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Article

Effects of Flight Heights and Nozzle Types on Spray Characteristics of Unmanned Aerial Vehicle (UAV) Sprayer in Common Field Crops

Saurav Ranabhat [1,*] and Randy Price [2]

1 Department of Entomology, Louisiana State University, Baton Rouge, LA 70803, USA
2 Dean Lee Research Station, LSU AgCenter, Alexandria, LA 71302, USA; rprice@agcenter.lsu.edu
* Correspondence: sranabhat@agcenter.lsu.edu; Tel.: +1-3187531350

Abstract: Effective spraying is an important component of precision agriculture, directly influencing the efficiency of the spray materials. Despite their potential, optimal settings for sprayer drones remain underexplored due to limited research data. This study evaluates the effects of various flight heights and nozzle types on spray characteristics in cotton, soybean, and sugarcane crops using an unmanned aerial vehicle (UAV) sprayer. Three different flight heights and two or three nozzle types were evaluated for their impacts on spray deposition, coverage percentage, and droplet size distribution at three different canopy levels of these crops. The results indicated that lower flight heights significantly increased spray deposition and coverage in the upper canopy levels of cotton and sugarcane. Centrifugal nozzles consistently produced greater coverage and spray deposition in sugarcane. Some significant interactions among these factors were also explored. The findings highlight the potential for UAV sprayers to optimize spraying in crops with various morphologies by adjusting flight height and nozzle type.

Keywords: sprayer drone; UAV; nozzle; field crops

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1. Introduction

Agriculture has been the backbone of human civilization, sustaining the global population by providing food, fiber, and fuel. It is the world's largest industry, employing more than a billion people and generating over USD 1.3 trillion worth of food every year [1]. The US is the world's second-largest trader in agriculture, after the European Union [2]. In 2023, the US exported USD 27.9 billion, USD 13.1 billion, USD 5.9 billion, and USD 6.1 billion worth of soybeans, corn, cotton, and wheat, respectively [3]. Louisiana is one of the important states in the US for agriculture. With fertile alluvial soil and a warm, humid subtropical climate [4,5], the major row crops grown in this state include sugarcane, rice, soybean, cotton, and corn. In 2023, 980,000 acres of soybeans, 115,000 acres of cotton, and 505,500 acres of sugarcane were harvested in Louisiana [6].

Precision agriculture is an emerging concept that maximizes yield and profitability with increased efficiency and effective management practices by introducing advanced technologies. Sprayer drones are one of these innovative technologies, specifically used to apply agricultural materials, including pesticides, fertilizers, and other agrochemicals. They are unmanned aerial vehicles (UAVs) equipped with tanks and sprayer nozzles that can be flown over crop fields autonomously [7]. They offer advantages such as a higher speed of spraying, lower water usage, reduced pesticide usage, reduced health risks, and higher field coverage. However, the disadvantages include limited battery endurance, higher acquisition costs, lower tank volume, chances of air accidents, high spray drift risk, and complex regulations [8].

Although interest in sprayer drones in agricultural spraying systems is steadily increasing, their adoption is still in its early stages in the US. There are limited published research data that evaluate sprayer drone performance and utility specifically addressing the agricultural system in the US [9]. For farmers and adopters to assess the best spraying practices, some fundamental information about the parametric adjustments regarding spray deposition, nozzle types, flight altitudes, and spray positions in a sprayer drone can be helpful. Most sprayer drones are equipped with hydraulic nozzles (flat fan, air induction (AI), or hollow cone) or rotary (centrifugal) atomizer nozzles [10], chosen based on the spray patterns and distribution requirements, crop types, and compatibility [11]. Studies suggest that centrifugal nozzles can spray finer particles and are more suitable for low-volume and uniform droplets but are more prone to drift with weak droplet penetration [12]. Hydraulic nozzles, commonly used in ground sprayers, have a wider spraying range and larger flow rate but have poor stability with a high failure rate [13]. Several studies have compared different types of nozzles on various crops with various adjustments and environments such as the LU110-01, LU110-015, and LU110-02 nozzles for rice [14], the hydraulic rotary nozzle, the air-injector flat fan nozzle with hollow cone nozzles for vineyards, and XR 11001, AirMix 11001, and COAP 9001 nozzles [15]. Different flying heights of the drone also affect droplet spray characteristics [16]. Several studies on flight heights have shown the best results at heights of 1.5 m [17] and 2 m [18] for rice and 2.5 m or below for pineapple [19].

There are not enough research data that address the effects of different flight heights and nozzle types to assess the coverage pattern and penetration of the spray in different important field crops, especially since both factors influence almost all spray characteristics. Crop growers, especially in the southeast of the US, generally prefer spraying by drone at a height of about 10 ft above the canopy. Still, no relevant studies have directly recommended this. Our research aimed to provide information on the optimum flight height of a sprayer drone for better spraying. Most commercial sprayer drones are equipped with centrifugal nozzles, whereas traditional spray tools are usually mounted with horizontal flat fan nozzles. Knowing the performance of different nozzle types and the right flight height further helps farmers make optimal spraying decisions. Additionally, since most of the existing research studies were conducted outside the US, there is a need for studies of sprayer drones in crop plants relevant to US agriculture, as fields in the US, especially in the southeast, are much larger, plainer, and exist in varying environments. To address this research gap, a comprehensive experiment was conducted to explore the droplet characteristics from a sprayer drone for different flight heights above the canopy, nozzle types, levels of canopy penetration, and their respective interactions on soybean, cotton, and sugarcane crops.

2. Materials and Methods

The experiment was conducted in Lecompte, Louisiana (31.17649, −92.40604), from June 15th to July 15th of the 2024 crop season.

