Effect of downwash airflow distribution of multi-rotor unmanned aerial vehicle on spray droplet deposition characteristics in rice crop

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The UAV downwash airflow pattern generated by rotor propellers is one of the significant factors influencing the characteristics of spray droplet deposition distribution. UAV sprayer and battery operated sprayer were used to study the effect of downwash airflow distribution of UAV on spray droplet deposition characteristics in a paddy field. The UAV sprayer was operated with optimized operational parameters and spray droplet characteristics, viz. spray deposition rate (μl cm^{-2}), spray droplet size (μm), spray deposition density (No's cm^{-2}) and spray deposition uniformity (%) were analysed using Deposit Scan software. The UAV sprayer showed better results in spray droplet deposition rate, spray coverage per unit area and spray droplet deposition densities than the conventional battery-operated manual sprayer. Additionally, it was found that the UAV sprayer increased the chemical's penetration into crop leaves, leading to higher chemical deposition on both the upper and lower layers of rice leaves.

Keywords: Chemical spray deposition, deposition uniformity, downwash air, droplet size, manual spray, water sensitive paper.

MULTI-ROTOR drones have become one of the dominant approaches, especially for spraying operations. The primary benefit of using a multi-rotor (hexa) drone for chemical spraying is that it produces strong downwash airflow during flight operation due to its unique rotor structure and principle of rotor motion, changing crop disturbance and enhancing liquid penetration. Liquid sprayed by a multi-rotor drone positively impacts better deposition at the crops' bottom[1]. When plants are sprayed, the drone sprayer downwash airflow velocity produced by the multi-rotor propeller can produce a high strong velocity distribution, enabling spray droplets to atomize much further and deposit more evenly onto the crop leaf surface. Hence, chemical spray droplet flow velocity along with downwash airflow significantly impacts the width of spray, spray droplet deposition rate and spray particle drift[2].

Earlier research on the downwash airflow velocity of multi-rotor drone sprayers reported a positive impact of the downwash airflow on the spray droplet deposition rate. Lan *et al.*[3], chose a DJI T16 drone for spray operation and analysed the spray deposit characteristics using USDA DepositScan software. Wang *et al.*[4] created an innovative spatial chemical spraying deposition performance balancing test for the unmanned aerial vehicle (UAV) model (3WQF80-10) and reported a stronger functioning effect when flying backwards, with the spray deposition rate ratio of the bottom half of backward flight reaching up to 60%.

The effect of drone sprayer downwash airflow on spray droplet velocity in a sugarcane crop was examined in an earlier study. Zhang *et al.*[5] found that the multi-rotor drone sprayer downwash flow distribution was the main factor influencing spray droplets' final vertical velocity. The downwash airflow increased the droplet deposition area by 150%, and the rotor rotation rate improved the uniformity of the deposition[6]. Yang *et al.*[7] used an SLK-5 six-rotor drone sprayer to study both downwash and windward airflow effects on the movement of the spray droplet group. Radial basis neural networks and computational fluid dynamics were combined to conduct the investigation.

The operational parameters of vertical take-off and landing (VTOL) multi-rotor drone sprayer, viz. spray height, forward travel speed, payload capacity and hexacopter model configuration, have a positive effect on the spray droplet distribution and spray droplet penetration due to strong positive relations between downwash airflow velocity and droplets. The drone sprayer's spray height and forward travel speed have a good impact on the spray droplet distributions[8,9]. The drone sprayer's spray height, forward travel speed and nozzle discharge rate also impact the spray droplet penetration[10]. The vertical velocity of the VTOL drone sprayer downwash flow close to the crop canopy will decrease as the height of the spray rises[11].

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Figure 1. Autonomous hexa-copter battery-operated drone sprayer.

Using the XV-2 model, Zhilun *et al.*[12] investigated the impact of the VTOL drone sprayer downwash airflow pattern on spray width. The findings indicated that the drone sprayer's spray height mostly affected spray width, with a 6 m spray height producing an effective spray width of 10 m. Berner and Chojnacki[13] tested the correlation between the VTOL drone's multi-rotor rotational speed and spray deposition. Choi *et al.*[14] tested a six-rotor UAV with three operational spray heights and two operational forward travel speeds. It was revealed that spraying at 3 m height with 3 m s^{-1} was the best option after measuring the spray width, spray droplet amounts and particle sizes using water-sensitive paper (WSP). The vertical downwash airflow velocity is strongly associated with spray droplet penetration[15]. Wang *et al.*[16] investigated the vertical downwash airflow of a one-rotor drone sprayer (model: 3WQF80-10), using water-sensitive paper to enhance the spray droplets, and then assessed the downwash airflow distribution of three different types of UAVs based on droplet deposition in different layers. Qing *et al.*[6] examined droplet distribution influenced by eight rotors using particle image velocimetry (PIV) technology and observed that the downwash airflow distribution velocity not only changed the spray droplet deposition zone but also influenced their spray droplet distribution pattern. Lan *et al.*[3] conducted similar research on the effect of rotor propellers downwash airflow distribution on the spray droplet deposition rate using a UAV DJI T16 drone sprayer and discovered that as the UAV height of spray increased, the downwash airflow distribution changed, gradually reducing droplet deposition in the effective spray area and increasing the uniformity of their deposition. The studies mentioned above also investigated the influence of downwash airflow distribution on the spray droplet penetration, along with the interaction between the drone sprayer's spray operational parameters and downwash airflow distribution. The movement and deposition laws of sprayed droplets were significantly distinct from those of conventional spraying instruments, as they would have been influenced by the rotor's downwash flow[17].

The effectiveness of pesticide application is crucial in pest control operations. The precise dosage must be applied consistently, the toxicant must reach the target, and the droplet size and density must be ideal. A loss of 23% of rice production was recorded in 2019 as a result of a general lack of spray penetration inside the plant canopy to attack the stem borer, which lives in the lowest part of the plant[18]. Therefore, it is paramount to study the influence of multi-rotor drone sprayer downwash airflow patterns on the spray droplet deposition rate in the rice crop.

