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Research Article

Influence of the downwash airflow in Hexacopter Drone on the spray distribution pattern of boom sprayer

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Abstract
The spray characteristics of drone sprayers are significantly influenced by the downwash airflow produced by Drone multi-rotors. The present study aimed to study the influence of downwash airflow and the operational parameters of Drone sprayer, *viz.,* flight height, travel speed, rotor configuration, payload and wind velocity on the spray distribution pattern for boom sprayer attachment to Drone. The boom type sprayer consisted of four numbers of flat fan nozzles placed at three different spacing *viz.,* 30, 45 and 60 cm between each nozzle. The spray distribution pattern of the Hexacopter Drone was studied at three different operating pressures, *viz.,* 3.0, 4.0 and 5.0 kg cm^{-2}. A spray patternator of 5 m x 5 m was developed per the Bureau of Indian Standards (BIS) standard to study the spray uniformity of volume distribution pattern. The best spray uniformity was found as 0.37 % CV value at 60 cm nozzle spacing and 4 kg cm^{-2} operating pressure. The optimised parameters *viz.,* 60 cm of nozzle spacing and 4 kg cm^{-2} operating pressure, the influence of downwash airflow on the spray volume distribution of hexacopter Drone with boom spray attachment were studied. The Drone hovered at three different heights, *viz.,* 1.0, 2.0 and 3.0 m from the top of the patternator and spray operating pressure was maintained at 4 kg cm^{-2}. It was observed that less volume of spray was collected at the middle portion when the Unmanned Aerial Vehicle (UAV) was hovered at 1.0 m height due to the direct impact of downwash airflow of rotors. The uniform spray volume distribution pattern was observed when Drone hovered from 1.0 m to 3.0 m height. A round vertex pattern of spray pattern was generated with boom type nozzles configuration due to the direct impact of downwash airflow of rotors. This study will be helpful in the configuration of nozzles attached to the drone sprayers, optimization of spray operational parameters, and revealing spray volume distribution pattern.

Keywords: Boom spray, Downwash airflow, Flat fan nozzles, Hover height, Rotor propeller, Spray distribution, UAV Sprayer

INTRODUCTION

Modern farming methods depend on sprayers applying pesticides effectively. Better pest control, less pesticide expenditure, less waste and increased environmental safety are all advantages of proper application. One of the conditions for precise pesticide application is the evenness of the lateral dispersion of liquid from a sprayer (Padhee*et al.,* 2019).

Drone sprayers with easy take-off and landing systems, hovering capabilities, and high spraying efficiency are essentially needed to spray pesticides for crops in a timely and effective manner, especially in dispersed plots and hilly terrain (Lan et al., 2021). Recently, multi-rotor drones have become progressively important in crop spraying against diseases, pests, and weeds (Huang et al., 2009; Giles and Billing, 2015; Xue et al., 2016). The essential benefit of using a multi-rotor Unmanned aerial vehicles (UAVs) for chemical spraying is that, due to its unique rotor structure and principle of motion, it generates a powerful downwash airflow during flight operation and improving liquid penetration and also influencing spray droplet deposition distribution characteristics (Yang, 2014; Berner andChojnacki, 2017). As a result, spray droplet velocity positively affects spray swath, deposition drift and influences the operation's consequences (Li *et al.,* 2018). Qing *et al.* (2019) investigated the influence of the downwash airflow produced by drone rotors on the change of speed of droplets, spray angle and deposition of liquid sprayed by the cone nozzle (TR80-005C Lechler).

Spray uniformity is considered a crucial parameter in evaluating spraying efficacy, discharge rate, and operating pressure. The spray uniformity should be assessed to ensure a satisfactory deposition consistently throughout the entire height of the crop canopy (Subr*et al.,* 2017).

Luck et al. (2016) constructed an automated spray pattern measuring system that used digital liquid level sensors to calculate the coefficient of variation (CV) for various nozzle designs. The performance of nozzles was measured using a spray patternator in terms of discharge, swath width, spray angle, and lateral distribution. The primary application of a patternator is to achieve a uniform volume distribution pattern on a horizontal surface (Sehsah, 2016). The lateral distribution of water from spray nozzles may be examined using a patternator, which collects spray from a nozzle in several uniformly spaced channels that make up the patternator's surface (Pachuta et al., 2018). It will be helpful in determining the nozzle uniformity (Singh et al., 2006). It is also appropriate for checking and recalibrating nozzles whose properties may have altered after usage.