Two complimentary spray drones (Table 1) were constructed with two different spray systems; one with a standard hydraulic nozzle orifice system (Figure 1A) and the other with a centrifugal rotary nozzle spray system (Figure 1B). The hydraulic nozzle system is predominantly used in traditional ground-based spraying systems, while the rotary system represents an innovative approach tailored for sprayer drones. The hydraulic orifice nozzle system was outfitted with four AIXR11002 nozzles mounted under each motor on a 20 cm post and with a 6 cm offset nozzle mount. This arrangement provided an 18.7 to 21.5 L/ha (2 to 2.3 gallons per acre) application rate with a 4.6 to 6 m swath width depending upon application height and speed, creating droplets with a volume median diameter (VMD) of 400 µm (Table 1). The centrifugal rotary nozzle system used four Shanrya rotary disk nozzles (Model # B09R9MWW9K) with a 15 cm offset post and a 6 cm offset. This configuration created a 4.6 to 6 m swath width (like the hydraulic orifice nozzle drone) with only the two rear nozzles to be operated during the test with a combined flow of 7.5 L per minute (L/m) (0.8 GPM) total with a rotation speed of 5300 rpm (27% of the full speed) to create a volumetric median droplet size of 275 to 300 µm. A 3.75 L/min (0.4 GPM) orifice was used in each nozzle and a pressurized pumping system was used to create an equal flow between the two nozzles. All these parametric settings closely imitate the settings of a commercial sprayer drone.

(A) (B)

Figure 1. Spray drones used in the test mounted with (**A**) standard hydraulic orifice system and (**B**) centrifugal/rotary spray system.

Table 1. Unmanned aerial vehicle specifications.

Parameter	Description	
	Drone 1	**Drone 2**
Dimensions (cm)	1270 mm × 1270 mm × 600 mm	1270 mm × 1270 mm × 600 mm
Configuration	X-Quad	X-Quad
Propellers	3411	3411
Tank Capacity (L)	16	16
Method of Operation	Remote Control	Remote Control
Spraying System	Atomized Spraying–Hydraulic Orifice Nozzles	Atomized Spraying–Centrifugal/Rotary Nozzles
Number of Nozzles	4—Outside Nozzle Mounts Only	2—Rear Only
Mean Droplet Size (VMD)	400 µm at 0.2 GPM liquid flow per nozzle	300 µm at 60% disk speed/0.4 GPM liquid flow per nozzle
Application Width (m)	3.6–6 m (dependent upon application height, speed, wind, and flow rate). Best combination: 2.3 GPA at 3 m application height and 5 ms^{-1} travel speed with a 4.6 m swath width.	3.6–6 m (dependent upon application height, speed, wind, and flow rate). Best combination: 2.3 GPA at 3 m application height and 5 ms^{-1} travel speed with a 4.6 m swath width.
Application Rate (GPA)	2–2.3	2–2.3
Operating Speed (m/s)	5	5

Table 1. *Cont.*

Parameter	Description	
	Drone 1	**Drone 2**
Positioning Mode	GPS or manual	GPS or manual
Hovering Time (min)	12–22 min	10–20 min
Max Wind Resistance	Continuous wind level 3	Continuous wind level 3
Pump	8 L diaphragm (Hobbywing)	8 L diaphragm (Hobbywing)
Battery	Tattu 22,000 mAh 24 cell/48 volt	Tattu 22,000 mAh 24 cell/48 volt
Working Voltage	42 to 50 volts	42 to 50 volts

Soybean, cotton, and sugarcane fields were selected for the experiment (Figure 2). These fields consisted of a soybean (Pioneer 42-884) variety (Figure 2A) with a late vegetative to early flower stage planted in a tight three-row configuration over a raised sugarcane bed, a cotton field (Delta Pines 21–27 variety) with approximately 25 cm of row space between plants (Figure 2B), and a sugarcane field (L 01-299 variety) planted on a 30 cm high by 1.8 m wide bed with approximately 50 to 75 cm between the plants (Figure 2C). The soybean plants had an average LAI (leaf area index) of 6.13 and 3 to 6 cm between rows (or no gap) between the plants. The cotton and sugarcane plants had LAIs of 2.01 and 2.77, respectively, and were in middle to late vegetative stages.

(**A**) (**B**) (**C**)

Figure 2. Different crops tested for spray infiltration into the canopy; (**A**) soybeans, (**B**) cotton, and (**C**) sugarcane.

Experiments were conducted in each of the three fields utilizing a 40 m by 5-row area chosen based on homogeneity and location (easy access, nearby take-off and landing area, etc.). Just before each test (flight), water-sensitive cards (WSPs) by TeeJet Technologies (26 × 73 mm each) were clipped to the top, middle, and bottom levels of three different plants separated by 1 to 3 m in that row (Figure 3). The water-sensitive cards were placed on the adaxial side of the leaf using a small binder clip (Office Depot) and on two randomly selected plant leaves directly below the top card leaf in the middle and bottom (or last leaf position location) areas of the plant. Care was taken while clipping to prevent damage to the leaves or causing undue weight, pulling the leaf down (especially in soybean), sometimes clipping the card to two to three stacked together or a leaf stem. All cards were facing up.

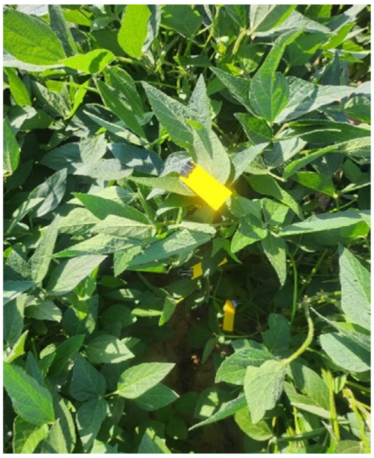

Figure 3. Soybean plant showing top, middle, and bottom placement of water-sensitive cards.