Materials and methods

Equipment

The drone sprayer used in the current experiment was an E610P six-rotor battery-operated UAV (M/s EFT Electronic Technology Co, Ltd in Hefei City, China). It mainly consists of brushless direct current (BLDC) motors, lithium polymer (LiPo) batteries, flight controller, remote control (RC) receiver, global navigation satellite system real-time kinematic unit, chemical tank, spray pump, nozzles and supporting frame, as shown in Figure 1. A 10 litre payload capacity of a chemical tank and two LiPo batteries with a combined capacity of 16,000 mAh each power the propulsion system on the drone sprayer. To pressurise spray liquid and atomise it into small spray droplets, a pump is connected to a 12 V BLDC motor. Four 2020A-132 series flat fan nozzles (M/s Ningbo Licheng Agricultural Spray Technology Co., Ltd., Zhejiang, China) are fitted and screwed beneath the BLDC motor base plate on this drone sprayer. The intelligent/precise spray liquid flow control system, water flow sensor, high-precision obstacle avoidance radar, terrain radar, low battery indication, one-key return home function, GPS route planning and breakpoint return features of the drone sprayer enable it to complete aerial spraying tasks on its own. Table 1 provides the most important indicators of performance.

UAV hexa-copter wind flow distribution system

Figure 2 shows the motor rotation law and wind flow distribution in two motion states of adjacent wings. The adjacent wings, rotor – A, rotor – C and rotor – E rotate in a clockwise direction; rotor – B, rotor – D and rotor – E rotate counter-clockwise. The rotational directions of rotor – A and rotor – B are opposite, while both rotors induce airflow into the inner circle. On the contrary, the rotor – B and rotor – C induce airflow to the outer circle[19]. The airflow induced and outflows are indicated as green arrows and red arrows respectively.

Table 1. Specification of hexa-copter battery-operated drone sprayer

Particulars	Norms and numerical value
Type and model	Hexa-copter, E610P
Size	
Unfold (L × W × H) (mm)	2050 × 1830 × 660
Folding (L × W × H) (mm)	955 × 860 × 660
Source of power	Lithium polymer battery
Liquid tank (litre)	10
Self-weight (kg)	6.9
Speed of travel (ms^{-1})	0–8
Maximum take-off weight (kg)	26
Height if flight (m)	1–20
Spray nozzle	Flat fan
Nozzle quantity	4
Chemical discharge rate ($l\ m^{-1}$)	0–3.2
Spray width (m)	3–5
Spray operating pressure ($kg\ cm^{-2}$)	3.4
Range of remote controller (km)	1.5
Hovering time (without payload) (min)	30
Spraying endurance (with payload)	20
Battery charging duration (min)	90
Hovering accuracy	
Horizontal direction (m)	± 1.5
Vertical direction (m)	± 0.5
Maximum tilt angle (°)	30
Maximum yaw speed (°/sec)	150
Maximum vertical speed (ms^{-1})	6
Maximum wind resistance (ms^{-1})	
Wind	4
Gust	5

UAV sprayer machine and operational parameters

Selection of nozzle type, spray discharge rate and operating pressure: It was decided to use the flat fan nozzle (2020A-132 series) for the drone sprayer. The portable ground station device allows for adjustment of the spraying chemical discharge rate. The chemical discharge rates of four nozzles were evaluated using a handheld portable type sensor-based digital nozzle tester instrument (AAMS, Maldegem, Belgium). The output of a water spray hose pipe was linked to a digital liquid pressure gauge for measuring liquid operating pressure, and the lateral hose pipe's nozzles were connected to the opposite end. At 100% spray motor speed mode, the maximum chemical discharge rate of a single nozzle was recorded to be $0.8\ l\ m^{-1}$. The combined four nozzle flow rates and liquid pressure were recorded as $3.2\ l\ m^{-1}$ and $3.4\ kg\ cm^{-2}$ respectively (Figure 3). Table 2 displays the selected UAV and manual sprayer operational parameters during the field condition.

Measurement of effective spray width: The effective spray width experiment was conducted at Agricultural Machinery Research Centre (AMRC), Tamil Nadu Agricultural University (TNAU), Coimbatore, India. The WSP samples were used to collect the spray droplet from the UAV sprayer. The WSP samples were placed in three rows, each with nine pieces. The spacing between each WSP sample was 1.0 m, while between rows was 3.0 m. The layout of spray droplet deposition on WSP sampling points is shown in Figure 4.

Application rate of chemical usage: The main pests in the rice crop are stem borers and rice brown planthoppers

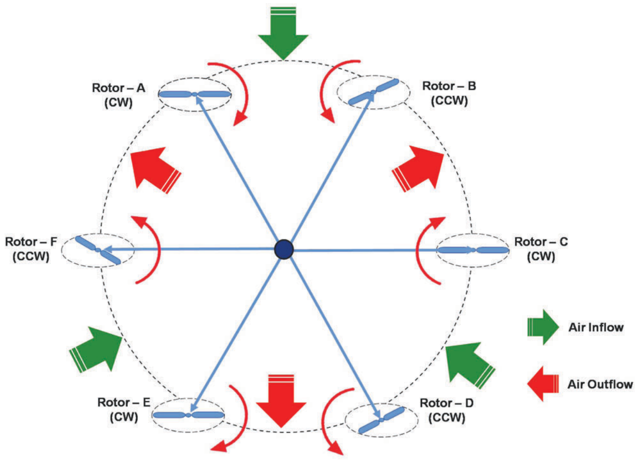

Figure 2. Motor rotation law and wind distribution of UAV hexa-copter model.

Figure 3. Recording the observations of nozzle discharge rate using nozzle tester.

