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Spray Uniformity of a Remotely Piloted Aircraft System for Precision Agriculture

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Abstract

Remotely Piloted Aircraft Systems (RPAS) offer fast, precise, and efficient application of pest control chemicals, playing a vital role in effective crop management. RPAS are a key innovation in mechanized agriculture, offering precise application of fertilizers and pesticides to reduce waste, minimize environmental impact, and enhance crop yield when combined with other modern farming practices. This study evaluates the spray uniformity of a remotely piloted aircraft system at different flight speeds (3 m/s and 5 m/s) to determine its effectiveness in aerial spraying applications. The experiment assessed droplet deposition, size distribution, and uniformity using water-sensitive paper (WSP) and the DepositScan software. Data were analyzed using descriptive statistics and an independent t-test to compare to treatments. Results indicate that droplet density and uniformity were highest at the center of the spray path, with greater dispersion occurring at the edges. The effective swath width was 8.8 m at 3 m/s and 8.0 m at 5 m/s, with coefficient of variation (CV) values of 10.45% and 17.72%, respectively, indicating variability in coverage. The RPAS achieved an output rate of 6–11 L/min, corresponding to application rates of approximately 39–47 L/ha. Higher flight speeds improve RPAS spraying efficiency but reduce spray quality, as increased speed (3–5 m/s) leads to smaller droplets and less uniform distribution. Optimizing flight parameters is key to balancing coverage and accuracy. This study highlights RPAS's potential in enhancing spraying uniformity for precision agriculture, particularly in smart farming and mechanized rice production, and emphasizes the need for further research to optimize calibration, reduce drift, and minimize environmental impact.

Introduction

Farming remains the most prevalent source of employment in the Philippines, serving as the backbone of the economy. However, the current industrial agriculture system, while contributing to high productivity, has significant drawbacks. One of the major issues is the heavy reliance on agrochemicals, including synthetic fertilizers and pesticides, which can have detrimental impacts on local economies, the health of farmers, and the environment (Li, 2021). Although the use of agrochemicals has contributed to increased agricultural output, the efficiency of their application remains a critical concern. The challenge lies in the careful and precise delivery of these chemicals, as improper application can lead to waste, environmental contamination, and negative health effects (Wang, 2023).

Efficient and uniform application remains a persistent challenge, particularly in flooded or waterlogged rice fields where ground-based spraying equipment is difficult to operate. The uneven and soft terrain often leads to operator fatigue, inconsistent walking speed, and irregular nozzle positioning, all of which contribute to variable spray distribution. Conventional boom or knapsack sprayers typically produce non-uniform spray patterns, excessive overlap, and high coefficients of variation in droplet deposition, ultimately compromising pest control effectiveness and increasing chemical use.

Traditional agricultural sprayers are ineffective, requiring large and heavy-duty machinery that often leads to inaccurate chemical distribution (Ahmad, 2021). These sprayers, which are influenced by weather conditions and inadequate nozzle settings, frequently cause over-application of chemicals. This increases ecological damage and operating expenses. To address these challenges, remotely piloted aircraft systems (RPAS) have emerged as potential solutions, offering greater precision in pesticide and fertilizer delivery. By employing advanced sensors and automated systems, RPAS can selectively spray at the optimal time and location, reducing waste and enhancing sustainability (García-Munguía *et al.*, 2024). Although numerous studies have assessed Unmanned Aerial Vehicle (UAV)-based spraying systems, most have been conducted under controlled laboratory or simulation settings or focused on large-scale crops such as cotton, maize, and soybeans. Field-based assessments of RPAS spraying performance under rice cultivation environments where aerodynamic, thermal, and humidity conditions differ markedly remain limited. A notable gap persists in local studies evaluating RPAS spraying efficiency under Philippine rice farming environments, where terrain, wind, and humidity factors differ significantly from those in other regions.

Among the operational parameters influencing spray performance, flight speed is a critical factor affecting droplet size, deposition, and uniformity. Faster speeds increase operational efficiency but may reduce spray quality by producing smaller droplets and uneven distribution. Understanding this trade-off is essential for optimizing RPAS calibration and ensuring effective pest control.

However, the use of RPAS in agricultural spraying remains limited due to challenges such as droplet drift, flight stability, and efficiency at different flight speeds. This study aims to evaluate RPAS performance in agricultural spraying applications, with a focus on flight speed, droplet size, and spray uniformity. Specifically, to evaluate and analyse droplet deposition characteristics generated and to evaluate the RPAS on its distribution uniformity (CV%), effective swath width, output rate, and application rate. The results will provide valuable insights into the optimization of RPAS systems, contributing to the future development of efficient and eco-friendly agricultural practices. Furthermore, the study underscores the potential economic and environmental benefits of precision spraying in local farming systems, reducing chemical use, lowering production costs, minimizing drift-related pollution, and promoting sustainable, eco-friendly agricultural practices in the Philippines.