The drones' settings during the experiment are shown in Table 1. Flights were performed randomly and over the middle row of the crop where the cards were placed with a slight offset (0.3 to 0.8 m) to not be directly over the center of the drone (where low-density spray areas could exist) and in a racetracsk-type pattern (Figure 4). The drone was then landed, the cards were picked up, and the next test was performed. Three different application heights—low altitude [1.2 m or 4 ft], medium altitude [3 m or 10 ft], and high altitude [6 m or 20 ft]—were tested. Each treatment combination is shown in Table 2 and was completely randomized during testing. Tank loads (during testing) consisted of normal tap water with no adjuvants.

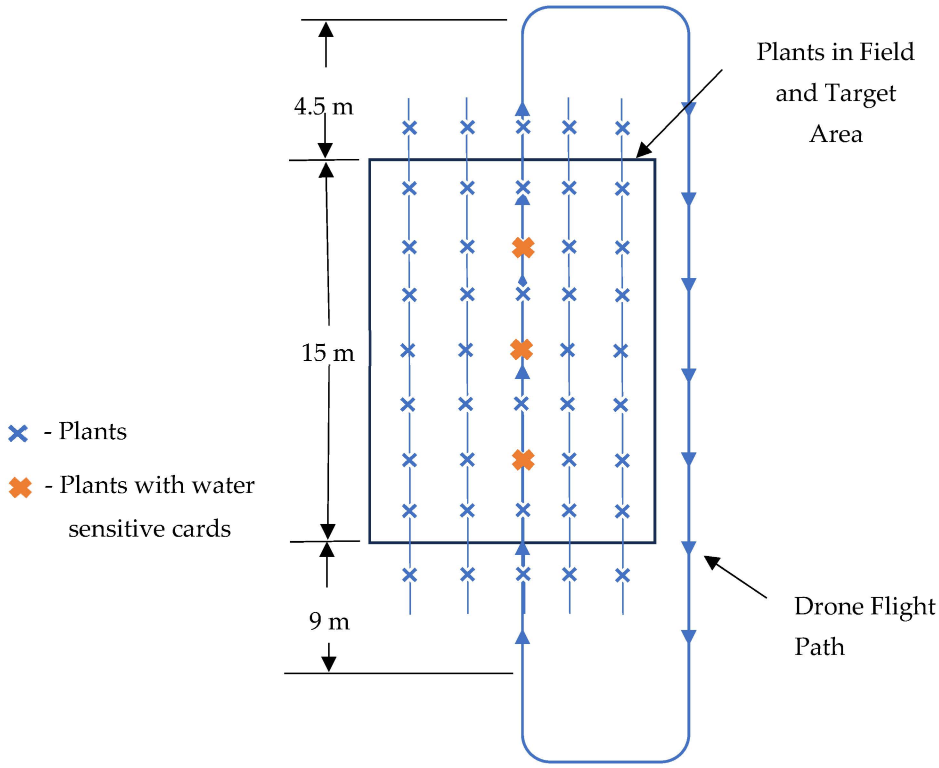

Figure 4. The flight pattern of the drone in an experiment plot.

Table 2. Treatment combinations tested during the experiment.

Treatment ID	Treatments (Fixed Effects)		
	Nozzle Type	Flight Heights (m)	WSP Positions in the Canopy
T1	Centrifugal	1.2	Upper
T2	Centrifugal	1.2	Middle
T3	Centrifugal	1.2	Lower
T4	Centrifugal	3	Upper
T5	Centrifugal	3	Middle
T6	Centrifugal	3	Lower
T7	Centrifugal	6	Upper
T8	Centrifugal	6	Middle
T9	Centrifugal	6	Lower
T10	Horizontal	1.2	Upper
T11	Horizontal	1.2	Middle
T12	Horizontal	1.2	Lower
T13	Horizontal	3	Upper
T14	Horizontal	3	Middle
T15	Horizontal	3	Lower
T16	Horizontal	6	Upper
T17	Horizontal	6	Middle
T18	Horizontal	6	Lower

Since environmental factors such as wind velocity, relative humidity, precipitation, and temperature highly influence the spraying characteristics causing a higher spray drift, the coagulation of droplets, and difficulty in precise spray deposition, their regulation is crucial since they can be a potential source of variation in our experiments. All flights were performed during low wind conditions (<2 miles per hour) and into a headwind (if any wind existed) to prevent off-target spray movement. The average temperature and humidity recorded during testing were 90 F and 60% relative humidity.

After each spray test, the WSPs (cards) were collected and labeled on the back for plant, location, and test and put into a moisture-resistant bag and stored in a dry place. The WSPs (cards) were analyzed using a computer (Dell Latitude by DELL™, Model no. PP05L, Made in Malaysia), software (Droplet Scan, Version 2.4, WRK of Arkansas, Fayetteville, AR, USA), and a scanner (EPSON XP-4100, Model C636B, Made in Indonesia) and analyzed for spray deposition (GPA) and percentage coverage. RStudio 2024.04.2 Build 764 [20] with libraries dplyr [21], car [22], lmtest [23], and Agricolae [24], and Microsoft® Excel® for Microsoft 365 MSO (Version 2409 Build 16.0.18025.20160) [25] were used for the statistical analysis and data visualization. All the response variables were first tested for the assumptions of ANOVA. The Shapiro–Wilk test was performed to test the normality of the residuals, the Levene test was performed to check the homogeneity of variance, and the Durbin–Watson test was used to test for the presence of autocorrection. If the assumptions were accepted, a 3-factor factorial CRD ANOVA was performed for the significance test followed by Tukey's HSD test for the mean separations. If the assumptions were not accepted, the data were transformed before performing ANOVA. A series of square root transformations, log transformations, and cube root transformations were performed every time they rejected the assumptions of ANOVA. If none of the transformations successfully accepted the assumptions, ANOVA was performed with the original data regardless as ANOVA is generally robust and provides reliable analysis, even with non-normal data or data with an unequal homogeneity of variance [26].