Table 2. Details of spray operational parameters of drone sprayer and battery-operated knapsack sprayer

Operational parameters	UAV sprayer	Battery sprayer
Sprayer type and model	Hexa-copter, E610P	Knapsack, KK-BBS199
Fluid tank capacity (litre)	10	16
Power source	LiPo battery	12 V DCbattery
Type of nozzle	Flat fan shape	Faucet
Number of nozzles	4	1
Forward speed (ms^{-1})	3.5	0.4
Spray height (m)	1.3	0.3
Spray width (m)	2.8	2.2
Chemical discharge rate ($l\ m^{-1}$)	3.21	1.6
Liquid pressure ($kg\ cm^{-2}$)	3.4	2.1

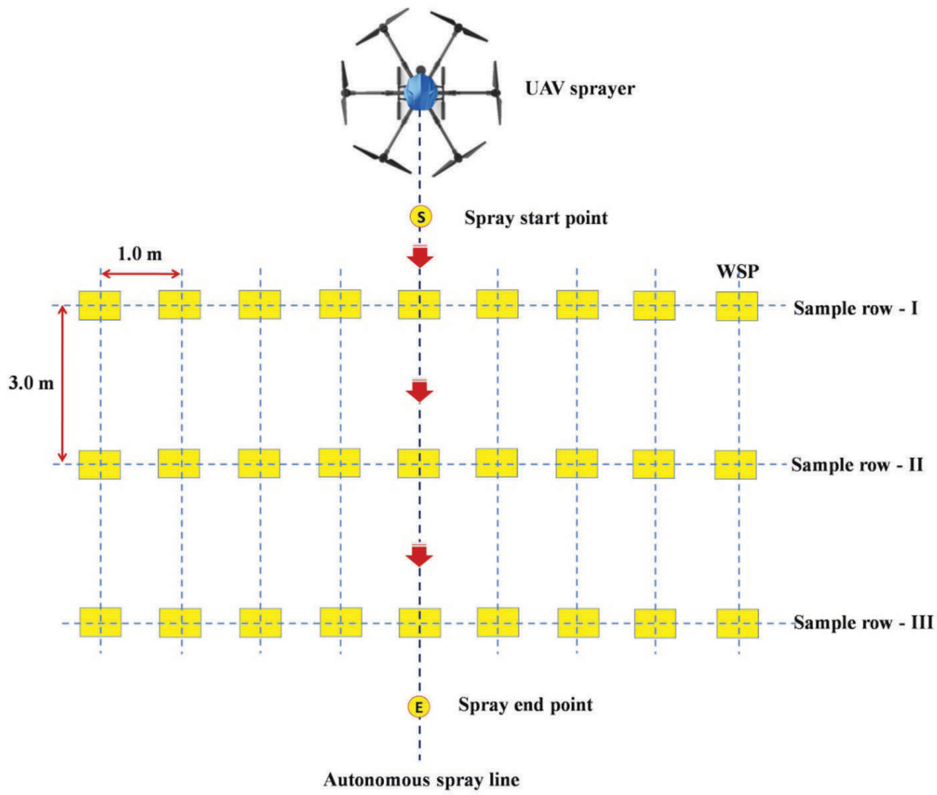

Figure 4. Layout of WSP samples for measuring effective spray width.

(bph). As per the rice crop package of practise published by the TNAU, CORAGEN (Chlorantraniliprole 18.5% w/w –150 ml) insecticide was mixed with water at a ratio of 0.4 ml/litre. The diluted chemical was sprayed using a UAV drone sprayer and a manual-operated knapsack sprayer. The spray operational parameters for both methods of sprayer are presented in Table 2.

Field test

The impact of the downwash airflow distribution of the UAV sprayer on spray droplet deposition characteristics experiment was carried out at the wetland field (N11.003247, E76.924474) at TNAU. A battery-operated knapsack sprayer (M/s Kisan Kraft, KK-BBS199, 16 litre capacity) was used to spray the solution as a control treatment. The layout of the rice crop research plot and arrangement and locations of WSP samples on rice crop leaf for UAV spray and manual spray are shown in Figure 5. The details of crop parameters measured during the spraying operation are illustrated in Table 3.

Arrangement of spray droplet deposition samples: For the experiment, a type of WSP made by AAMS, Maldegem, Belgium, was used. Its surface is dye-coated, and aqueous droplets that land on it leave visible stains[20]. The number of spray droplets deposited on the surface of the leaves at

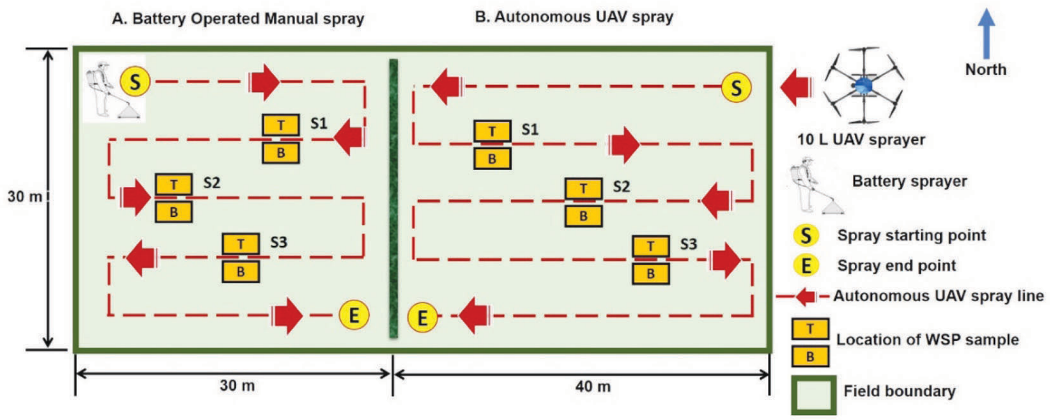

Figure 5. Layout of rice crop field and placement of WSP spray samples.

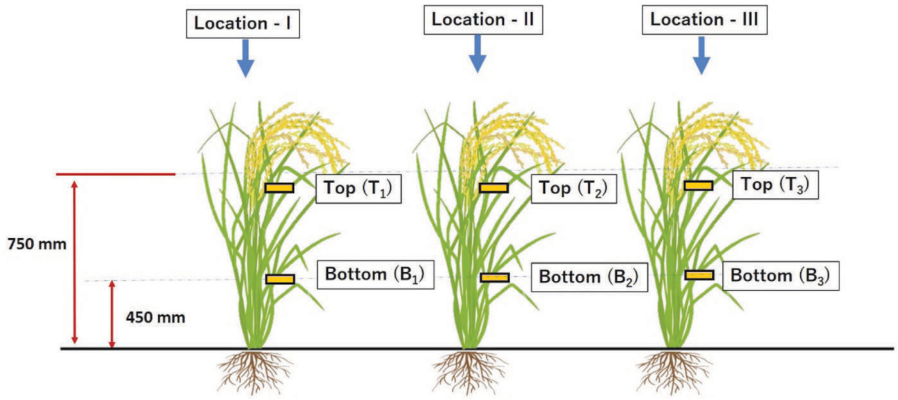

Figure 6. Layout of WSP samples on the top (T_1, T_2, T_3) and bottom (B_1, B_2, B_3) sides on the rice crop leaf.