Most of the developed patternators with Bureau of Indian Standards (IS: 10064-1982) specifications are small in size (Chapple *et al.,* 1993, Tajuddin, 1995 and Shridar, 1997) and generally, customised patternators in the market are also very small in width and are not suitable for checking drone sprayers with boom configuration type of spray nozzle that cover a larger area in a single pass (Butts*et al.,* 2019 and Khoshnam*et al.,* 2022). Hence, a strong need was felt to develop a suitable larger-size horizontal spray patternator to study and test of drone spray volume distribution pattern with a boom nozzles arrangement system.

The overall goal of this research was to develop a suitable size patternator for measuring and analysing spray distribution pattern measurements from boom spray (multirole nozzles) of Drone sprayer in hovering conditions with the specific objectives viz., 1) development of a suitable customised spray patternator for measuring spray pattern distributions; 2) evaluation for optimising the nozzle spacing and operating pressure for boom arrangement on Drone sprayers; and 3) investigation on the impact of Drone sprayer downwash airflow on spray distribution systems at different hover heights in outdoor conditions.

MATERIALS AND METHODS

Drone

The UAV used in the present investigation was an E610P six-rotor electric (M/s. EFT Electronic Technology Co., Ltd., Hefei City, China) is shown in Fig. 1. The spraying system of the UAV sprayer mainly consisted of Flight controller (1), Brushless direct current (BLDC) motors arm (2), Fluid hose pipe (3), BLDC motor (4), Support frame (5), Pesticide tank (6), Landing gear (7), Foldable propeller (8), Lithium polymer (LiPo) batteries (9) (Table 1).The UAV sprayer has two LiPo batteries of 6 cells each with a capacity of 16000 mAh to supply the necessary current required for the propulsion system. A 24 V BLDC motor coupled with a pump was used to pressurize the spray liquid and then atomize it into fine spray droplets. This UAV model has the functions of GPS route planning and breakpoint return, which could complete aerial spraying operations autonomously.

Development of spray patternator

The patternator (5.0 m × 5.0 m) was fabricated using M.S channel for the frame and sheet (Fig. 2.). The spray patternator's surface was composed of 0.2 cm thick M.S. sheet positioned horizontally over the frame. The patternator has 91 continuous V- type channels at equal spacing mounted on the rectangular frame. According to IS: 8548 -1977 standard, channels should have 25± 0.25 mm width and 100 mm depth. These constraints make patternator difficult and costly to develop. Bended M.S sheet in V shape channels with 55 mm width is more than the recommended width to eliminate splash-back between the measurement grooves due to heigh downwash airflow produced by the rotor

Fig. 1. *Electric battery operated Drone sprayer* 1. Flight Controller and Sensors;2. BLDC motor arm; 3. Fluid hose pipe; 4. BLDC Motor; 5. Support frame; 6. Pesticide tank; 7. Landing gear; 8. Foldable propeller; 9. LiPo Battery

propellers of the drone sprayer. The rectangular frame on which sheets were placed, was made up of 5 mm × 5 mm L-shaped MS channel. Measuring cylinders of 190 ml capacity wereplaced below each channel to collect the spray liquid. The arrangemet of measuring jars and funnel in spray patternator is shown in Fig. 3 and Fig.4, respectively. Patternator has 25 degree slope for easy movement of water to the jar. The developed spray patternator is shown in Fig. 5. The specifications of the developed spray patternator are mentioned in Table 2.

Laboratory test for optimization of nozzle spacing and operating pressure for boom sprayer attachment to Drone

The experiment was conducted for spray volumetric distribution patterns using a specially designed and fabricated spray patternator at the Agricultural Machinery Research Centre (AMRC), Department of Farm Machinery and Power Engineering, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore (Tamil Nadu) to identify the spray uniformity for different nozzle spacing and operating pressure. The Drone sprayer volume distribution test was conducted as per the IS: 8548-1977 and ASAE S386.2 standards.

Experimental setup

A set of four numbers of flat fan nozzles was placed on the boom. For optimising the nozzle spacing for boom-type nozzle configuration, three different operating pressures (3.0, 4.0 and 5.0 kg cm^{-2}) and three different nozzle spacing (30.0, 45.0 and 60.0 cm) were selected. A Light Detection and Ranging (LIDAR) distance metre instrument (M/s, DEKOPRO, LRE520 80M) was used to adjust the height of the spray to 485 mm (distance between the tip of the nozzle and the top of the patternator V channel surface). The spray distribution was determined by directing it onto V shaped channelled with calibrated collecting tubes at the ends. The spray was horizontally directed and landed on the equidistance V-shaped channels. When the fluid reaches the patternator surface, it is separated into different channels and flows down the incline. When the fluid reaches the base of the patternator, each channel flows into its own graduated cylinder. After completing each experiment, the spray liquid from the collecting tubes of the patternator was collected and the quantity of fluid from each channel was measured and noted. The layout of the boom-type nozzle configuration without a drone for understanding the spray volume distribution and spray uniformity is shown in Fig. 6 and Fig.7, respectively.

