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# Impact of Different Drone Sprayer Nozzle Types on Bio-Fertilizer Application in Wetland Paddy Cultivation

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## ABSTRACT

The effectiveness and efficiency of chemical spray applications on cropland are strongly influenced by the size of the nozzle. This research study focuses on examining the spray characteristics associated with two different nozzle sizes using bio-fertilizer. The experimentation took place on a 13.85-ha paddy field. To collect spray deposits, water-sensitive papers (WSPs) were strategically placed in a setup consisting of 39 WSPs arranged at distances of 0.5 m apart in three rows spaced 1 m apart. An agricultural spraying drone was deployed at a speed of 3 m/s and a height of 2 m to conduct the tests. Parametric data, essential for both descriptive and inferential statistical analyses, were generated using the DepositScan software. The results of the characteristic test indicated that approximately 50% of the collected droplet sizes were below 89.11±20.59 and 239±78.44

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μm for the fine and coarse nozzle sizes, respectively. The coefficients of variation were calculated as 0.27 for the very fine nozzle and 0.85 for the coarse nozzle, indicating varying levels of droplet size uniformity. The *t*-test analysis revealed a significant difference ($P \leq 0.05$) between the two nozzle sizes for all investigated parameters, except for the drift collected within a 30-m distance from the target. Specifically, the fine nozzle type produced very fine droplets with superior spray uniformity, while the coarse nozzle types generated moderate to large droplet sizes. This highlights the critical role of selecting the appropriate nozzle in determining the overall quality of spray applications.

*Keywords*: Climate action, droplet size, foliar fertilizer, Malaysia, spray distribution, spray drift, Zero Hunger

## INTRODUCTION

The adoption of drone technology in agriculture has revolutionized farming practices by enhancing precision, efficiency, and sustainability. Unmanned aerial vehicles (UAVs), commonly known as drones, are increasingly used for crop monitoring, field mapping, and aerial spraying, offering a promising alternative to conventional, labor-intensive methods (Ahirwar et al., 2019; Nhamo et al., 2020; Tsouros et al., 2019). Equipped with advanced cameras, sensors, and spraying systems, drones enable farmers to apply fertilizers and pesticides with unprecedented accuracy, reducing waste and environmental impact. The characteristics of the spray, influenced by factors such as nozzle type, pressure, and environmental conditions, play a critical role in determining droplet size, drift potential, and deposition uniformity, all of which directly impact crop health and yield (Hunter et al., 2019; Ismail et al., 2021; Taylor et al., 2004).

In Malaysia, drone technology for fertilization and pesticide spraying is gaining traction, mainly through service providers in key rice granaries like Tanjung Karang and Sekinchan, as well as large plantations. Studies have highlighted its advantages (Dorairaj & Govender, 2023; Rosedi & Shamsi, 2022), such as the reduction of labor by 75%, cost savings of RM49.15/ha, and increased efficiency (2.4 ha/hr vs. 0.7 ha/hr manually). Adoption is driven by labour shortages, 52.5% faster operations, and sustainability goals, backed by government initiatives such as the Civil Aviation Authority of Malaysia (CAAM)'s free-fly zones and training programs, including My Drone Services. However, barriers persist, such as high costs, dependence on service providers (70%), regulatory hurdles, and skill gaps, with 53.7% of farmers having only average drone knowledge (Harun et al., 2024). While drones enhance precision, reduce chemical exposure, and attract youth to agriculture, self-operated use remains challenging in resource-limited rural areas.

In response to the environmental challenges associated with chemical fertilizers, such as soil degradation, water pollution, and greenhouse gas emissions, bio-fertilizers have emerged as a sustainable alternative. Unlike conventional fertilizers, bio-fertilizers use beneficial microorganisms to enhance nutrient availability, support soil biodiversity, and promote healthier crop growth (Bahadur et al., 2006; Iqbal et al., 2020). This eco-friendly approach reduces dependency on chemical inputs, aligning with global efforts like the European Union's target to reduce chemical fertilizer use by 50% by 2030 (Montanarella & Panagos, 2021). In addition to improving soil health, bio-fertilizers can also contribute to climate resilience and biodiversity conservation, making them a promising solution for sustainable agriculture (Bumandalai & Tserennadmid, 2019; Youssef & Eissa, 2014).