Materials and Methods

RPAS - Sprayer Specifications

The RPAS used in the study is a multi-rotor type with six (6) rotors that were designed for agricultural use. The aircraft features a 30-liter (7.93-gallon) tank, composed of sixteen (16) spray nozzles for irrigation or pesticide application. The drone is equipped with a high-precision positioning system, such as GPS, which allows it to navigate and fly autonomously over the designated agricultural area. It uses an electric pump to generate pressure and deliver the liquid to the spraying nozzles. These nozzles release the liquid in a controlled manner, ensuring even coverage of the crops.

Sprayer Nozzle System

Table 1. The specification of the XR series 11001VS spray nozzle tip used.

Item	Specification
Color	Orange
Material	Stainless Steel
Pressure	15-60 PSI
Spray Angle	110°
Drop Size	1000 µm

The RPAS sprayer is equipped with sixteen (16) spray nozzle tips. The model of the spray nozzle used was the XR series Teejet spray tip (11001VS nozzles) as shown in Table 1. Various types of nozzle tips are intended for specific uses. For pesticide application, the XR series Tejeet is recommended.

Weather Parameters

Table 2. Weather data during the RPAS spray test

Parameter	Time, AM			
	7:00	8:00	9:00	10:00
Wind speed, km/hr	2.8	3.2	3.9	5.2
Temperature, °C	29.3	32.1	34.3	34.5
Relative humidity, %	60	60	60	60
Rainfall, mm	0.0	0.0	0.0	0.0
Barometric pressure, hpa	10 017	10 017	10 017	10 017
Wind direction	South-west	South-west	South-west	South-west

Tests were conducted when wind speeds were less than 16 km/h to minimize errors due to crosswinds. Wind speed and temperature were monitored hourly at the testing site by using a handheld digital anemometer (BENETECH GM816 Mini Digital Anemometer). The available weather station nearby, PAG-ASA Weather Station, CLSU, Science City of Muñoz, Nueva Ecija, Philippines, provided the humidity value, rainfall data, wind direction, and barometric pressure.

The test proceeded as the collected weather data met the conditions set by ASABE S386.2. The test time was 7:00 to 10:00 AM. The weather parameters collected before and during the aerial spraying are presented in Table 2. At 7:00 am, the recorded wind speed and temperature were 2.8 km/h and 29.3°C; at 8:00 am, 3.2 km/h and 32.1 °C; at 9:00 am, 3.9 km/h and 34.3°C; and at 10:00 am, 5.2 km/h and 34.5°C. According to the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAG-ASA) CLSU station, 60%, 0.0 mm, 10 017 hpa were the obtained mean values of humidity, rainfall data, and barometric pressure, respectively, during that day.

Experimental Field Layout and Design

This study employed a simple comparative evaluation with the two flight speeds and dependent variables of droplet density, droplet sizes, and distribution uniformity (expressed as coefficient of variation, CV%) along three sampling points in one direction of spray path. Data were collected along three sampling points positioned across the spray path. Descriptive statistics (mean, range, and standard deviation) were used to summarize the data. To statistically compare spray performance between the two flight speeds, an independent samples t-test was conducted for each key variable (droplet density and CV%) at a 5% significance level. This analysis provided a quantitative basis for determining whether flight speed significantly influenced spray uniformity and droplet deposition.

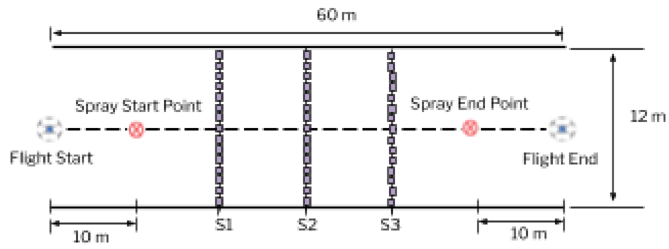


Figure 1. Experimental field layout

Flight speed was used as the treatment to evaluate the performance of the RPAS sprayer. The test followed ASABE Standards S561.1 (2018), with flight speeds categorized as slow (3 m/s) and fast (5 m/s) at a recommended aerial spraying height of 3 m. The RPAS sprayer underwent six trials. Different levels of treatment were used with three (3) replicates for each trial. Each replication consisted of three sampling lines (S1, S2, and S3) using a single aircraft pass in the same direction. To minimize bias, the order of flight speed treatments was randomized for each trial to account for potential variations in wind speed, humidity, or temperature. Randomization and replication ensured that differences in spray characteristics could be attributed to treatment effects rather than external factors. The experimental field layout is presented in Figure 1.

Parameters evaluated were droplet density, size distribution, and uniformity (CV%) across three sampling points along a single spray path. Data analysis included mean droplet density, CV%, and range to evaluate variability. Results were visually compared using bar graphs.

