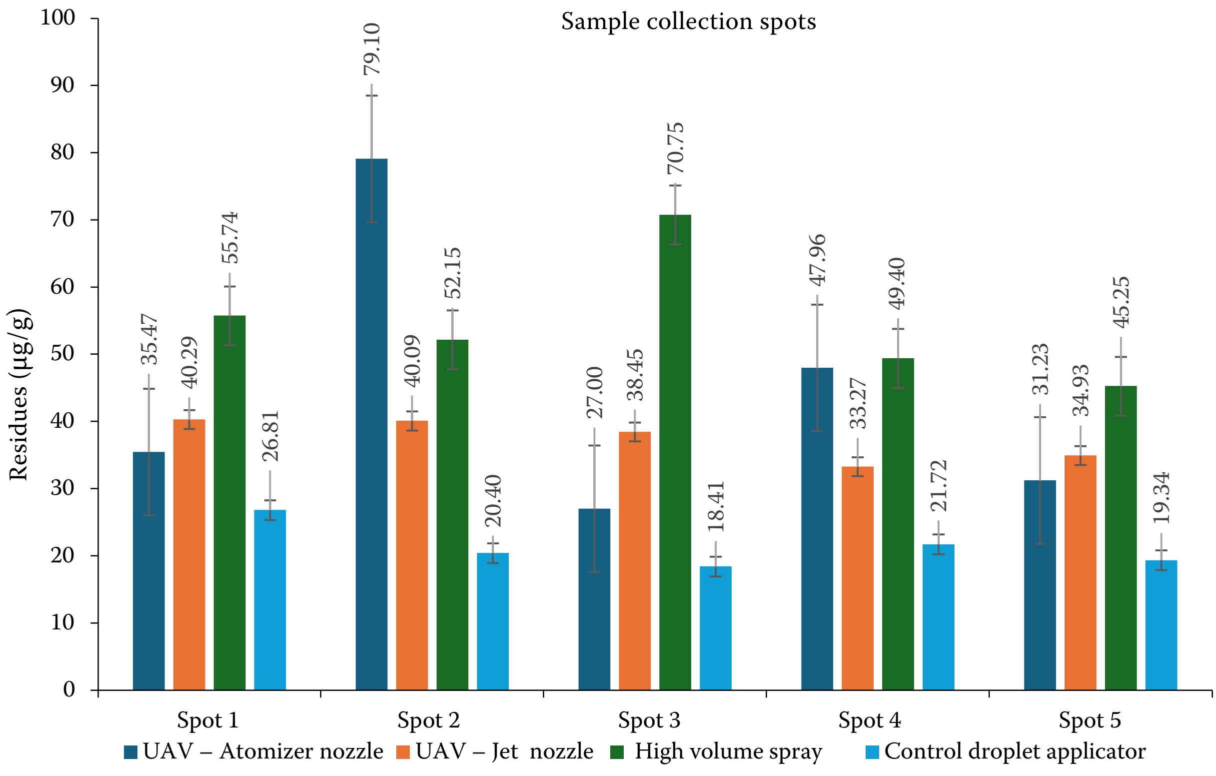

Figure 6. Chlorantraniliprole 18.5% SC residues in maize leaves under different spraying systems (UAV – unmanned aerial vehicle)

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DISCUSSION

Spray droplet distribution in the maize leaves is one of the important aspects to consider in deciding the spraying system's suitability. VMD should be in the range of 140 to 200 μm for effective control of insects (Matthews 1975). The smaller droplets are more prone to drift, and the prevailing wind carries them. On the other hand, larger droplets do not adhere to the plant and are prone to runoff (Cox et al. 2000). VMD > 150 μm is considered desirable to reduce the risk of drift in spraying systems (Forster et al. 2014). Wolf and Daggupati (2009) inferred that smaller droplets tend to have a greater affinity for plant surfaces, especially on grasses, due to their primarily vertical orientation. In the present study, the VMD of spray particles does not vary much between 3 m and 5 m swath widths. The atomizer and flat fan nozzle are equally effective in spray droplet distribution. Qin et al. 2014 observed that 7 m working height and 7 m spraying swath were optimum for achieving maximum maize deposition.