Rice, a staple food for over half of the world's population, particularly in Asia, South America, and parts of Africa, faces increasing demand and production challenges (Ghani et al., 2024; Papademetriou, 2000). In Malaysia, for example, rice production fell from over 1.85 million metric tons in the year 2014 to 1.44 million metric tons in 2023, as self-sufficiency remains elusive due to fluctuating per-hectare yields and reliance on imported rice (Economic Planning Unit [EPU], 2015; Siddharta, 2025). As global demand for agricultural products is projected to increase by 60% by 2030, sustainable practices are essential to ensure food security and environmental health (Montanarella & Panagos, 2021). The integration of UAV technology for bio-fertilizer application in rice cultivation holds significant potential to address these challenges by enhancing productivity and reducing environmental impacts.

Selecting the correct nozzle size is crucial for optimizing fertilizer application efficiency and maximizing crop yield. It ensures precise application rates, preventing over- or under-application, which can lead to nutrient runoff, environmental pollution, or nutrient deficiencies. A properly sized nozzle provides uniform coverage, minimizing waste and ensuring consistent crop growth, as demonstrated in studies on spray pattern uniformity (Matthews et al., 2014; Zhu et al., 2011). It also optimizes droplet size for better nutrient absorption, whether through leaf uptake in foliar applications (de Castro & Schjoerring, 2024) or soil penetration for liquid fertilizers (Niemoeller et al., 2011). By reducing fertilizer drift and evaporation (Chethan et al., 2019), the right nozzle selection enhances efficiency, lowers input costs, and improves overall yield. This precision is particularly critical for modern practices, such as drone-based applications, where nozzle choice directly impacts droplet deposition accuracy and environmental sustainability (Han et al., 2025; P. Wang et al., 2024).

This study examines the effects of bio-fertilizer spray characteristics on paddy cultivation using drone sprayers equipped with different nozzle sizes. By comparing the spray deposition, drift potential, and droplet size achieved with various nozzle configurations, this research aims to identify optimal spray parameters for effective bio-fertilizer application in rice fields. This information is crucial for guiding farmers and policymakers on the appropriate use of UAV technology in precision agriculture, ultimately supporting more sustainable and efficient rice production systems.

## MATERIALS AND METHODS

### Test Site

The test was conducted on 20th August 2020 in a 13.85-ha paddy field at Kg. Padang Raja Melor, Kota Bharu, Kelantan, Malaysia (05°57'43''N, 102°17'21''E), managed by the Kemubu Agricultural and Development Authority (KADA) (Figure 1). The age of paddy was 54 days after transplanting (DAT) with an average height of 68 cm, and a water level of 20-30 cm was maintained.

The test took place between 9:00 and 11:00 a.m. to ensure minimal and stable wind conditions and avoid direct overhead sun. Weather data, including temperature, relative humidity, wind speed and direction, and altitude, were collected before the experiment using a handheld anemometer (SKU-H9619, Kkmoon, China). Measurements were taken approximately 2 m above the ground, in the upwind direction, for less than 5 s. The experimental site experienced an average temperature of 32.1±1.9°C and a relative humidity of 65.10±12.8%. Wind speed was measured at 2.05±0.8 m/s, predominantly blowing from the North-West direction. The experiment was conducted at an altitude of 5.4 m above sea level. The recommended relative humidity should be above 50% and wind speed below 5 m/s to prevent treatment volatilization, as suggested by C. Wang et al. (2023) and Lodwik et al. (2020).