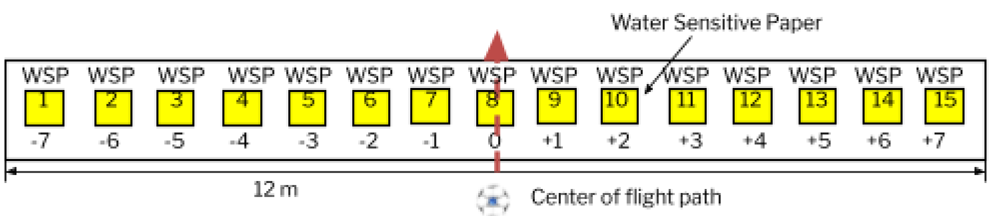


Figure 2. Layout of spray deposit collector (WSP).

A 60m by 12m area was measured and marked (at both ends) at both ends on the ground to serve as an alignment guide for the flight path. The center of the sample line was marked by using flaglets. Three ribbon frames were placed along the 60m flight path at 10m intervals and secured to the ground with pegs, allowing them to lie flat on the surface. Each test was repeated along all three sampling lines. In each sampling line, fifteen sampling points were separated by 0.8m (S386.2 standard), so that the spacing of the targets shall not exceed 1m, resulting in 45 total sampling points per flight trial (15 points × 3 lines). Across six trials, this produced 270 individual samples for analysis. The fifteen sampling points on each of the three sampling lines were grouped to represent the spray quality at one pass. Arranged sampling points of WSP (-7, 0, and +7), 0 was the center of the flight path of the aircraft, and both -7 and +7 were the edges of the center of the flight path. By using a pair of non-latex gloves, rigid, yellow water-sensitive paper (76mm x 26mm) that was stained dark blue by water droplets was placed at each sampling point (Figure 2).

All field activities and data collection procedures were conducted in compliance with the Central Luzon State University (CLSU) Institutional Research Ethics and Safety Guidelines and the Philippine Department of Agriculture (DA) regulations governing the safe operation of aerial spraying equipment in agricultural areas. The study did not involve human or animal subjects. Appropriate permissions were obtained before field testing, and all operations adhered to local environmental and occupational safety standards.

Data Gathering and Analysis

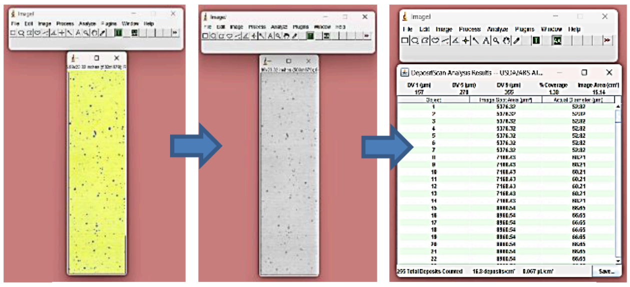
a. Water Sensitive Paper

The WSPs used in this experiment were gathered systematically, and following the spray test, they were scanned immediately by a scanner. The WSPs were scanned at a resolution of 600 dpi, and the droplet diameter, area of coverage, coverage rate, and quantity of spray deposits on the WSPs were extracted and analyzed using the imaging program DepositScan (USDA, UAS).

b. DepositScan Software

The DepositScan software program was designed to determine droplets and the quantities of droplets. The spray pattern in each test was analyzed according to the following parameters.

1. Volume Median Diameter (µm) – All detected droplets were sorted from smallest to largest. $DV0.1$, $DV0.5$, $DV0.9$ will represent the volume of small, medium, and large-sized droplets, respectively.
2. Droplet Density – (number of droplets/cm^2). This represented the number of droplets per square centimeter.
3. Droplet Deposition – (µL/cm^2). This parameter provided the estimate of the DV within a given region. This was calculated as the sum of the DV divided by the surface area.



(a) (b) (c)

Figure 3. Flowchart of droplet deposition analysis using DepositScan software

The flowchart of the analysis procedure is presented in Figure 3, which illustrates the sequential steps: (a) importing the WSP image, (b) image conversion and area marking, and (c) droplet analysis using the green AA tool.

Performance Evaluation

a. Droplet deposition

The droplet deposition was determined and analysed. The amount of liquid used was measured by measuring the amount remaining in the tank and subtracting it from the initial level. The time consumed in each operation was also recorded. In Table 3, the droplet size classification based on ASABE S5721 is the instrument and materials used to evaluate the spray distribution uniformity, and the coefficient of variation (CV) values were tabulated and graphed to determine the effective swath width.

Table 3. Droplet size classification based on ASABE S572.1

Size Classification	Size Of Droplets	VMD* Range (Microns)	Retention On Difficult To Wet Leaves	Used For	Drift Potential
Extremely Fine	Small	<60	Excellent	Exceptions	High
Very Fine		61-105	Excellent	Exceptions	
Fine		106-235	Very Good	Good Cover	
Medium		236-340	Good	Most Products	
Coarse		341-403	Moderate	Systemic herbicides	
Very Coarse		404-502	Poor	Soil Herbicides	
Extremely Coarse		503-665	Very Poor	Liquid Fertilizer	
Ultra-Course	Large	>665	Very Poor	Liquid Fertilizer	Low