Analysis of spray distribution system

The coefficient of uniformity and spray width were the two main parameters for optimising the nozzle spacing and operating pressure. These parameters directly influence work efficiency and spray quality.

Liquid distribution uniformity coefficient

The liquid distribution uniformity coefficient (CV) compiles all the patternator data points and summarizes them into a simple percentage, indicating the amount of variation within a given distribution. The uniformity coefficient (CV) is commonly used to quantify the uniformity of spray systems; higher CV values indicate poor uniformity in the spray pattern (Luck *et al.,* 2016 and Padhee*et al.,* 2019). The uniformity coefficient is calculated according to the following equation:

$$Coefficient of Variation (CV) = \frac{SD}{X} x\ 100$$
Eq. 1

$$Mean(X) = \frac{\sum X_i}{N}$$
Eq. 2

$$Standard deviation (SD) = \sqrt{\frac{\sum_1^N (X_i - X)^2}{N-1}}$$
Eq. 3

Where,
CV – Liquid distribution uniformity coefficient
X – Volume of liquid contained in specific container, ml
X_i – Average volume of liquid, ml
N – Number of analysed containers

Spray distribution uniformity can be obtained with a low coefficient of variation. The above procedure was followed throughout this investigation to determine the coefficient of variation of spray uniformity distribution of the Drone sprayer with boom arrangement.

Effective spray width

The effective spray width is the distance between the points on either side of a single swath where the deposit rate equals one-half of the effective application

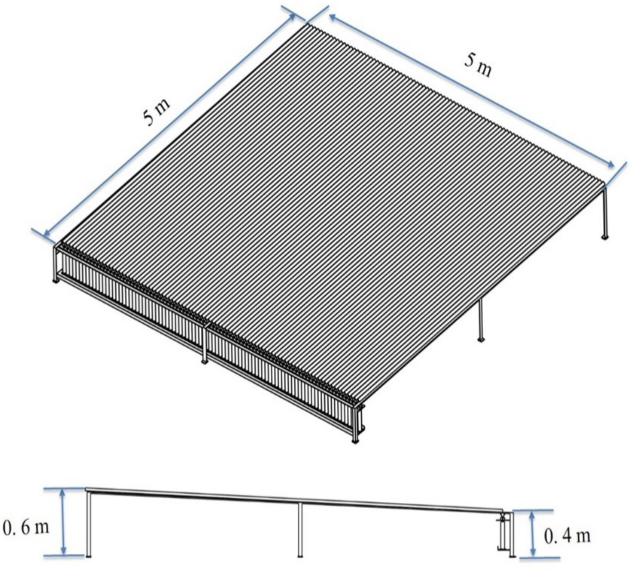


Fig. 2. *Isometric view of spray patternator*

rate. The effective spray width was determined in a manner that will give the most uniform overall application rate.

Test of multi rotor Drone spray distribution pattern in hover outdoor condition

The optimised nozzle spacing and operating pressure of operational parameters based on the uniformity coefficient was selected to study the spray distribution in outdoor condition. A four flat fan nozzles were mounted on the boom with optimised nozzle spacing (60 cm) and attached below the drone sprayer's fluid tank and landing gear structure. The arrangement of optimised nozzle spacing on the spray boom and attachment to Drone sprayer is shown in Fig. 8 annd Fig.9.

To record and analyse the spray volume distribution pattern for boom nozzle configuration, the Drone sprayer hovered at three flight heights,*viz.,* 1.0 m, 2.0 m, and 3.0 m. These are the independent variables that mainly influence the functional performance of the Drone spray volume distribution pattern in terms of quantity of spray volume collected (ml), coefficient of uniformity (%) and spray width (mm). For each treatment, a 10 litre water tank was filled, and the spray volume was measured in each measuring jar. Each treatment was carried out three times. The coefficient of uniformity and spray width were calculated for three spray hover heights. This spray volume distribution pattern test procedure was followed as per ASAE S386.2 and IS: 8548-1977 standards. Fig. 10 and Gig. 11 show the volumetric distribution of the sprayer in the patternator and the volume of liquid collected in the measuring jar.