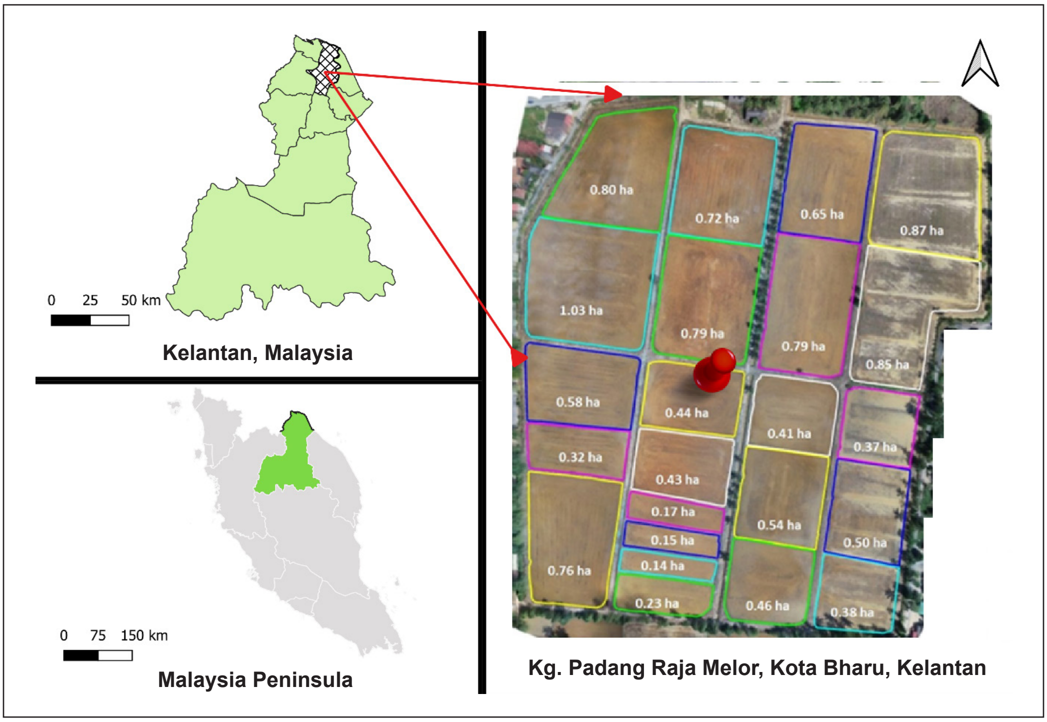


*Figure 1*. Map of the paddy field

## Spray Systems

The spray system for the test was a Pola V-16s agriculture spraying drone (Poladrone Solutions Sdn. Bhd., Malaysia) (Figure 2). The drone is equipped with a spray system situated underneath it for precision spray control and features an extended spray boom with a trapezoidal geometry, where the rear nozzles are more closely spaced than the fore pair. The fore and rear nozzle pairs are controlled separately by two compatible pumps, providing the system with three spraying modes. The spray system on the unmanned aircraft system (UAS) responds to commands and spray operations accurately and effectively. The drone is equipped with a Global Positioning System (GPS) real-time kinematics (RTK) differential system, which offers precise differential positioning and is capable of recording flight parameters on the go. The technical parameters of the UAS are presented in Table 1.

Table 1
*Unmanned aircraft system technical parameters*

| Classification | Parameters |
|---|---|
| Motors | 6 |
| Total weight (kg) | 35.5 |
| Dimension (Extended) (mm) | 2,364.6 × 2,144.6 × 556 |
| Battery capacity (mAh) | 22,000 × 2 units |
| Maximum runtime (min) | 20 |
| Operation method | Remote control/ Autonomous |
| Height above crop canopy (m) | 1.5 - 10 |
| Number of nozzles | 4 |
| Unit flow (L/min) | 0.6 – 2.0 |
| Load capacity (L) | 16 |
| Spraying width (m) | 1.5 - 3.5 |

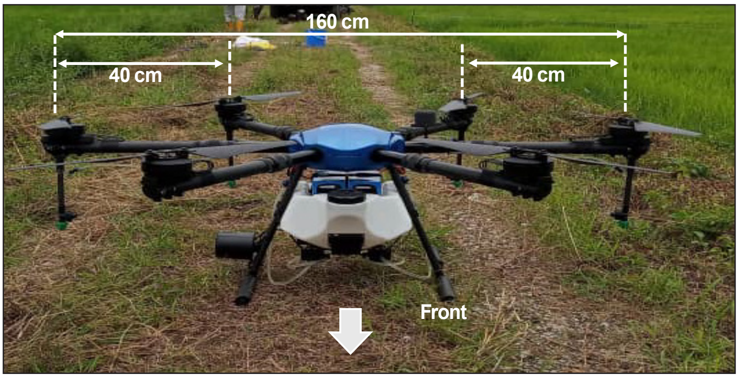


*Figure 2*. Drone configuration with four nozzles beneath each rear rotor, spaced 40 cm apart

## Spraying Test

The nozzles used for the spray tests were the Teejet® XR11008VS and XR110015VS (Spraying Systems Co., USA) flat fan nozzle types (Table 2). They spray at a maximum angle of 110° and have operational parts made of steel for increased durability. The XR11008VS produces a medium-coarse spray (color code: white), while the XR110015VS nozzle produces a fine spray (color code: green).