* *Volume median diameter*

The droplet size distribution is a crucial factor in spray application. A balanced distribution minimizes drift while ensuring adequate coverage. Smaller droplets are more prone to drift. Drift is the unintended movement of spray droplets away from the target area. The extent to which the target area is effectively treated. Larger droplets will reduce drift but can also reduce coverage if not distributed evenly.

a. Distribution Uniformity

The coefficient of variation (CV) is the standard deviation of the results divided by the mean of the overlap spray deposition patterns (ASAE S386.2). The CV shall be used to determine and express the uniformity of distributions of applications. A lower CV value denotes a more uniform and stable droplet distribution, while a higher CV indicates greater variability and uneven deposition. According to established agricultural spray application standards, a CV below 15% reflects high uniformity, while values between 15% and 30% indicate moderate uniformity (ASAE EP458, 1989; ASABE S572.1, 2020). In general, a CV not exceeding 20% is considered acceptable for field spraying operations, as this range ensures adequate coverage and minimizes the risk of over- or under-application of agrochemicals (ASAE Standards, 2003; Nuyttens *et al.*, 2007). These thresholds provide a quantitative benchmark for assessing spray quality in aerial and ground-based application systems. This CV can be computed by using equations 1, 2, and 3.

$$\bar{x} = \frac{\sum Xi}{n} \quad (1)$$

$$\text{Standard Deviation} = \frac{n\ (\sum Xi^2 - \sum Xi^2)^{1/2}}{n\,(n-1)} \quad (2)$$

$$CV = \frac{\text{Standard Deviation}}{\bar{x}} \times 100\% \quad (3)$$

Where:

$\bar{x}$ = Arithmetic mean
Xi = Quantified deposit for one sampling point (WSP) for the combined swaths
n = Number of sampling points

a. Effective Swath Width

The CV is the accepted measure for spray swath uniformity from materials sprayed aerially. It is a statistical indicator of the uniformity of spray deposits over the swath width. The findings of the spray pattern deposition collectors will be examined to establish an effective swath. The largest swath width with a minimum acceptable coefficient of variation (CV) is considered to be the effective swath width.

b. Output Rate

The amount of liquid remaining in the tank will be measured and subtracted from the initial amount to determine the output rate. The unit value of the output rate is liters per minute (L/min).

c. Application Rate

The average values of output rate, ground speed, and effective swath width will be used to calculate the application rate using equation 4 based on the ASABE standard:

$$R = \frac{QK^3}{VS} \quad (4)$$

Where:

R = Application rate, L/ha
Q = Output rate, L/min
K^3 = Constant, 600
V = Number of sampling points
S = Effective swath width, m

Results and Discussion

Droplet Deposition

Droplet deposition is a critical parameter in agricultural spraying, influencing the efficacy of pesticide application and environmental impact. It is typically measured in microliters per square centimeter (μL/cm²), indicating the volume of spray liquid deposited on a given area. Smaller droplets (<150 μm) can enhance coverage but are more susceptible to drift, and larger droplets (>200 μm) reduce drift but may result in uneven deposition. Optimal droplet size balances coverage and drift control (García-Munguía *et al.*, 2024).

Table 4. Mean droplet deposition in the spraying test at 3 m/s flight speed.

Sample Point	Spray Droplet Size (μm) $D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	Droplet Density (number of droplets/cm²)
-7	105.3	213.0	333.0	5.6
-6	127.0	236.0	340.3	10.0
-5	132.0	254.3	383.7	15.2
-4	130.3	221.3	320.0	18.5
-3	139.7	252.7	366.3	46.8
-2	138.7	255.7	358.7	54.2
-1	140.0	240.3	361.0	50.9

0	159.0	279.7	416.0	38.4
1	153.3	292.7	451.0	42.0
2	155.0	296.0	437.7	47.8
3	160.7	283.7	460.3	40.6
4	134.7	243.7	426.3	21.6
5	145.3	265.7	410.0	22.9
6	132.3	245.7	405.0	17.2
7	168.3	253.0	350.3	6.5

Table 5. Mean droplet deposition in the spraying test at 5 m/s flight speed.

Sample Point	Spray Droplet Size (µm)			Droplet Density (number of droplets/cm²)
	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	
-7	83.7	173.3	237.3	9.3
-6	89.0	164.0	284.0	9.8
-5	104.3	210.7	321.3	10.0
-4	111.3	203.7	315.3	12.6
-3	137.3	224.3	381.7	16.0
-2	120.0	209.7	328.3	16.5
-1	118.7	220.0	367.7	21.6
0	171.0	274.7	474.3	48.1
1	158.3	280.3	450.7	39.0
2	158.7	279.3	431.7	42.8
3	137.7	233.3	371.0	41.4
4	135.3	225.7	372.3	31.7
5	118.3	209.7	322.7	32.6
6	125.0	212.0	358.3	19.0
7	91.0	203.0	286.7	2.4

The mean droplet deposition of each sample point in the spraying test at 3 m/s flight speed, determined by WSP analysis using the Deposit Scan Program, is shown in Table 4. The spray droplet size varies as it moves away from the point of application in the aerial spraying test at a flight speed of 3 m/s was analysed. The three key droplet size values were considered: $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$, which represent the droplet sizes corresponding to the 10th, 50th, and 90th percentiles of the droplet distribution, respectively. Additionally, we'll consider the droplet density (number of droplets/cm²) at each point.