Table 3. Crop parameters measured during spraying operation

Crop parameters	Norms and numerical value
Crop	Rice
Variety	Co51
Date of plantation	08.01.2022
Height of crop (mm)	750–830
Stage of crop (days)	Flowering stage (68 days)
Number of tillers (per plant)	37
Number of panicles (No's m^{-2})	320

three different locations was measured using the WSP samples[21,22]. As illustrated in Figures 6 and 7, WSP was clamped with a double-ended clip at each sampling location and retained on the leaves at two distinct plant heights, viz. 450 mm and 750 mm above the ground.

Autonomous UAV spraying operation: For UAV autonomous spraying operations on the rice crop, a mobile application called Agri Assistant (JIYI K++V2, V1.5.1) was used. The application offered real-time status of the UAV spray operating characteristics, including spray swath width, spray motor speed, spray height, field GPS location, and satellite connection strength. Input spray operation modes for the UAV sprayer, such as flight forward speed, spray height, spray swath width, and nozzle flow rate, were then selected. Initially, GPS coordinates of the rice crop field boundary, such as latitude, longitude and altitude, were entered. The optimized spray operation parameters, such as a flying speed of 3 ms^{-1}, and a flight height of 1.3 m above the crop canopy with a swath width of 2.8 m, were selected[22]. For the entire spray operation, a spray height of 1.3 m (vertical distance between the crop canopy and the tip of the drone sprayer nozzle) was set. Figure 8 depicts the spray height and crop height configuration.

After providing the field boundary and spray operational parameters to the Agri Assistant app, the UAV sprayer was started at auto take-off mode and spraying operation was initiated by clicking the auto take-off option on the Agri Assistant mobile device at the ground station. After completing the spraying task, it returned to its original home point for a safe landing. The UAV autonomous spraying operation on the Agri Assistant app screen is shown in Figure 9.

Once the spray operational parameters are input into Agri Assistant, the app automatically displays the live status of the drone sprayer machine parameters (flight mode,

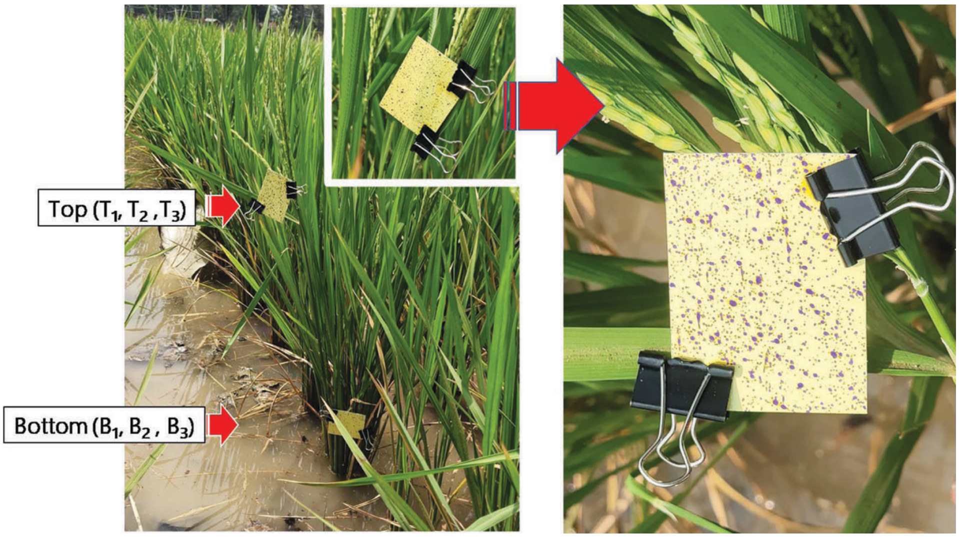

Figure 7. Position of WSP samples on the rice crop leaf.

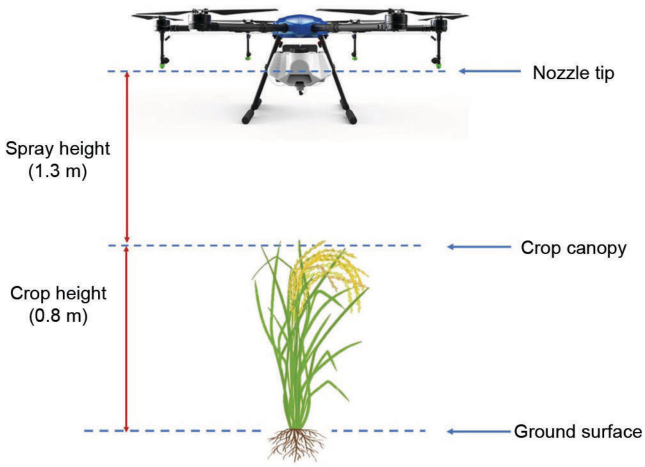

Figure 8. Height of spray and crop height experimental setup schematic for UAV spraying operation.

battery voltage, number of satellites connected, GPS status, remote controller and flight controller connection strength, auto take-off option, return to home), spray field plot (field satellite map view, field location and field size), and that of the spray operational parameters (flight speed, discharge rate, swath adjustment, spray start point, spray finish point and return to home point). The app also provides live display information of the actual auto spray line (green colour) and GPS-marked spray line (blue colour) during spraying operation in the rice field, as shown in Figures 10 and 11 respectively.