Actual flow rate tests were conducted for both nozzles by collecting the water from the nozzles in a conical flask at a system application rate of 20 L/ha for 1 min. The spray liquid was a 10 ml/L solution of bio-fertilizer in water. For each nozzle size, the tests were replicated three times to validate the results. Each nozzle was calibrated prior to the spraying operation, with average unit flow rates of 0.927±0.003 and 0.530±0.00 L/min for the white and green nozzles, respectively (Table 2). The spray nozzle tips were made of stainless steel, chosen to be used during the test for being more durable and less prone to wear out due to excessive liquid pressure and heavy utilization.

The spray treatment used for the tests was Booster Grow 8+ bio-fertilizer (DNG Worldwide, Malaysia), enriched with nitrogen, phosphorus, potassium, and beneficial microbes to enhance plant growth, improve soil fertility, and strengthen disease resistance. The recommended application rate ranges from 2.5–10 ml/L, depending on the crop type, including tree crops, field crops, and vegetables. In this study, a 10 ml/L solution in water was prepared at a total volume of 20 L and applied using a UAS at a constant rate of 20 L/ha, with a mean travel speed of 3 m/s. WSPs (Chongqing Liuliushanxia Plant Protection Technology Co., Ltd., China) measuring 30 mm × 25 mm were precut from their original 80 mm × 30 mm size for droplet collection and analysis.

The WSPs were arranged on a frame standing at the height of the rice plants and spanning 6m in length. Three frames, spaced 5 m apart and arranged parallel to the direction of the prevailing wind, constituted a unit test. The WSPs were positioned on the frame with a total coverage swath width of 6 m at 0.5 m intervals, with the zero (0) mark at the center of the WSP arrangement and the negative parts upwind. A setup was made for drift collection in both directions of the swath at 1.5, 6.5, 10.5, and 28.5 m from the swath path,

Table 2
*Drone flying and spraying parameters and nozzle specification*

| | | |
|---|---|---|
| Spray volume (L/ha) | 20 | |
| Spray height (m) | 2.00±0.010 | |
| Horizontal UAS speed (m/s) | 3.00±0.10 | |
| Total number of nozzles | 4 | |
| Spraying angle | 110° | |
| Nozzle type | XR11008VS | XR110015VS |
| Nozzle color | White | Green |
| Calibrated unit flowrate (L/min) | 0.927±0.003 | 0.530±0.000 |
| Droplet size classification | Medium | Fine |
| Nozzle type with stainless steel tips |  |  |

*Note*. UAS = Unmanned aircraft system

with the outer rows spread at 30° from the mid row to accommodate the unpredictability of the wind. This entire setup, as shown in Figure 3, was replicated three times under each flight mission, spaced at 60 m apart. The UAS flowed across the WSP arrangement, passing through the zero mark while spraying the bio-fertilizer mix at a constant height and speed (Figures 4 and 5). The details of the UAS spray operation are found in Table 2. The spray deposits were allowed a few minutes to settle before the sample papers were collected using disposable gloves. The samples were carefully collected into labelled plastic office file jackets and later scanned using an HP ScanJet Pro 2500 f1 Flatbed Scanner (HP Inc., USA). The images were scanned at an optical resolution of 600 dpi and saved in JPEG file format.

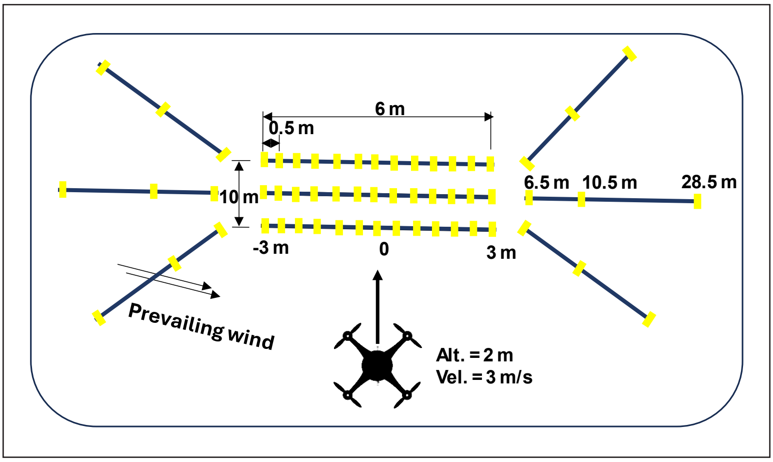


*Figure 3*. Experimental field layout
*Note*. Alt. = Altitude; Vel. = Velocity

*Figure 4*. Unmanned aircraft system spraying test operation in the paddy cultivation