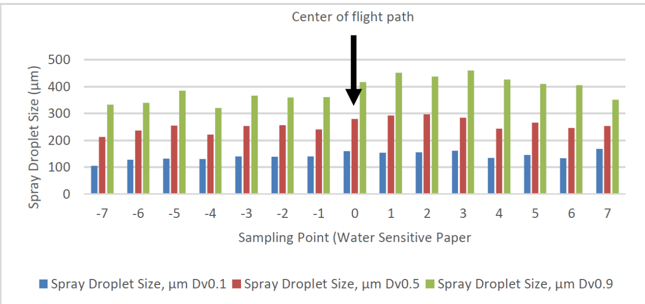


Figure 4. Droplet size classification of VMD values in spraying test at 3m/s flight speed.

The mean droplet size classification values in the spraying test at 3 m/s flight speed (Figure 4). The spray droplet size variation shows that $D_{v0.1}$ (10th Percentile) generally increases from the ends towards the center of the flight path (point 0), from point -7 (105.3 µm) to the +7 point (168.3 µm), with some variation across points. The highest value of $D_{v0.1}$ occurs at the farthest point (+7), indicating that smaller droplets tend to grow slightly in size as they travel farther from the nozzle. At the $D_{v0.5}$ (50th Percentile), it also shows an increasing trend with distance from the center (point 0), starting at 213.0 µm at point -7 and reaching 296.0 µm at +2 before slightly decreasing again to 253.0 µm at point +7. This suggests that the median droplet size becomes more uniform between points -1 to +3, with a peak at points closer to point 0 and a slight reduction after point 3. While at the $D_{v0.9}$ (90th Percentile), as with the other two percentiles, $D_{v0.9}$ increases from 333.0 µm at point -7 to 460.3 µm at point +3, but then decreases slightly to 350.3 µm at point +7. The larger droplets are typically more affected by environmental conditions (e.g., wind or air resistance), which may explain their variation in size as they travel away from the spray source.

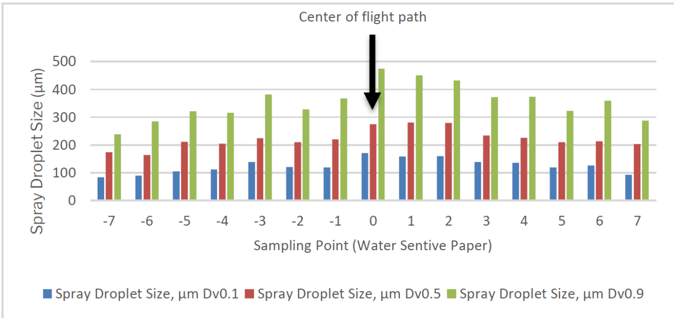


Figure 5. Droplet size classification of VMD values in the spraying test at 5m/s flight speed.

The droplet deposition characteristics during an aerial spraying test at a flight speed of 5 m/s (Table 5). The table shows the droplet size distribution ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ and droplet density (number of droplets/cm²) at various sample points, ranging from -7 to +7 relative to the spray point (0). The droplet size classification values in the spraying test at 5 m/s flight speed (Figure 5). Data shows on $D_{v0.1}$ exhibit an increasing trend from both ends towards the center of the flight path at point-7 (83.7 µm) and point +7 (91.0 µm). However, the rate of increase is relatively low compared to the 3 m/s flight speed. The increase in droplet size at the furthest points may be due to coalescence or droplet growth during flight. At the central region (points -2 to +3), droplet sizes tend to be larger than those at the extreme points, suggesting that the center experiences more optimal spraying conditions. (e.g., less dispersion or better nozzle efficiency). The median droplet size ($D_{v0.5}$) increases from 173.3 µm at point -7 to a peak of 274.7 µm at point 0, then decreases again to 203.0 μm at point +7. The increase in droplet size from the edges towards the center reflects the concentration of droplets in the middle of the spray path. After reaching the peak at the center of the flight path (point 0), the size begins to decrease, likely due to drift or the dispersive nature of the spray as it moves away from the center of the flight path.

The results highlight that slower flight speeds (3 m/s) favor uniform coverage with reduced drift, making them suitable for precision spraying, whereas faster speeds (5 m/s) may improve operational efficiency but require careful management to mitigate drift and maintain effective coverage. These findings can guide RPAS operational planning, nozzle selection, and application rates, helping balance efficiency, cost, and environmental safety.

The study's results may be influenced by environmental factors such as wind, temperature, and terrain slope, which were not fully controlled in this study. Variability in these factors may affect spray uniformity, highlighting the need for further research under diverse environmental and crop conditions to validate and generalize these findings.