Recording of meteorological parameters during outdoor condition test

During the Drone spray volume distribution pattern test, the different meteorological parameters such as air temperature, wind velocity, humidity and rainfall were recorded during the spray volume distribution pattern performance during the outdoor condition. A portable anemometer was mounted on a square iron pipe (20x20x2 mm) at 2.0 m above the ground level to measure the wind velocity. Weather conditions, including wind speed, air temperature, and relative humidity during the study, are presented in Table 3.

RESULTS AND DISCUSSION

Effect of nozzle spacing and operating pressure on spray uniformity in the laboratory condition

Table 4 and Fig. 12 showed that the maximum CV value was 52.08 at 3 kg cm^{-2} operating pressure and 300 mm nozzle spacing and the minimum CV value was 36.99 per cent at a pressure of 4.0 kg cm^{-2} and 600 mm nozzle spacing representing the better spray uniformly distribution. Based on the spray uniformity distribution value, the optimised nozzle spacing of 600 mm and a 4.0 kg cm^{-2} operating pressure was selected for boom spray arrangement on the Drone sprayer.

Fig.3. *Arrangement of measuring jar in spray patternator*

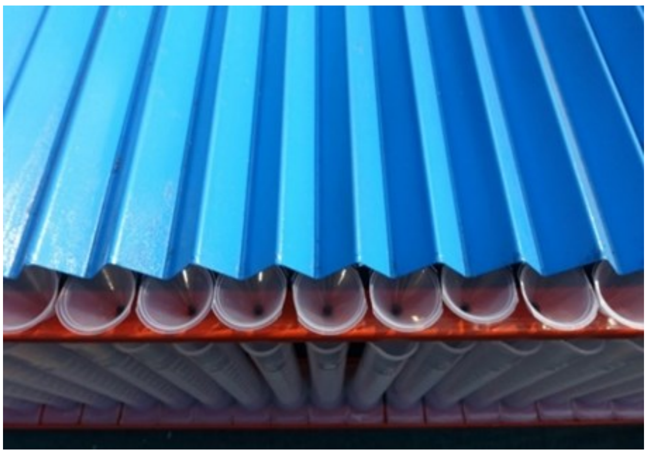


Fig. 4. *Arrangement of funnel in spray patternator*

Table 1. Specifications of Drone sprayer

Sl. No.	Main parameter	Norms and Numerical values
1	Type	Hexacopter
2	Item Model	E610P
3	Unfold fuselage size, (L × W × H), mm	2000 x 1800 x 670
4	Folding Size, (L × W × H), mm	950 x 850 x 670
5	Power source	12S 16,0000 mAhLiPo Battery
6	Payload capacity, L	10
7	Self-weight, kg	6.9
8	Take-off weight, kg	26
9	Flight height, m	1 – 20
10	Forward travel speed, ms^{-1}	0 – 8
11	Type of spray nozzle	Flat fan shape (2020A-132 series)
12	Number of nozzle	4
13	Discharge rate, $l\ m^{-1}$	0 – 3.2
14	Swath width of spray, m	3 – 5
15	Liquid pressure, $kg\ cm^{-2}$	3.4
16	Remote controller distance, km	1.5
17	No-load flight time, min	25
18	Charging time, min	90

Table 2. Specifications of developed spray patternator

Sl. No.	Main parameters		Norms and Numerical Values
1	Overall Size, (L × W × H), mm		5000 x 5000 x 600
2	Support frame structure		L-shaped M.S channel
		Size (L x W), mm	2500 x 1250
3	Sheet material	Material	M.S sheet
		Number of sheets	12
		Numbers	91
4	V channel	Width, mm	55
		Depth, mm	35
5	Patternator inclined slope, degree		25
6	Number of measuring cylinders		91

Fig. 5. *Developed spray patterntor for spray volume distribution measurement*

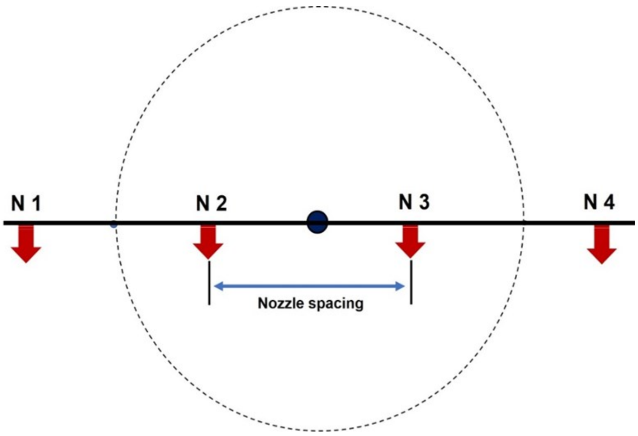


Fig. 6. *Top view of mounting of spray boom type nozzle arrangement without drone*