Recording of meteorological parameters during spray droplet deposition: Several meteorological parameters, including natural wind speed, air temperature, humidity and rainfall, impact the effectiveness of UAV and manual spraying operations. To measure the natural wind speed, a portable anemometer (make: LUTRON, model: AM 4202, type: Vane, range: 0.4 – 30.0 m s^{-1}) was fixed on a square iron pipe at a height of 2.0 m above the crop canopy[23]. Table 4 lists the various meteorological parameters noted during the investigation.

WSP sample acquisition and spraying effectiveness analysis: After completion of spraying test using autonomous UAV sprayer and manual battery operated sprayer (Figure 12), WSPs were immediately collected and transferred to the laboratory for further study. The uniformity of spray deposition is expressed as VMD (volume median diameter), NMD (numeric median diameter) and uniformity coefficient (VMD/NMD ratio). According to the method of Zhu *et al.*[24] the deposit amount and coverage density of the droplets at upper and bottom locations were analysed.

DepositScan software: Micro Droplet Analyzer and Macro Droplet Analyser devices (developed by LABLINE-DMS 101, India) were used for analysing WSP and DepositScan software (developed by USDA, Wooster, USA) was used to process the scanned image. Spray droplet dialysis was done on the deposition rate ((µl cm^{-2}), droplet size Dv0.1, Dv0.5, and Dv0.9 (µm), deposition density (No’s cm^{-2}), and the deposition uniformity (%).

The spray deposition rate (µL cm^{-2}); spray droplet size (Dv0.1, Dv0.5 and Dv0.9 µm); spray deposition density (No’s cm^{-2}); and spray droplet penetrability (%) were studied. Mean deposition, mean deposition density, and coefficient of variation (CV) were also calculated. Dv0.1 is the droplet diameter (µm), wherein 10% of the spray volume contained in droplets was smaller than this value. Similarly, Dv0.5 and Dv0.9 are droplet diameters, wherein 50% and 90% of the spray volumes contained in the droplets were smaller than these values respectively. The Dv0.5, also known as the volume median diameter (VMD), is the droplet

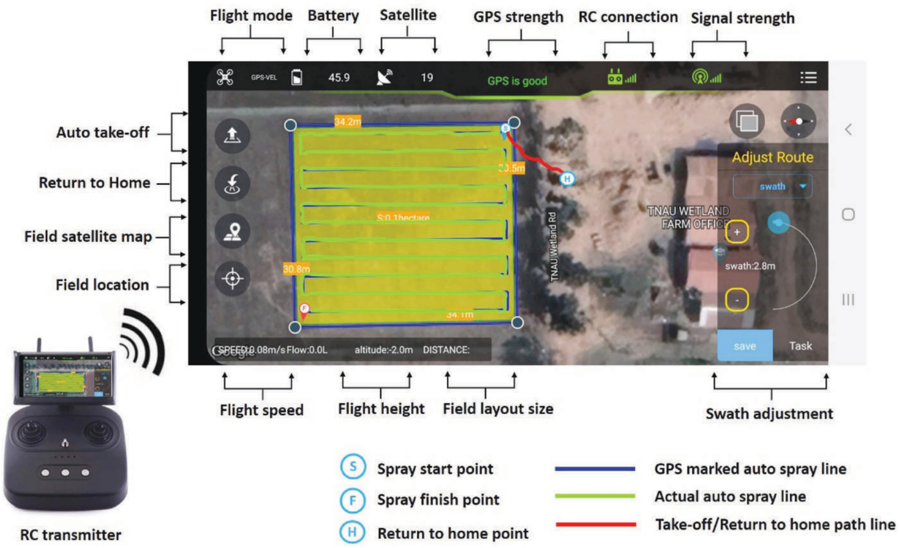

Figure 9. View of operational parameters for UAV autonomous spraying operation.

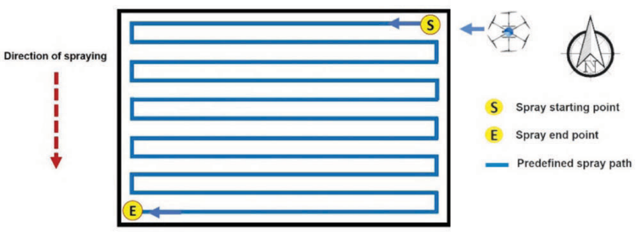

Figure 10. Predefined autonomous spray path map.

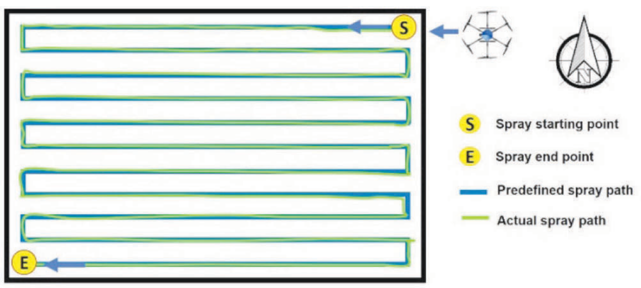

Figure 11. Actual autonomous spray path map.

size median at which the accumulation of all droplets, from small to large, equals 50% of the total volume of the droplets, which is a critical index to measure the size of the spray droplet[25].

The step-by-step process for droplet size analysis using stereo micro- and macroscope devices with DepositScan software is shown in Figure 13. As illustrated in Figure 14, droplet deposition rates (μl cm^{-2}) were calculated using DepositScan software in accordance with Zhu *et al.*[24].

Uniformity of spray droplet deposition: The CV for the spray droplet deposition density at each collection point was measured in order to describe the spray uniformity of droplet deposition rate between the different collection points. The CV of the amount of spray droplet deposition rate on the top and bottom layers of each collection point was computed to assess the uniformity of droplet deposition. The droplet deposition rate was more uniform, and the penetration was better when the CV value was smaller[19,26]. The spray droplet deposition uniformity was calculated using the below formula

$$\text{Coefficient of variation (CV)} = \frac{SD}{X} \times 100, \quad (1)$$

$$\text{Mean } (X) = \frac{\sum X_i}{N}, \quad (2)$$

$$\text{Standard deviation } (SD) = \sqrt{\frac{\sum_{1}^{N} (X_i - X)^2}{N-1}}, \quad (3)$$

where X is the deposition value of every sampling point (μl cm^{-2}), X_i average deposition value of every sampling point (μl cm^{-2}) and N is the number of sampling points.