The atomizer nozzle will be highly suitable at a higher swath (5 m) as it recorded more droplet density/cm^2 (52 cm^2) than the flat fan nozzle (42 cm^2) in the present investigation (Table 3). A droplet density of 30/cm^2 could achieve satisfactory levels of insect control (Song et al. 2020). The deposition of the droplets on the target surface has to be uniform to achieve satisfactory levels of control (Munthali et al. 1986; Shan et al. 2022). The droplet density in the upper leaves of sugarcane was 54.61 per cm^2, which was considered ideal and even (Zhang et al. 2020). In the present study, the droplet density was higher in upper leaves than in lower leaves.

The spray volume used was 30 L/ha for the UAV application's atomizer and flat fan nozzle. The spray volumes of 30 l/ha and 22.5 L/ha didn't differ significantly in reducing FAW infestation (Shan et al. 2022). In UAV systems, increased spray volume would increase coverage, deposition, and droplet density (Chen et al. 2020). The larger application volume will have an excellent biological effect (Wang et al. 2019) besides increasing the efficacy, cost, and duration.

In our studies, the UAV drone spraying reduced the fall armyworm damage on par with the high-volume spraying in both locations. The efficacy of chlorfenapyr and chlorantraniliprole through drone application reduced the fall armyworm menace by up to 94.94% (Qin et al. 2014). The efficacy of UAV application against fall armyworms ranged from 59.4% to 85.4% (Shan et al. 2022). Lou et al. 2018 recorded 64.0% and 90.0% control efficiency against cotton aphids in UAV and boom sprayer application on the fifth day after spraying.

The coverage of spray fluid in different spraying systems shows differences. High-volume spraying offers thorough coverage compared to drone atomizer spray. The manual spraying quickly targets the central whorls where the fall armyworm larvae cause severe damage. However, the flat fan nozzle did not deliver spray fluid precisely to the central whorls where the larva resides, which was evident from the relatively poor efficacy. The higher spray volume (> 16.8 L/ha) with coarse nozzles recorded comparable deposition and higher efficiency against rice blast and leaf folder (Wang et al. 2020). The spray coverage increased from 27.5–59.5%, and the droplet density increased from 36.6–50.9% when the spray volume in UAV increased from 9 L/ha to 18 L/ha.

The canopy coverage is essential for the higher biological efficiency of any spraying mechanism. The real-time residues in the leaf surface will indicate crop canopy coverage. The average coverage of upper, middle, and lower layers in cotton was 2.5%, 3.2%, and 1.9%, respectively (Lou et al. 2018). They also revealed that an increase in flight height up to 2 m weakens the vertical field above the crop canopy and results in the drifting of droplets. The solid downward airflow from the rotor causes the cotton plants to sway substantially and causes a significant change in the deposition of droplet density on the cotton canopy (Wolf & Daggupati 2009). More significant momentum will cause the droplets to move deeper into dense canopies (Spillman 1984). In the present studies, deposits in the bottom leaves were lower than in the upper and middle leaves. The maize plant structure differs from that of cotton, and the vital rotor moment may hurt the deposition, including the breaking of leaves perpendicularly on the midribs, as observed during our experiments. Further, reduced deposition in the middle and lower canopy poses no harm in maize, specifically to tackle fall armyworms, as the FAW larva resides only in the top canopy, in the central whorls. Higher deposits on upper leaves and lower penetration in lower leaves were also observed in sugarcane (Zhang et al. 2020).

The present investigation used 3 m/s forward speed and 0.6 m height above the crop canopy.

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The flight height and forward speed combination of 0.55 m and 2.0 m/s and 0.55 and 3.00 m/s were highly effective in managing the whitefly and brown plant hopper population (Parmer et al. 2021). Effective fall armyworm management is possible when the applied insecticides enter the whorls. After the saturation point on the leaves, the insecticide droplets will run off and reach the maximum stable retention (Zhu et al. 2011). The droplets deposited on the maize top leaves through the UAV atomizer may run into the whorls where larvae of the target pest inhabit, ultimately resulting in more control efficacy.

CONCLUSION

Reducing the fall armyworm *S. frugiperda* damage in maize was achieved by a UAV equipped with an atomizer nozzle, which proved equally effective as a high-volume sprayer. The UAV atomizer nozzle's droplet density was similar to a flat fan nozzle's. Deposition investigations confirmed that the UAV atomizer nozzle had a higher pesticide persistence than the other spray methods. An atomizer nozzle-equipped UAV can cut down on FAW infestation in maize, spraying time, labour costs, and labour intensity. The spray directed towards the maize central whorls will target the FAW larvae that reside inside the whorls more effectively than whole crop canopy coverage. The UAV delivery systems can be modified slightly to reduce FAW damage effectively.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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