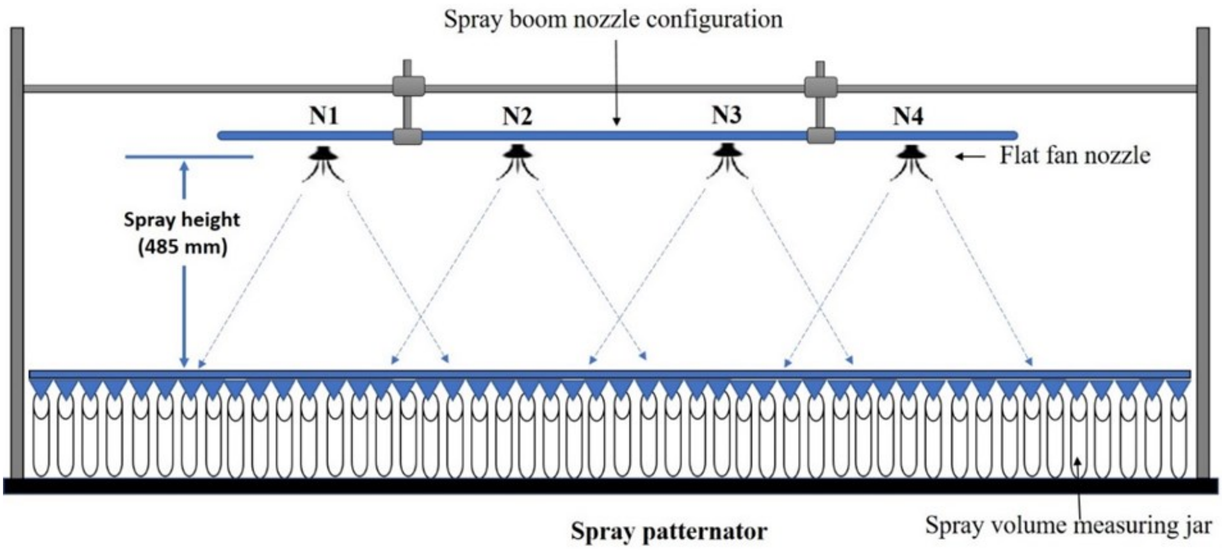


Fig. 7. *Experiemntal layout for mounting of spray boom type nozzles arranegement on spray patternator*

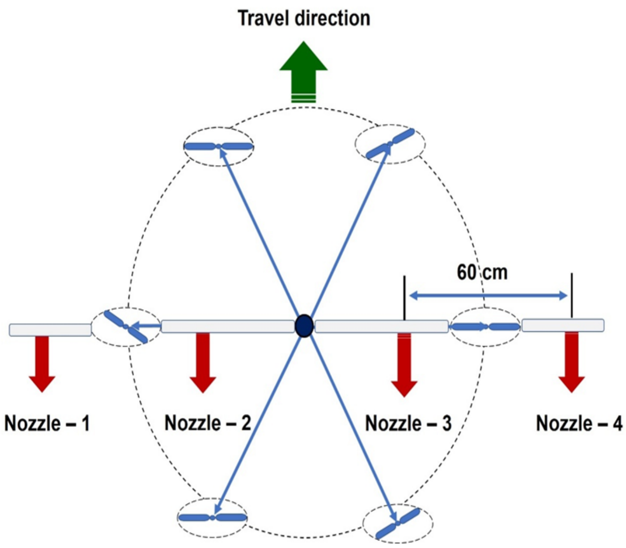


Fig. 8. *Top view of mounting of spray boom type nozzle arrangement to drone sprayer*

Fig. 9. *Arrangement of spray nozzles on boom configuration and attachment to Drone sprayer*