Droplet Density

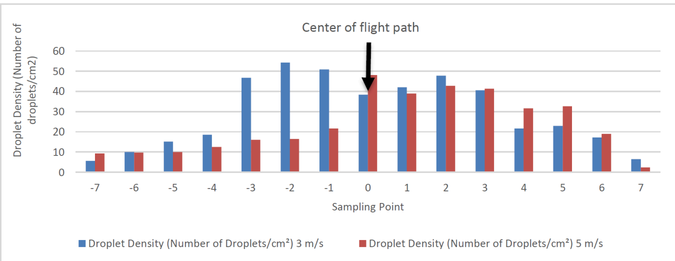


Figure 6. Droplet density of the spraying test at different flight speeds.

The droplet density (number of droplets/cm^2) of the spraying test at different flight speeds (Figure 6). The mean droplet density (mean number of droplets/cm^2) at 3 m/s flight speed, the highest droplet density was observed at the center of the flight path (point 0) with 38.4 droplets/cm^2, decreasing toward the edges (5.6–6.5 droplets/cm^2 at points -7 and +7). This reduction is attributed to drift, evaporation, and spray dispersion. The drop in droplet density with distance suggests reduced spray efficiency, influenced by factors like spray angle and wind. Optimizing RPAS performance requires balancing flight parameters and nozzle design to maintain consistent droplet size and density, improving efficiency and minimizing environmental impact.

At 5 m/s flight speed, with the highest density (48.1 droplets/cm^2) near the center (point 0). Density decreases as we move away from the center, with a significant drop beyond points +3 and -3. At point +7, the density is lowest at 2.4 droplets/cm^2, indicating that the spray becomes less concentrated with distance, a common pattern in aerial spraying due to droplet dispersion and evaporation. The overall trend shows that droplets are more densely packed near the center of the swath, with a higher concentration of droplets near points 0 to +3 and -3 to 0. As distance increases, the spray becomes less concentrated, which may reduce the efficiency of pesticide application at the edges of the spray area.

The results emphasize the need to balance flight speed, droplet size, and density for optimal coverage and reduced drift, offering potential improvements in RPAS spraying efficiency for agriculture. Droplet sizes increased toward the center of the spray field, indicating more stable airflow and reduced dispersive forces. Larger droplets at the center were less prone to drift, improving application precision. Droplet density was highest at the center and decreased towards the edges, which reduced effectiveness at farther distances (Li *et al.*, 2022). Lower speeds improve coverage uniformity and reduce chemical waste, whereas higher speeds increase operational efficiency but require adjustments in nozzle design, spray volume, and flight planning to maintain adequate coverage across the swath. These results can inform operational guidelines for RPAS pesticide application, improving precision, efficiency, and cost-effectiveness.

Droplet Size Classification range

Table 6. Mean droplet size classification range on different flight speeds, m/s.

Flight Speed (m/s)	Droplet Sizes (μm) Dv0.1	Dv0.5	Dv0.9
3	105.30 – 159.00	213.00 – 296.00	320.00 – 460.30
5	83.70 – 171.00	164.00 – 280.30	237.30 – 474.30

Table 6 presents the mean droplet size classifications range at 3 m/s and 5 m/s flight speeds based on ASABE S572.1 (Table 3). The sizes range from Very Fine (61-105 μm) to Very Coarse (402-502 μm). At 3 m/s, the smallest droplet size (Dv0.1) ranges from 105.3 μm to 159.0 μm, increasing drift risk, while the median droplet size (Dv0.5) is ideal for balancing coverage and drift control (213.0 μm to 296.0 μm). The largest droplets (Dv0.9) range from 320.0 μm to 460.3 μm, reducing drift but potentially affecting uniformity. At 5 m/s, the smallest droplet size decreases (83.7 μm to 171.0 μm), increasing drift, while the median size (Dv0.5) is in the medium-to-coarse range (164.0 μm to 180.3 μm), and the largest droplets increase (237.3 μm to 474.3 μm), reducing drift but potentially compromising coverage. Overall, the droplet size distribution at 5 m/s is more even, balancing drift control and coverage.

The findings show that increased speed from 3 m/s to 5 m/s results in a broader range of droplet sizes. The smallest droplets (Dv0.1) become even smaller, increasing drift risk. The median droplets (Dv0.5) also decrease in size, potentially increasing drift. The largest droplets (Dv0.9) increase in size, reducing drift but potentially compromising coverage. Overall, the 5 m/s flight speed of the RPAS sprayer shows a less even distribution of droplet sizes compared to the 3 m/s flight speed.

The results indicate that higher RPAS flight speeds intensify downwash airflow, increasing droplet size variability and reducing overall spray uniformity (Li *et al.*, 2022; Önler *et al.*, 2023). Beyond the aerodynamic effects highlighted in these studies, the present research shows that flight speed directly affects droplet size distribution within the effective swath, emphasizing the trade-off between drift control and coverage efficiency.

These results suggest that flight speed must be carefully selected to balance spray coverage, drift control, and operational efficiency. At higher speeds, adjustments in nozzle selection, spray volume, and flight planning are necessary to maintain optimal deposition and minimize chemical loss, supporting cost-effective and environmentally responsible RPAS spraying practices.