Results

Effective spray width and application rate of chemical usage

At 1.3 m height of spray above the crop canopy, the effective spray width was found to be 2.8 m. The spray width ranged from 2.5 to 3.4 m when the flying height was between 1.0 and 3.0 m. This concurs with an earlier research[5]. The

Table 4. Meteorological reports while conducting UAV and manual spray in a rice field

Location	Wetland field (11.003247 N, 76.924474 E), TNAU	
Environmental parameters	Air temperature (°C)	25.8–31.4
	Relative humidity (%)	55.7–60.3
	Natural wind velocity (m s^{-1})	1.1–1.5
	Rainfall (mm)	0

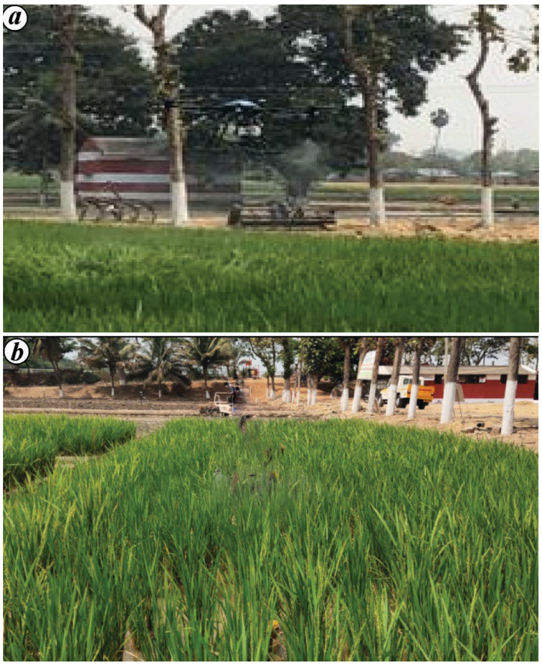

Figure 12. Spray operation on rice crop. ***a***, Autonomous UAV sprayer. ***b***, Manual battery operated sprayer.

autonomous spray mode was selected to maintain an average forward speed of 3.5 ms^{-1}. The actual field capacity of the drone sprayer was found to be 3.22 ha h^{-1}.

It was found that the theoretical and actual application rate was 54.6 l ha^{-1} and 51.2 l ha^{-1} respectively. This CORAGEN (chlorantraniliprole 18.5% w/w) chemical application rate was in line with the recommendations issued in the paddy crop practise package released by TNAU.

UAV spray droplet deposition rate and distribution characteristics analysis

The WSP samples were mounted with a pin on the rice crop leaf at 200 mm and 400 mm from the ground surface level. Upper and lower layers were distinguished between the sampling sites. The actual spray droplet deposition level of the sprayed droplets is represented by an important indicator referred to as droplet deposition. Each WSP sample of spray droplet size, droplet density, droplet deposition, droplet area coverage, droplet deposition rate, and uniformity of deposition were determined and analysed using DepositScan software. The results are shown in Table 5.

Spray droplet deposition rate

It was observed from Table 5 that for the UAV spray method, spray droplet deposition rate in the upper layer was found to be 8.66 ± 0.82%, 8.23 ± 1.03% and 9.60 ± 0.65% for locations 1, 2 and 3 respectively and the bottom layer was found to be 8.25 ± 0.6%, 8.31 ± 0.6% and 8.52 ± 1.1% for locations 1, 2 and 3 respectively. In the knapsack sprayer method, the droplet deposition rate in the upper layer was found to be 1.20 ± 0.08 μl cm^{-2}, 1.24 ± 0.10 μl cm^{-2} and 1.47 ± 0.06 μl cm^{-2} for location 1, 2 and 3 respectively and the bottom layer was found to be 0.26 ± 0.04 μl cm^{-2}, 0.34 ± 0.05 μl cm^{-2} and 0.27 ± 0.05 μl cm^{-2} for location 1, 2 and 3 respectively. From Figure 15, the average droplet deposition rate in the upper and bottom layer was found to be 0.89 μl cm^{-2} and 0.80 μl cm^{-2} respectively, for UAV sprayer, and 1.31 μl cm^{-2} and 0.29 μl cm^{-2} respectively, for knapsack sprayer.

Spray droplet coverage area

It was observed from Table 5 that the UAV spray droplet coverage per unit area in the upper layer was found to be 9.74 ± 0.87%, 11.12 ± 1.4% and 10.02 ± 0.2% for locations 1, 2 and 3 respectively, and the bottom layer was found to be 2.66 ± 0.3%, 3.21 ± 0.8% and 2.71 ± 0.5% for locations 1, 2 and 3 respectively. Knapsack spray droplet coverage per unit area in the upper layer was found to be 10.49%, 11.34%, 9.64%, 11.23% and 9.83% for location 1, 2, 3, 4 and 5 respectively, and the bottom layer was found to be 2.14%, 2.21%, 2.19%, 2.34% and 2.27% for locations 1, 2, 3, 4 and 5 respectively. From Figure 16, The average spray droplet coverage per unit area in the upper and bottom layers was found to be 8.4% and 7.3% respectively, for the UAV sprayer, and 10.5% and 2.2% respectively, for the knapsack sprayer.

The UAV spray method helps in the even coverage per unit area in the upper and bottom layers at the rate of 8.83% and 8.36% respectively, compared to the manual spray method in upper and bottom layer at 10.30% and 2.86% respectively. This is because the downwash airflow produced by the rotors propeller of the drone sprayer has positive significance on the rice crop canopy and helps in uniform droplet distribution in the upper and bottom layers[27]. Similar results were obtained by Xue[28] using UAV sprayer in a paddy field.