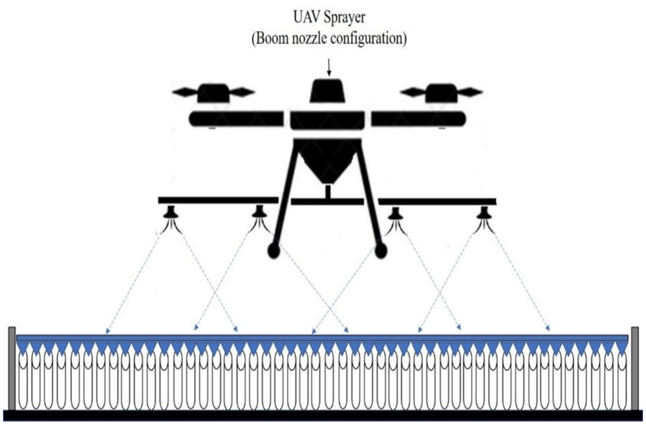


Fig. 10. *Schematic diagram of nozzles arrangement in boom configuration attachment to UAV sprayer for outdoor test*

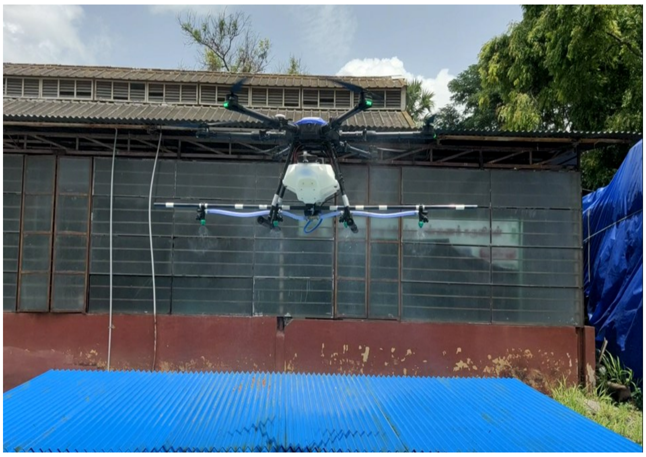


Fig. 11. *UAV Spray volume distribution test in spray patternator at outdoor conditions*

Effect of the height of spray on spray distribution characteristics at the outdoor condition

The drone sprayer with boom spray nozzle configuration hovered and spray volume was collected from each jar during outdoor conditions. The effects of hover height on spray width, the total quantity of liquid collected and spray uniformity distribution are shown in Table 5 and Fig. 13.

Effect of hover height on spray width

It was observed that the spray width was increased by increasing the height of the spray from the patternator. From Fig. 8 and Table 5, when the Drone sprayer was operated from 1.0 m to 3.0 m hover heights, the minimum spray width was found to be 4450 mm at 1.0 m height of spray and the maximum spray width was found to be 4900 mm at 3.0 m height of spray. The height of spray does not influence the discharge rate during the laboratory trials.

Effect of hover height on quantity of liquid collected

Drone sprayed a total of 10 litresunder outdoor conditions at an optimised operating pressure of 4 kg cm^{-2}. The central portion of the drone sprayer collected less water (5190 ml) when hovered at 1.0 metre height compared to 2.0 (5416 ml) and 3.0 metre (6230 ml) hover heights.

Effect of hover height on uniformity distribution of spray

According to the coefficient of variation results given in Table 5, spray height had a significant impact on spray uniformity distribution. Lesser spray uniformity distribution was 57.21 per cent at 1.0 m height of spray and maximum spray uniformity distribution was 47.26 per cent at 3.0 m height of spray. It was also observed that better spray uniformity distribution was found when the Drone sprayer hover height was increased from 1.0 m to 3.0 m from the top of the patternator.

Finally, it was also observed that more round vertex patterns were generated during the 1.0 m hover height compared to the 2.0 and 3.0 m hover heights due to the direct impact of downwash airflow generated by the rotors. At 1.0 m hover height, most of the spray droplets were distributed back to the upper side and did not move towards the downside V-channel surface of the patternator. Downwash airflow produced by rotor pro-

Table 3. Meteorological data during the UAV spray volume distribution pattern test

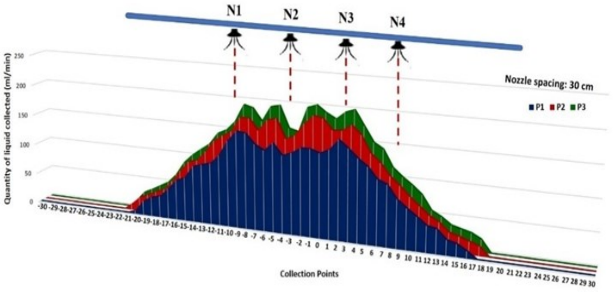
Sl. No.	Environmental parameters	Values
1	Air temperature, ° C	28.3 to 30.9
2	Relative humidity, %	54.5 to 60.2
3	Wind velocity, ms^{-1}	0.11 to 0.21
4	Rainfall, mm	0