3. Results and Discussion

3.1. Flight Heights

The effect of different flight heights on spray deposition and coverage percentage was statistically significant ($p < 0.05$) in cotton. The highest spray deposition was achieved at a lower flight height of 1.2 m (4 ft) above the canopy, averaging 10.10 L/ha. This was statistically similar to the flight height of 3 m (10 ft), which resulted in an average spray deposition of 7.58 L/ha. The lowest spray deposition of 4.40 L/ha was observed at the highest flight height of 6 m (20 ft). Similarly, a larger coverage of the spray was observed at the lower flight height of 1.2 m (4 ft) (2.75%), which was statistically higher than the coverage at 3 m (1.91%) and 6 m (1.15%) (Table 3). This trend suggests that as the flight height of the sprayer drone decreases, its ability to spray at a higher volume with greater coverage in cotton plants decreases.

Table 3. Droplet characteristics of the spray with different flight heights (m) of sprayer drone above the canopy in cotton.

Flight Heights (m)	Spray Deposition (L/ha) [1,2]	Coverage (%) [1,2]
1.2	10.10 a	2.75 a
3	7.58 a	1.91 b
6	4.40 b	1.15 b
HSD	2.91	0.808

Notes: [1] Averages values with different lowercase alphabet letters in the column differentiate each other according to Tukey's HSD test at a 5% significance level. [2] The normal distribution of the residuals, homogeneity of variances, and independence of the residuals seen after the cube root transformation of the original data; HSD values are the critical values of Tukey's HSD test.

The reduced volume and coverage of the spray at higher flight heights in cotton can be explained by several factors. Firstly, at greater heights, released droplets naturally take longer to reach the crop canopy, increasing the chances of drifting. Environmental factors such as wind, evaporation, humidity, and air resistance can contribute to spray drift. Smaller droplets, with a size of less than 150 µm, are particularly susceptible to drift, which can be problematic for drones equipped with centrifugal nozzles [27,28].

Lower flight heights of sprayer UAVs in cotton have been widely recommended and adopted in many previous experiments worldwide. Liao (2019) [29] found the optimum flight height for a UAS for cotton to be 1.5 m. A flight height of 2 m above the canopy was found to be superior when compared to 3 m for cotton harvest aid efficacy [30]. Another study in China observed the best results in controlling cotton aphids using sprayer UAVs when flown at a height of 1 to 1.5 m [31]. These findings strongly support our experiment's results, suggesting that a lower flight height ranging from 1 to 2 m above the canopy is likely optimal.

However, our findings might not be true in all instances. Factors such as the plant's canopy structure, environmental conditions, plant stages, differences in UAV type, spraying techniques, spray materials, and the drone's parametric settings could potentially influence spraying efficacy at any flight height. Since our experiments did not study the effects of these factors on the spraying efficacy, they did not provide information on their influence.

Interestingly, no significant differences were observed in the spray deposition and coverage across the different flight heights for sugarcane and soybean. Previous studies showed that for a typical UAV sprayer, a flight height of 2 m for soybean [32] and 2–4 m above the canopy for sugarcane [33] was desirable. However, these studies did not test higher flight heights (>4 m), leaving the effects of these heights on the spray characteristics unexplored. Our results did not provide evidence that different flight heights for sugarcane and soybean at the late vegetative to early reproductive stage have significant effects, suggesting that further research should be considered with robust methodologies with more extensive data.

3.2. Nozzle Types

The three different nozzle types had significant effects only on the volumetric median diameter (VMD) for soybeans. The centrifugal nozzle produced larger droplets with a mean VMD of 375.29 µm, which was statistically similar ($p < 0.05$) to that of the hydraulic nozzle AIXR11001, with a mean VMD of 338.51 µm. The AIXR11002 produced the smallest droplets, averaging 282.38 µm, statistically different from the centrifugal and AIXR11001 nozzles. The spray depositions ranged from 2.34 to 3.46 L/ha, and the coverage percentages ranged from 0.64% to 0.93%. Both the spray deposition and coverage percentages were not statistically significantly different (Table 4).

Table 4. Droplet characteristics of the spray with different flight heights (m) of sprayer drone above the canopy in cotton.

Treatments	Soybean		
	Spray Deposition (L/ha) [1,3]	VMD (µm) [1]	Coverage (%) [1,3]
Centrifugal	3.46	375.29 a	0.93
AIXR11001	2.99	338.51 a	0.86
AIXR11002	2.34	282.38 b	0.64
HSD	ns	46.00	ns
Treatments	**Sugarcane**		
	Spray Deposition (L/ha) [1,2]		**Coverage (%) [1,2]**
Centrifugal	5.97 a		1.69 a
AIXR11002	3.37 b		0.85 b
HSD	1.25		0.334

Notes: Spray deposition and coverage percentages are presented for both soybean and sugarcane. VMD data are only available for soybean. The AIXR11001 nozzle is not tested in sugarcane. [1] Mean values (before transformation if transformed) separated by lowercase letters indicating significant differences at the 0.05 level of significance according to Tukey's test. 'ns' indicates non-significant results at the 0.05 level of significance. HSD values represent the critical HSD value from Tukey's test. [2] Assumptions of the ANOVA were fulfilled only after the cube root transformation of the original data. [3] All assumptions of the ANOVA were not fulfilled, even after the transformation.