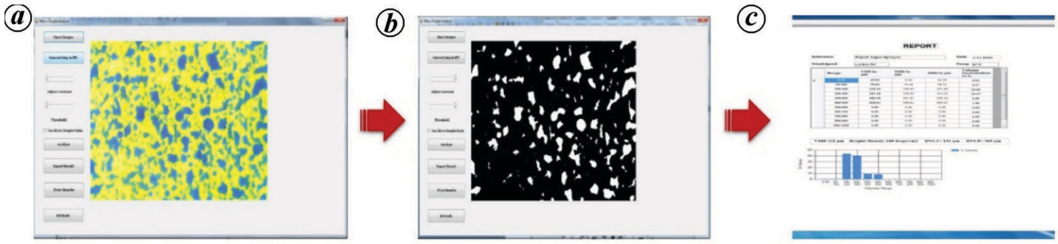

Figure 13. Flowchart for the process of measuring droplet size using a micro- and macro-droplet analyser. ***a***, Image view of spray droplet sample under microscope. ***b***, Convert the image to BW and adjust contrast and threshold. ***c***, Output results of VMD, DD and percentage volume coverage.

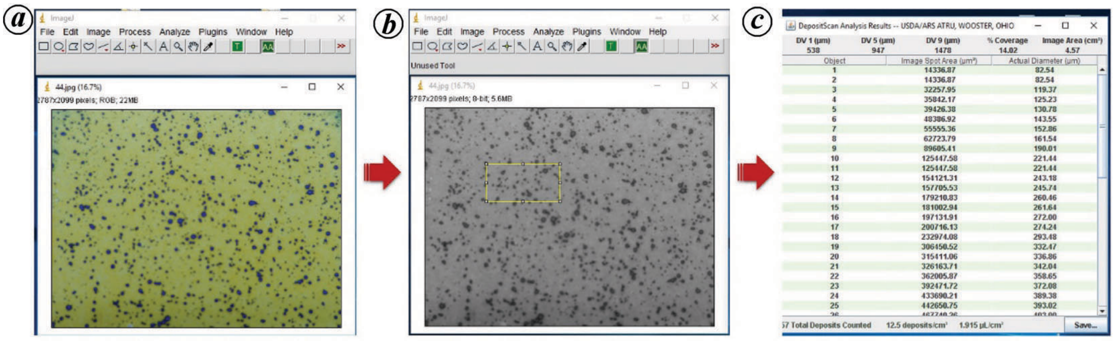

Figure 14. Flow chart for measurement of spray droplet deposition rate under DepositScan software. ***a***, Import WSP image to DepositScan software. ***b***, Convert the import colour image to black and white under (8-bit) and Select '□' TOOL. ***c***, Select the green AA TOOL analysis

Spray droplet density

It was observed from Table 5 that the UAV spray droplet deposition densities per centimetre square area in the upper layer was found to be 36 ± 2.52, 33 ± 3.61 and 39 ± 5.69 droplets cm^{-2} for location 1, 2 and 3 respectively, and the bottom layer was found to be 30 ± 2.31, 29 ± 4.04 and 31 ± 2.08 droplets cm^{-2} for location 1, 2 and 3 respectively. Similarly, for the knapsack spray method, in the upper layer, it was found to be 44 ± 3.61, 37 ± 2.52 and 41 ± 7.94 droplets cm^{-2} for locations 1, 2 and 3 respectively, and the bottom layer was found to be 14 ± 3.61, 16 ± 3.51 and 10 ± 2.08 droplets cm^{-2} for location 1, 2 and 3 respectively.

It was observed from Table 5 and Figure 17, that the average droplet densities cm^{-2} on the upper and bottom layers were 36 and 30 droplets cm^{-2} respectively for the UAV sprayer, and 41 and 13 droplets cm^{-2} respectively for the knapsack sprayer.

Spray deposition uniformity

It was observed that overall, the UAV spray operation's droplet deposition rate, droplet density and area coverage were almost equal at the upper and bottom layers. This was due to the influence of the downwash airflow pattern generated by the rotor propeller of the UAV sprayer[29]. However, in the manual method of spray operation, droplet deposition rate, droplet density and area coverage were highest in the upper layer and lowest in the bottom layer.

It was observed from Figure 18 that the deposition uniformity was better in the upper layer for both the UAV sprayer and knapsack sprayer, with the CV of deposition density reaching 4.2% and 8.0% respectively. There was an uneven deposit density of 8.21% and 14.78% respectively, in the upper and bottom layers during knapsack spraying operation due to more spray chemical deposition on the upper than the bottom layer. The downwash airflow also contributes to improving the spray droplet distribution in the downwash area because of the high-speed rotation of the rotor propeller of UAV sprayer[12,18,19,29].

Discussion

In this field study, a drone sprayer (10 litre) with hexa standard flat type nozzle arrangement and a manual knapsack sprayer were used to investigate the influence of rotor propellers' downwash airflow distribution on spray droplet deposition characteristics in a rice crop. The spray deposition characteristics were compared between the drone sprayer and manual knapsack sprayer. The operational parameters of the drone sprayer, viz. flight forward speed (3.0 ms^{-1}), spray height (1.3 m), spray swath width (2.8 m) and nozzle flow rate (3.2 l m^{-1}) were set for complete spray operation in autonomous mode. The spray droplet WSP samples from drone and knapsack sprayers test spray deposition were analysed using DepositScan software.

There was almost an equal deposition rate in the upper (0.89 μl cm^{-2}) and bottom layer (0.80 μl cm^{-2}) using the

Table 5. Sprayer droplet characteristics of UAV sprayer and knapsack manual at each position and locations in rice crop