Table 4. Results of boom spray distribution pattern test

Sl. No	Nozzle Spacing (mm)	Operating pressure (Kg cm^{-2})	CV (%)
1	300	3	52.08
		4	56.04
		5	54.29
2	450	3	45.72
		4	44.61
		5	44.21
3	600	3	37.63
		4	36.99
		5	38.35

Table 5. Results of boom spray distribution pattern test

Sl. No	Height of Spray (m)	Spray width (mm)	Quantity of liquid collected (ml)	CV (%)
1	1.0	4450	5194	57.21
2	2.0	4750	5416	52.86
3	3.0	4900	6231	47.26



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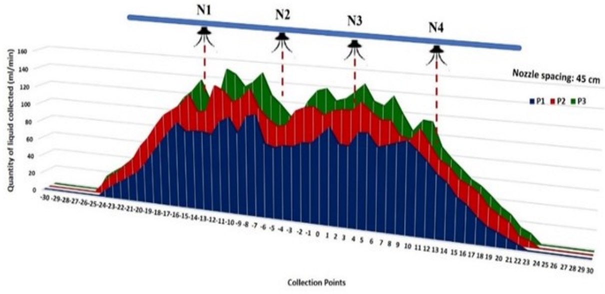

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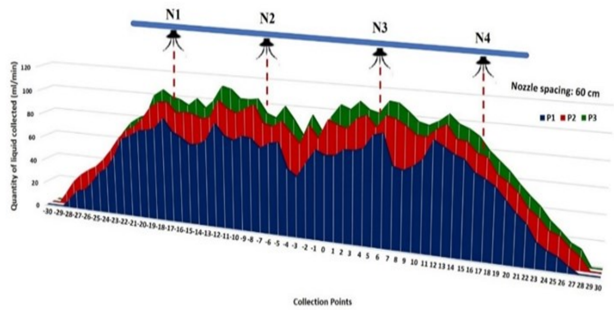

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Fig. 12. *Effect of nozzle spacing and operating pressure on volumetric spray distribution for boom type nozzles configuration: a) 30 cm, b) 45 cm and c) 60 cm nozzle spacing*