The fact that the centrifugal nozzles produced bigger droplets is unusual since finer droplets were expected. Previous studies suggest that a centrifugal nozzle normally produces droplets that are less than 200 µm and can range from 90 to 300 µm [34], whereas that of air induction hydraulic nozzles is 220 to 400 µm [13]. One possible explanation for this could be the coagulation of finer droplets from the centrifugal nozzle, resulting in bigger droplet sizes. Higher flight heights are more prone to drifting spray. Drifting not only changes the direction of the spray but also hinders the smooth falling of the droplets on the plants, potentially causing droplet coagulation. Also, the wind velocity was not accounted for in our experiments, limiting our justification. More data on the droplet characteristics from different nozzle types can further clarify this phenomenon.

For sugarcane, significant differences were observed between the AIXR11002 and centrifugal nozzles tested for both spray deposition and coverage (Table 2). The centrifugal nozzles produced a statistically larger spray deposition of 5.97 L/ha compared to the AIXR11002 nozzle, which produced 3.37 L/ha. The spray coverage percentage of the centrifugal nozzle was 1.69%, significantly higher than that of the hydraulic AIXR11002 nozzle, which had 0.85% coverage (Table 2). This could mean that better performance can be achieved with centrifugal nozzle-mounted drones. Compared to soybean and cotton, sugarcane has a dense canopy with more height.

No significant differences were observed in cotton on the spray deposition and coverage percentage. The VMD variable was not recorded for cotton.

3.3. Canopy Penetration

The spray deposition and coverage percentage across the different levels of canopy were statistically significant in all three crops ($p < 0.05$). In cotton, the upper canopy (high) received the highest spray deposition (12.07 L/ha) and coverage (3.12%). The middle (Mid) and lower (Low) canopy levels received spray depositions of 6.36 L/ha and 3.65 L/ha, respectively, with corresponding coverage percentages of 1.77% and 0.91%. Similarly, in soybean, the upper canopy level received the highest spray deposition, VMD, and coverage percentage of 6.36 L/ha, 400.52 µm, and 1.74%, respectively, while these variables were significantly lower in the middle and lower levels of the canopy. Similar results were observed in sugarcane, where the upper canopy level had higher values for spray deposition (7.39 L/ha) and coverage percentage (1.98%). Both variables decreased as the canopy levels were reduced to the middle (spray deposition: 4.30 L/ha; coverage: 1.16%) and lower (spray deposition: 2.34 L/ha; coverage: 0.67%) levels (Table 5).

Table 5. Spray droplet characteristics observed on different canopy levels in cotton, soybean, and sugarcane.

Treatments	Cotton	
	Spray Deposition (L/ha) [1,2]	Coverage (%) [1,2]
High	12.07 a	3.12 a
Mid	6.36 b	1.77 b
Low	3.65 b	0.91 c
HSD	3.096	0.830

Treatments	Soybean		
	Spray Deposition (L/ha) [1,3]	VMD (µm) [1]	Coverage (%) [1,3]
High	6.36 a	400.62 a	1.74 a
Mid	2.06 b	336.09 b	0.56 b
Low	0.47 b	258.72 c	0.14 c
HSD	1.861	46.987	0.534

Treatments	Sugarcane	
	Spray Deposition (L/ha) [1,2]	Coverage (%) [1,2]
High	7.39 a	1.98 a
Mid	4.30 b	1.16 b
Low	2.34 c	0.67 b
HSD	1.817	0.493

Notes: Spray deposition and coverage percentages are presented for cotton, soybean, and sugarcane. VMD data are only available for soybean. [1] Mean values (original value if transformed later) separated by lowercase letters indicating significant differences at the 0.05 level of significance according to Tukey's test. HSD values represent the critical HSD value from Tukey's test. [2] Assumptions of the ANOVA were fulfilled only after the cube root transformation of the original data. [3] All assumptions of the ANOVA were fulfilled after square root transformation.

These results were as expected since canopy penetration from the top level of plants to the bottom level typically occurs [35]. Similar observations were found in vineyards [36], sugarcane [33], peanuts [37], red gram [38], and corn [39]. The upper layer of a plant has a greater number of leaves, thus increasing the leaf area index (LAI). This blocks most of the droplets from penetrating to the lower-level leaves when sprayed from right above. However, sometimes, when plants are sprayed by a UAV, the downward force from the rotating wings of the UAV may blow the top-most canopies, easing the droplets to penetrate to the lower level or simply affecting the position of the upper-clipped WSP, meaning they receive fewer droplets on them.

4. Interactions

4.1. Flight Heights × Nozzle Types

The combinations of different flight heights (1.2 m, 3 m, and 6 m above the canopy level) and nozzle types significantly affected the coverage percentage of the spray in cotton. The highest coverage percentage (3%) was observed when the drone with the AIXR11002 nozzle was flown 1.2 m above the cotton plants, statistically similar to the centrifugal nozzle-mounted drone at 1.2 m and 3 m flight heights. The rest of the combinations resulted in lower spray coverage. These results can be due to some specific factors. Firstly, the AIXR nozzles typically have higher spray flow rates than the centrifugal nozzles, contributing to higher coverage [34]. Also, when the drone is flown from a lower height, the effective swath width is typically less, consequently increasing the spray deposition of the area.

The spray coverage from both nozzles subsequently decreased as the flight height was increased. However, the pattern was not the same (Figure 5). A higher difference in the spray coverage was seen at 3 m flight height from the nozzles. The centrifugal nozzle-mounted drone had consistent spray coverage from 1.2 m to 3 m, whereas a sharp decline was seen in the AIXR11002 nozzle-mounted drone. The different spray mechanisms in these nozzles can explain this phenomenon.