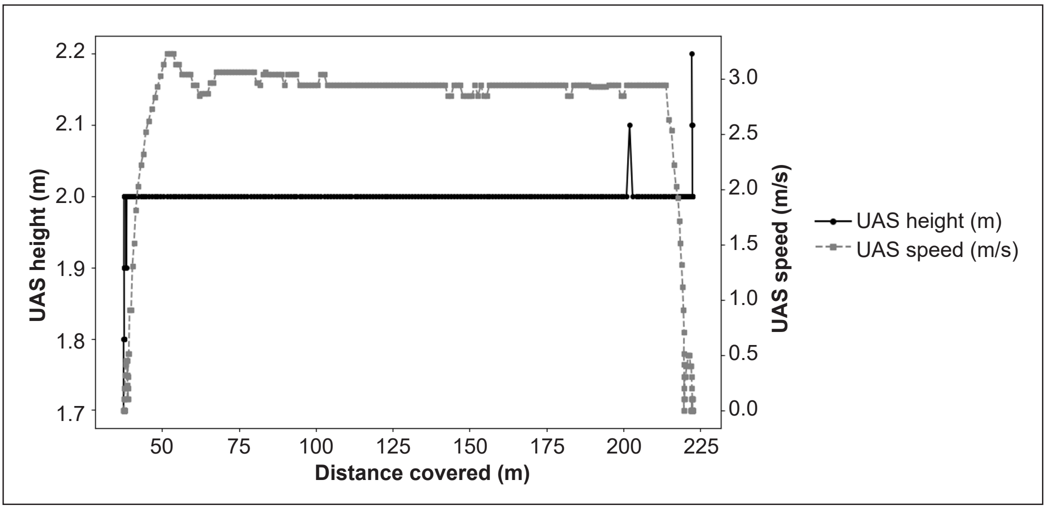


*Figure 5*. Recorded unmanned aircraft system (UAS) flight data showing stages (take-off, hovering, and spraying) and height status during the spraying operation

## Determination of Effective Spray Swath

To determine the effective spray swath, a deposition threshold limit was selected for the UAS flight and spray settings during the test. A deposition volume per area of 0.2 µl/cm² was chosen as the limit. The end-to-end sampling points with a deposition volume of at least 0.2 µl/cm² on both sides of the route were defined as the starting and ending points of the effective swath area. The distance between these two points was considered the effective swath width.

## Data and Statistical Analysis

The scanned documents were analyzed using DepositScan™ software (United States Department of Agriculture [USDA], USA) (Zhu et al., 2011), which calculates Dv0.1, Dv0.5, Dv0.9, percentage area, deposition, and droplet density. These metrics, derived from droplet size distributions, are essential for evaluating spray nozzle performance. Dv0.1, the 10$^{th}$ percentile volume diameter, represents smaller droplets (finer droplets, more prone to drift but better coverage), Dv0.5 indicates the median droplet size (larger values mean coarser sprays), and Dv0.9, the 90$^{th}$ percentile volume diameter, reflects larger droplets (less drift but potentially uneven coverage). In this study, spray performances were compared based on droplet density, deposition, and droplet size distributions, providing insights into nozzle efficiency and optimizing them for applications like minimizing waste or maximizing coverage.

Descriptive and inferential statistics were computed on the parametric data collected for all nozzle types after testing for normality. A *t*-test was used to test for significance between the green and white nozzles' parametric data collected at a 95% confidence level. The coefficient of variation (CV) was estimated for both nozzle types (American Society of Agricultural and Biological Engineers [ASABE], 2012). The CV is valuable in estimating the droplet distribution uniformity within sampled points. A smaller CV value indicates better uniformity of deposited droplets. It is estimated using the equation:

$$CV = \frac{S}{\bar{x}} \times 100\% \qquad [1]$$

While,

$$S = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \qquad [2]$$

where S is the standard deviation. $x_i$ denotes deposition at sample points, and $\bar{x}$ is the mean deposition of the total sampled points, while n refers to the number of sampled points.