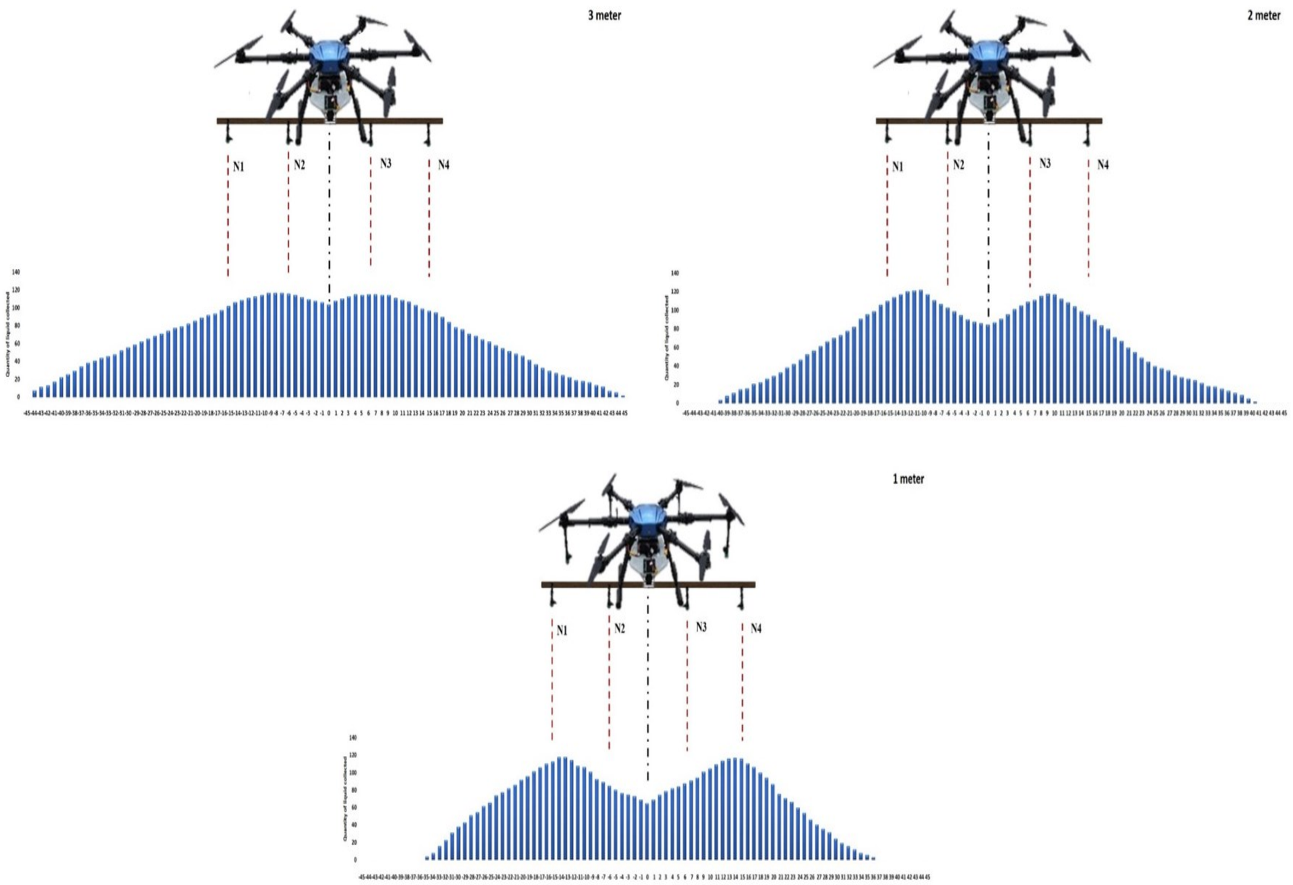

Fig. 13. *Spray volume distribution pattern of boom type nozzles configuration*

pellers caused a worsening of the liquid distribution uniformity coefficient. It significantly influenced the change of the lateral distribution pattern of spray drops produced by the flat fan spray nozzles.

The result indicates that the there is a change in the shape of liquid distribution pattern on the patternator due to the influence of downwash airflow produced by the drone rotor propellers (Berner and Chojnacki, 2017 and Qing *et al.,* 2017). Similarly, as in previous research works (Pachuta et al, 2018) the asymmetry of the airflow distribution generated by the drone rotors with respect to the nozzle axis is what causes the lateral spray liquid distribution of the settled liquid on the patternator to change shape. The volume of the liquid that was deposited in the patternator's later grooves also varied significantly (Chojnacki and Pachuta, 2021). A higher spray distribution amount of the liquid was sprayed from the twin flat nozzle than from the single flat nozzle (Coombes *et al.,* 2022). Earlier reported work were done at a constant spray height, where in the present investigation, the results were obtained at varying sprays heights (1.0, 2.0 and 3.0 m) and nozzle spacing (30,45,60cm) at a optimised operating pressure (5kg cm^{-2}).

Conclusion

A suitable, bigger spray patternator (5.0x5.0 meter) was developed to investigate the influence of downwash airflow on spray distribution characteristics. Initially, nozzle spacing and operating pressure for boom arrangement on the Drone sprayer were optimised. The optimised nozzle spacing of 600 mm and a 4.0 kg cm^{-2} operating pressure waschosen for the Drone sprayer distribution test at outdoor conditions based on the spray uniformity distribution value. The spray width increased from 4450 mm to 4900 mm when the drone sprayer hover height increased from 1.0 to 3.0 metres. The central portion of the patternator collected less water (5194 ml) when a drone sprayer hovered at 1.0 metre height compared to 2.0 (5416 ml) and 3.0 metre (6231 ml) hover heights. With the increase in hover height, the change in the downwash airflow led to a gradual decrease in spray volume distribution in the effective spray area. A better spray uniformity distribution was found when the drone sprayer's hover height was increased from the top of the patternator. A more round spray droplet vertex pattern was generated during the 1.0 m hover height compared to the 2.0 and 3.0 m hover heights due to the direct impact of downwash airflow generated by the rotors. Downwash airflow produced by rotor propellers reduced the liquid distribution uniformity coefficient and significantly influenced the change of lateral distribution pattern of spray drops produced by the flat fan spray nozzles. Thus the Drone sprayer should be operated at an appropriate spray height of 2.0 m to attain the recommended application rate of pesticides. The study provides references for the arrangement of nozzles in the airflow pattern below the rotor and establishes a reference for the spatial motion trend analysis of the spray volume distribution in the rotor-downwash airflow.

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Conflict of interest

The authors declare that they have no conflict of interest.

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