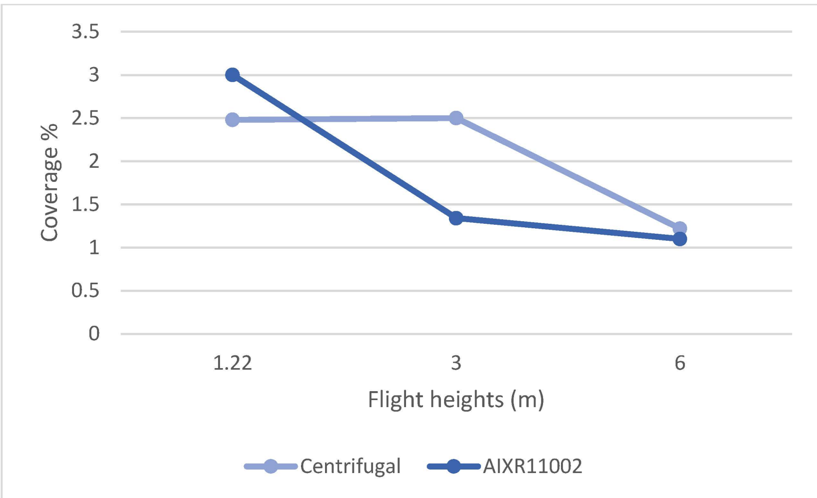

Figure 5. Mean spray coverage percentage of centrifugal and AIXR11002 nozzles on three different flight heights in cotton.

No significant effects were observed on spray deposition (Table 6). Although non-significant, the highest mean spray deposition was observed in the 1.2 m flown AIXR11002 nozzle-mounted drone.

For soybean and sugarcane, no significant effects were observed by the interaction of the flight heights and nozzle types on any of the response variables.

Table 6. Spray deposition (L/ha), and coverage percentage of the spray on the interaction of nozzle types and flight heights in cotton.

Flight Heights (m): Nozzle	Spray Deposition (L/ha) [1,2]	Coverage (%) [1,2]
1.2: AIXR11002	10.85	3 a
3: Centrifugal	9.63	2.5 ab
1.2: Centrifugal	9.35	2.48 ab
3: AIXR11002	5.52	1.34 b
6: Centrifugal	4.58	1.2 b
6: AIXR11002	4.30	1.1 b
HSD	ns	1.317

Notes: ns: non-significant at 0.05 significance level, HSD represents the minimum Honest Significant Difference value from Tukey's test. [1] Mean values (original values) separated by lowercase alphabets indicating significant differences at the 0.05 level of significance according to Tukey's test. [2] Assumptions of the ANOVA were fulfilled only after the cube root transformation of the original data.

4.2. Flight Heights × Canopy Levels

Different flight heights of the drone significantly affected the spray deposition and coverage percentage on the different levels of canopy penetration in cotton. When the drone was flown at the height of 1.2 m, higher spray deposition (18.52 L/ha) and coverage (4.95%) were observed on the upper canopy (Table 7). The rest of the data show that as the flight height increased, the droplet spray deposition and coverage percentage gradually decreased as we went down the canopy levels. However, the decreasing pattern was not uniform (Figure 6). This suggests that both spray deposition and coverage are optimized at lower flight heights, particularly when targeting the upper parts of the canopy in cotton. When reduced spray deposition and coverage are desired, higher flight heights can be chosen to target lower canopy levels.

No significant effects of flight heights with different levels of the canopy were seen in soybean and sugarcane for the response variables.

Table 7. Spray deposition (L/ha), and coverage percentage of the spray on the interaction of flight heights and levels of canopy in cotton.

Flight Height (m): Canopy Level	Spray Deposition (L/ha) [1,2]	Coverage (%) [1,2]
1.2: High	18.52 a	4.95 a
3: High	10.48 b	2.56 b
3: Mid	8.23 bc	2.3 bc
6: High	7.67 bc	2.06 bc
1.2: Mid	7.48 bc	1.98 bc
1.2: Low	4.30 bc	1.23 bc
3: Low	4.12 bc	0.87 bc
6: Mid	3.09 c	0.82 bc
6: Low	2.43 c	0.63 c
HSD	6.64	1.780

Notes: HSD represents the minimum Honest Significant Difference value from Tukey's test. [1] Mean values (original values) separated by lowercase alphabets indicating significant differences at the 5% level of significance according to Tukey's test. [2] Assumptions of the ANOVA were fulfilled only after the cube root transformation of the original data.