Distribution Uniformity (DU)

Table 7. Evaluation index of droplet distribution under two different flight speeds.

Flight Speed (m/s)	Arithmetic Mean (D_0)	Mean Droplet Density (number of droplets/cm^2	Droplet Deposition Coverage, %	Droplet Deposition Uniformity (CV), %
3	261.66	29.21	1.66	10.45
5	233.04	23.52	1.40	17.72

The DU of the spraying test at different flight speeds is shown in Table 7. The arithmetic mean of droplet size (D_0) represents the average size of droplets deposited. The D_o droplet distribution at different flight speeds, as flight speed increases from 3 m/s to 5 m/s, the mean droplet size decreases. This could be because the faster flight speed causes droplets to break into smaller sizes due to increased atomization or mechanical forces in the sprayer. Smaller droplets tend to drift more, which may affect deposition accuracy and increase variability.

The findings of the spray pattern deposition collectors were examined to establish the uniformity of distribution. To compare the flight speed's effects on droplet deposition in further detail, the arithmetic mean of droplet particle size (D_0), droplet deposition density, and droplet deposition coverage were used.

According to benchmark standards for aerial spraying, effective application is achieved when droplet density ranges from 20 to 40 droplets/cm^2, deposition ranges between 0.05 and 0.20 µL/cm^2, and spray coverage exceeds 1% (Wang *et al.*, 2018; Zhang *et al.*, 2021). The RPAS sprayer operated within or above these benchmark thresholds under both flight speeds, confirming its satisfactory spraying performance.

Droplet density reflects how thoroughly the target area is covered, with 3 m/s flight speed yielding 29.21 droplets/cm^2 and 5 m/s resulting in 23.52 droplets/cm^2. As flight speed increases, droplet density decreases, likely due to higher energy requirements for atomization, leading to fewer droplets per unit area. This reduction can negatively impact the uniformity and effectiveness of the spray application. At 3 m/s. The droplet deposition coverage is 1.66%. At 5 m/s, it decreases to 1.40%. This decrease indicates less thorough treatment at higher speeds. The droplet deposition uniformity (CV) obtained from the distribution uniformity (CV%) is 10.45%. The higher droplet density, wider coverage, and lower CV% at 3 m/s indicate more uniform spray distribution and improved surface wetting efficiency. These conditions are favorable for achieving consistent foliar coverage, which is essential for effective pesticide and fertilizer application.

At 5 m/s, it increases to 17.72%. DU on the different flight speed of aerial spraying of RPAS had a significant effect. Higher variability compared to 3 m/s flight speed, indicating a reduction in spray uniformity at 5 m/s. A higher CV indicates less uniform distribution. Faster speeds result in finer droplets prone to drift. However, this resulted in reduced lateral spread and non-uniform distribution along the edges of the application zone. This finding suggests that higher flight speeds promote localized droplet accumulation at the center but decrease overall spray uniformity.

These results demonstrate that flight speed has a direct influence on droplet behavior and deposition characteristics. Slower flight speeds promote stable atomization, uniform distribution, and broader coverage, whereas higher speeds increase droplet breakup and downward velocity but reduce lateral uniformity due to turbulence and drift effects. Similar observations were reported by Gao *et al.* (2024) and Zhou *et al.* (2021), who found that increased RPAS flight speed intensifies downwash turbulence, leading to greater central deposition and reduced edge coverage.

Increase flight speeds resulting in lower coverage and increased uniformity (Lin, 2024). And better spray uniformity distribution was found when the drone sprayer hover height was increased (Baldrias *et al.*, 2023).

These results suggest that RPAS spraying should optimize flight speed to balance coverage, deposition uniformity, and operational efficiency. Lower speeds improve deposition consistency but may increase operational time, whereas higher speeds reduce coverage and increase variability, potentially affecting pest control efficacy and increasing chemical usage costs. Adjustments in spray volume, nozzle selection, and flight planning can help mitigate these effects.

Effective Swath width

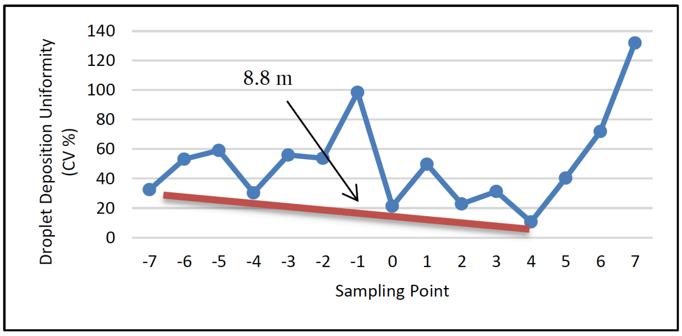


Figure 7. Effective swath width (evaluation of CV%) of spraying test at 3 m/s flight speed.