Method of spray	Position of WSP on leaf	Location of WSP in field	Spray droplet size (µm) DV$_{0.1}$	DV$_{0.5}$	DV$_{0.9}$	Droplet density (No's cm^{-2})	Coverage (%)	Deposition rate (µl cm^{-2})
UAV sprayer	Upper	U1	288 ± 8.19	576 ± 15.18	878 ± 14.29	36 ± 2.52	8.66 ± 0.82	0.88 ± 0.09
		U2	373 ± 11.93	578 ± 9.61	961 ± 19.86	33 ± 3.61	8.23 ± 1.03	0.82 ± 0.11
		U3	318 ± 15.53	546 ± 14.01	979 ± 11.59	39 ± 5.69	9.60 ± 0.65	0.97 ± 0.12
	Bottom	B1	261 ± 11.72	555 ± 19.86	883 ± 12.17	30 ± 2.31	8.25 ± 0.67	0.76 ± 0.14
		B2	280 ± 11.15	549 ± 17.00	856 ± 11.00	29 ± 4.04	8.31 ± 0.66	0.85 ± 0.10
		B3	251 ± 18.18	465 ± 10.58	665 ± 8.50	31 ± 2.08	8.52 ± 1.11	0.80 ± 0.13
Knapsack sprayer	Upper	U1	328 ± 18.93	621 ± 6.56	975 ± 11.59	44 ± 3.61	9.74 ± 0.87	1.20 ± 0.08
		U2	371 ± 16.04	658 ± 16.82	949 ± 17.35	37 ± 2.52	11.12 ± 1.47	1.24 ± 0.10
		U3	378 ± 8.33	678 ± 9.29	754 ± 11.72	41 ± 7.94	10.02 ± 0.22	1.47 ± 0.06
	Bottom	B1	206 ± 16.50	524 ± 7.21	960 ± 7.51	14 ± 3.61	2.66 ± 0.39	0.26 ± 0.04
		B2	246 ± 6.66	447 ± 7.55	660 ± 15.82	16 ± 3.51	3.21 ± 0.83	0.34 ± 0.05
		B3	162 ± 7.21	463 ± 6.08	756 ± 5.51	10 ± 2.08	2.71 ± 0.58	0.27 ± 0.05

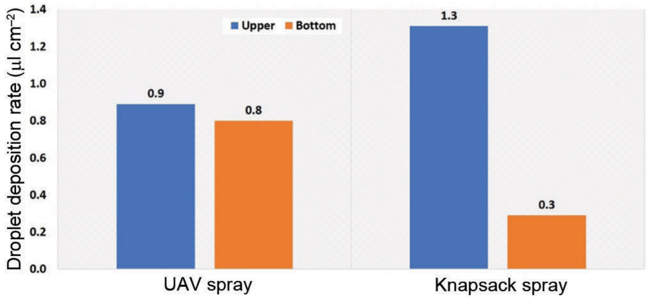

Figure 15. Spray droplet deposition rate of UAV sprayer and knapsack sprayer.

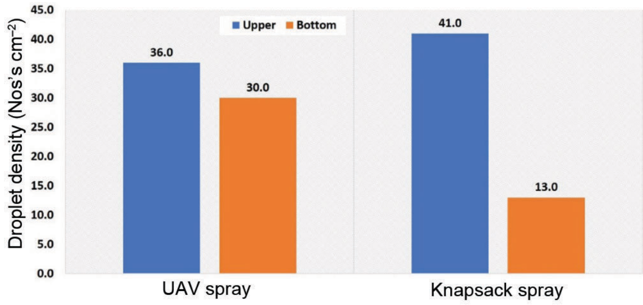

Figure 17. Spray droplet density of UAV sprayer and knapsack sprayer.

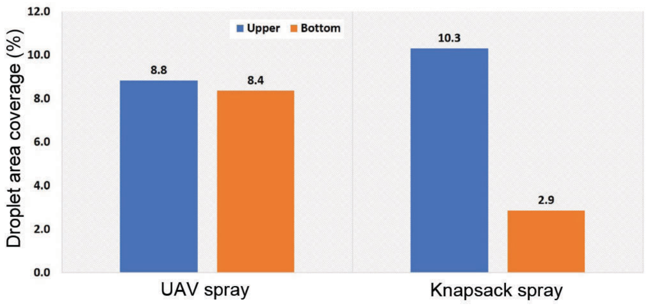

Figure 16. Spray droplet coverage area of UAV sprayer and knapsack sprayer.

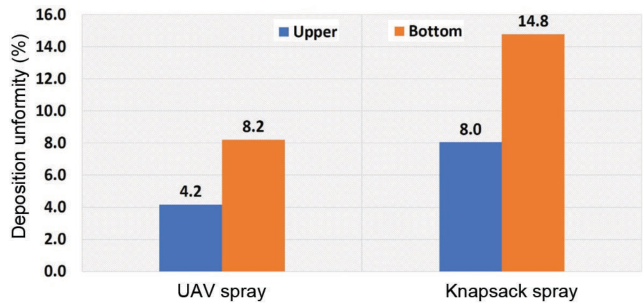

Figure 18. Spray deposition uniformity in UAV sprayer and knapsack sprayer.

UAV sprayer compared to knapsack sprayer – upper layer 1.31 µl cm^{-2} and bottom layer 0.29 µl cm^{-2}. On the whole, spray droplets reached the bottom of the crop leaf due to the effect of UAV downwash airflow, whereas it did not reach the bottom layer with a knapsack sprayer. The UAV spray method helps in even coverage per unit area in the upper and bottom layers, i.e. 8.83% and 8.36% respectively, compared to the manual spray method, which was 10.5% and 2.2% in upper and bottom layers respectively. The average droplet deposition densities on the upper and bottom layers were 36.66 and 30.66 droplets cm^{-2} respectively, for the UAV sprayer and 41.0 and 13.0 droplets cm^{-2} respectively, for the knapsack sprayer. Thus, the UAV spray method gave better and uniform droplet deposition densities compared to manual knapsack sprayer. The deposition uniformity was better in the upper and bottom layer with relatively smaller values of CV, i.e. 4.2% and 8.2% respectively, using the UAV sprayer compared to knapsack sprayer with uneven deposition uniformity in upper (8.0%) and bottom layer (14.8%). Equal distributions of droplet deposition rate and area coverage were found with the use of the UAV sprayer as compared to the knapsack sprayer. This may be due to the strong influence of the downwash airflow generated by the rotors propeller of the UAV sprayer on the spray droplet deposition.

In conclusion, the UAV multi-rotor downwash airflow positively impacted the spray droplet deposit rate in the rice crop, which will be useful for fighting stem borers, which are usually present in the lowest part of the plant. The findings of this study may be utilized as guidelines for nozzle placement in the airflow pattern underneath the propeller rotor and serve as a starting point for an analysis of the spatial motion trends of the droplets in the rotor downwash airflow field. Results obtained could also help in establishing the downwash airflow distribution model along the radial direction of the rotor with different hover heights and payloads, which would enable us to clearly understand the changing law of the airflow under the rotor.

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