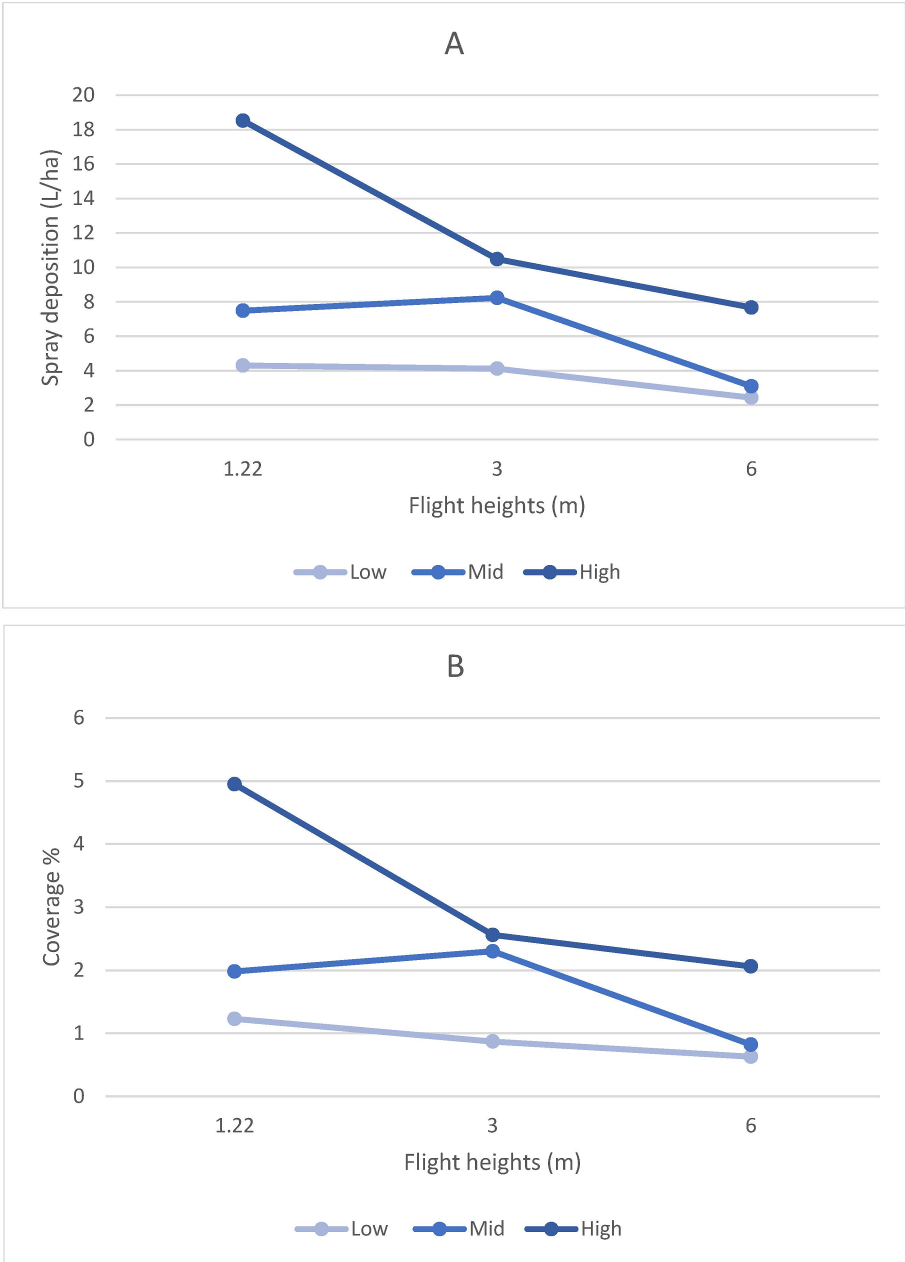

Figure 6. Mean spray deposition (**A**) and coverage percentage (**B**) from three different flight heights on upper, middle, and lower canopy levels in cotton.

4.3. Nozzle Types × Canopy Levels

The different nozzle types significantly affected the spray deposition and coverage percentage on different levels of the canopy in sugarcane. The highest spray deposition (9.73 L/ha) and coverage (2.69%) were observed on the higher canopy level when sprayed with a centrifugal nozzle-mounted sprayer drone (Table 8). As we went down the canopy level, the centrifugal nozzle saw a lower volume and coverage of the spray, suggesting its reduced effectiveness at lower canopy levels. The centrifugal nozzle's performance was superior to the AIXR11002 nozzles, as both the spray deposition and coverage from AIXR11002 were seen to be less than that of the centrifugal nozzles on all the canopy levels. Both nozzles showed decreased spray deposition and coverage as the canopy level decreased. A somewhat similar pattern was seen in the decrease in the spray deposition and coverage percentage on both nozzle types as we went down the canopy levels (Figure 7).

Table 8. Spray deposition (L/ha) and coverage percentage of the spray on the interaction of nozzle types and levels of canopy in sugarcane.

Nozzle Type: Canopy Level	Spray Deposition (L/ha) [1,2]	Coverage (%) [1,2]
Centrifugal: High	9.73 a	2.69 a
Centrifugal: Mid	5.61 b	1.57 b
AIXR11002: High	4.96 bc	1.27 bc
AIXR11002: Mid	2.99 bc	0.82 bc
Centrifugal: Low	2.62 bc	0.76 bc
AIXR11002: Low	2.06 c	0.53 c
HSD	3.162	0.858

Notes: HSD represents the minimum Honest Significant Difference value from Tukey's test. [1] Mean values (without transformation) separated by lowercase alphabets indicating significant differences at the 0.05 level of significance according to Tukey's test. [2] Assumptions of the ANOVA were fulfilled only after the cube root transformation of the original data.