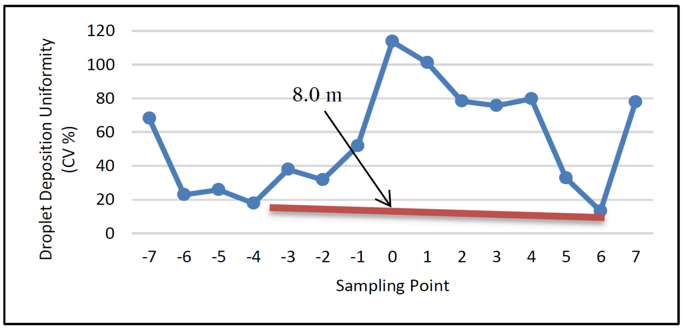


Figure 8. Effective swath width (evaluation of CV%) of spraying test at 5 m/s flight speed.

Figures 7 and 8 show the effective swath width (from the evaluation of CV%) across different flight heights. Results indicate that an effective swath starts from sampling point -7 to 4 on flight height of 3 m/s, and from sampling point -4 to 6 on flight height of 5 m/s. The effective swath width was approximately 8.8 m for a flight height of 3 m/s and 8.0 m for a flight height of 5 m/s. A high CV value implies a wider distribution of droplet sizes, including both smaller and larger droplets.

Table 8. Spraying performance of the RPAS at two different flight speeds.

Parameters	Different Flight Speed, m/s	
	3	5
Effective swath width, m	8.80	8.00
Output Rate, L/min	6.10	11.20
Application rate, L/ha	38.50	46.70

Table 8 shows the spraying performance of RPAS. The effective swath width was approximately 8.8 m for a flight height of 3 m/s and 8.0 m for a flight height of 5 m/s. The output rate increases with flight speed. At 3 m/s, the output rate was 6.10 L/min, increasing to 11.20 L/min at 5 m/s. At 3 m/s, the application rate was 36.50 L/ha, increasing to 46.70 L/ha at 5 m/s flight speed

The findings on the performance of RPAS at varying speeds. The data suggests that increasing the flight speed from 3 m/s to 5 m/s led to a slight decrease in effective swath width but a significant increase in both output and application rates.

Flight height and terrain characteristics were also found to influence the swath width, with higher altitudes and sloped terrains generally producing wider effective swaths (Wang *et al.*, 2024). While previous studies have primarily described these effects, the present findings contribute by comparing swath performance across multiple flight speeds and quantifying the trade-offs between swath width, output rate, and application efficiency. This comparison highlights gaps in prior research, particularly the need for operational guidance that optimizes RPAS parameters for both uniform deposition and efficient chemical use in variable field conditions.

Conclusion

This study evaluated the spray uniformity of a remotely piloted aircraft system (RPAS) at different flight speeds (3 m/s and 5 m/s) to determine its effectiveness in aerial spraying. The results demonstrated that lower flight speeds (3 m/s) resulted in better spray uniformity, with a lower coefficient of variation (CV = 10.45%) compared to the higher speed of 5 m/s (CV = 17.72%). Droplet deposition was more concentrated at the center of the spray path, with increased dispersion at the edges. The effective swath width was 8.8 m at 3 m/s and 8.0 m at 5 m/s. Furthermore, the output rate of the RPAS was 6.1 L/min at 3 m/s and 11.2 L/min at 5 m/s, resulting in application rates of 38.50 L/ha at 3 m/s and 46.7 L/ha at 5 m/s. The findings suggest that lower flight speeds enhance spray uniformity, minimize drift, and improve deposition efficiency. This study highlights the importance of optimizing RPAS flight parameters to achieve precision spraying, reduce chemical wastage, and support sustainable agricultural practices. To enhance the practical relevance of these findings, the results could be applied to develop or refine calibration standards for aerial spraying in specific crops such as rice, or to support the formulation of operational guidelines under the Department of Agriculture (DA) and the Department of Science and Technology (DOST). Future research should investigate the effects of additional variables, including wind conditions, nozzle configurations, flight altitude, and different liquid formulations, to further refine aerial application strategies and improve operational efficiency under varying environmental conditions.

Ethical Statement

The authors adhered all ethical guidelines during and after the study. Informed consent was obtained from all participants, and their privacy and confidentiality were protected. Participants were free to withdraw at any time. The researcher ensured that no one was harmed and that all data were safely stored and used only for academic purposes.

Conflict of Interest Statement

The authors declare no conflict of interest related to the conduct and publication of this research. All procedures followed were in accordance with institutional and ethical standards, and there were no financial or personal relationships that could have influenced the outcomes of this study.

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Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this work, the author utilized ChatGPT to assist in improving the clarity, organization, and grammar of the manuscript. After using this tool, I thoroughly reviewed and edited the content to ensure accuracy and originality. I take full responsibility for the final version and the integrity of the content presented in this publication.

Data Availability

All data supporting the findings of this study are available within the paper.

Author Contributions

ACV: Conceptualization and Writing (Original draft); **MMC:** Project administration; **JVF:** Data curation and Editing; **WCM:** Supervision and Writing (Review and Editing).

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