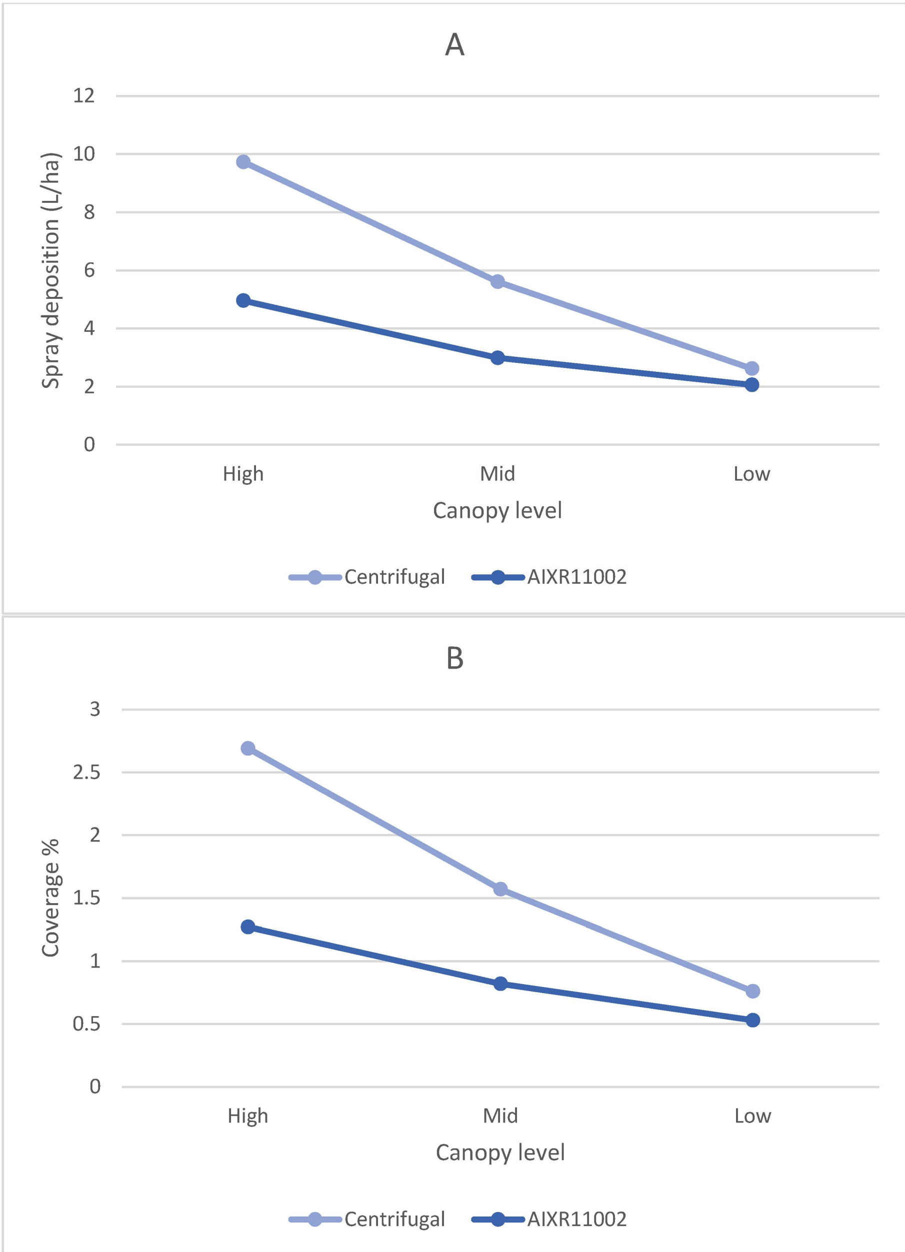

Figure 7. Mean spray deposition (**A**) and coverage percentage (**B**) from centrifugal and AIXR11002 nozzles on upper, middle, and lower canopy levels in sugarcane.

No significant effects of the nozzle types on different canopy levels were observed in soybean and cotton on any of the response variables.

5. Conclusions, Significance, and Future Outlook

This study demonstrates that the spray distribution of UAV sprayers can be optimized through the strategic adjustments of flight heights and nozzle types on different field crops, such as cotton, soybean, and sugarcane. Lower flight heights around 1 m above the canopy level can enhance spray deposition and coverage in the upper canopy region. This can be useful for spraying pesticides targeting pests or diseases located around the top of the crops. The efficacy of nozzle types can vary from crop to crop. While centrifugal nozzles can perform better in sugarcane, having a dense and tall canopy might not be significantly advantageous for other small and bushy crops such as soybeans. The selection of the nozzles on a sprayer drone can vary depending on many other factors that should be further studied. Typically, the distribution of the spray across the different canopy levels can be similar on different field crops, where the upper canopy levels potentially receive more spray than the middle or lower levels.

The results of this study are significant for advancing precision agriculture by using UAV-based sprayers. Their adoption in the US agricultural system has been reportedly increasing, especially since 2019 [40]. By understanding the effective settings of a sprayer drone, farmers and crop growers can reduce pesticide usage and minimize environmental impacts while maximizing efficacy and economic returns. This research highlights the importance of selecting the appropriate flight heights and nozzle types based on crop characteristics. Since this research is one of the first series of experiments of optimizing drone spraying systems in field crops of Louisiana, the US, farmers and drone operators can reliably use its recommendations in making conscious decisions on selecting the right nozzle types and flight heights of the sprayer drones while also knowing the nature of the spray distribution across the canopy levels.

Despite the contributions, this research has limitations that require further investigation. We attempted to control environmental factors such as wind effects, temperature, and humidity by selecting days with minimum to no apparent impact on the experiment. However, these factors may still have influenced the results, as reflected in the unexpected variations observed in the recorded data. Additionally, this study evaluated only limited parameters, leaving a significant optimization opportunity unexplored. Moreover, since the study was conducted within one season crop, on only specific crops, within one field location, the results may not fully represent the variability found across a larger and more heterogeneous condition that truly reflects a farmer's field.

These limitations present opportunities for future research. Additional studies should aim to incorporate broader variables comprising information on the spray drift, pattern, runoff, and non-target effects that account for different climatic conditions, crop varieties, and drone settings across multiple locations over multiple seasons/years. More advanced UAV technologies such as GPS enhancement, AI-driven path optimization, and real-time monitoring could also be integrated for the further improvement of a UAV-based spraying system. Collaborative research among researchers, technology developers, farmers, and other stakeholders can maximize the utility of UAV sprayers in promoting modern agriculture with environmental stewardship.

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