## RESULTS AND DISCUSSION

Table 3 summarizes the mean and standard deviation of several spray characteristics for two nozzle types, XR11008VS (white) and XR110015VS (green), measured at different points across the spray width. Key parameters include droplet size distribution (Dv0.1, Dv0.5, and Dv0.9), spray volume (µl/cm²), coverage percentage, and droplet deposition (Dep/cm²). The white nozzle produces larger droplets, with mean values for Dv0.1, Dv0.5, and Dv0.9 at 149, 261, and 363 µm, respectively, while the green nozzle averages 62.6, 90.2, and 128.4 µm, producing relatively smaller droplet sizes. The white nozzle delivers a higher mean spray volume per square centimeter, about 88.2% more than the green nozzle (white nozzle = 3.01 µl/cm² and green nozzle = 0.354 µl/cm²).

The green nozzle achieves a higher mean coverage percentage (16.7%) compared to the white nozzle (7.25%), reflecting a finer mist that spreads more uniformly across surfaces. The droplet deposition rate also shows a clear difference: the green nozzle has a significantly higher deposition rate (1,248 droplets per cm²) than the white nozzle (204 droplets per cm²), indicating a denser distribution of droplets.

### Droplet Size Distribution

The finer nozzle (green code) with a relatively lower CV value shows consistent and uniform spray compared to the coarse nozzle (white code). Therefore, a green nozzle is suggested to be more precise in delivering the bio-fertilizer applications in paddy cultivation, minimizing waste and improving effectiveness. The comparison of droplet size distribution for XR11008VS (white) and XR110015VS (green) nozzles reveals significant differences in spray quality, impacting their applications (Table 3). The white nozzle produces larger droplets, with mean values for Dv0.1, Dv0.5, and Dv0.9 at 149, 261, and 363 µm, respectively, while the green nozzle averages 62.6, 90.2, and 128.4 µm (Table 4). T-test results confirm these differences are statistically significant, indicating that the white nozzle generates substantially larger droplets than the green nozzle (Table 5). Additionally, the CV for the white nozzle is 85%, reflecting greater droplet size variability, which can enhance surface coverage. However, this high variability may also indicate inconsistencies due to nozzle wear, pressure fluctuations, or improper calibration, potentially affecting deposition uniformity. Conversely, the green nozzle's CV of 27% represents more consistent droplet sizes, resulting in a finer, more even spray pattern classified as "very fine". Ensuring proper nozzle calibration and pressure regulation is essential to minimize variability and optimize spray efficiency.

These findings imply that each nozzle is suited to different spraying requirements. The larger and more variable droplet sizes produced by the white nozzle make it well-suited

Table 3
*Mean and standard deviation (SD) of spray deposition for all tested parameters of XR11008VS and XR110015VS nozzles*

| **White nozzle type (XR11008VS)** | | | | | | |
|---|---|---|---|---|---|---|
| **Point (m)** | **Dv0.1 (µm)** | **Dv0.5 (µm)** | **Dv0.9 (µm)** | **Vol. D (µl/cm²)** | **Coverage (%)** | **Dep. D (Dep/cm²)** |
| -1.5 | 139±8.99 | 187±8.74 | 298±9.33 | 1.25±0.13 | 5.97±0.28 | 112±5.19 |
| -1.0 | 152±9.97 | 276±12.90 | 299±9.34 | 1.23±0.02 | 5.79±0.26 | 147±6.76 |
| -0.5 | 161±10.40 | 267±12.50 | 400±12.50 | 4.39±0.44 | 6.34±0.30 | 167±7.73 |
| 0 | 198±12.80 | 343±16.10 | 449±14 | 5.45±0.56 | 12±0.54 | 298±13.8 |
| 0.5 | 155±9.98 | 286±13.40 | 379±11.80 | 5.28±0.54 | 6.04±0.28 | 162±7.54 |
| 1.0 | 107±6.91 | 312±14.60 | 417±13 | 1.25±0.03 | 8.89±0.45 | 201±9.26 |
| 1.5 | 133±8.55 | 158±7.37 | 296±9.25 | 2.21±0.23 | 5.74±0.27 | 177±8.15 |
| Mean±SD | 149±49 | 261±103 | 363±86 | 3.01±2.44 | 7.25±4.75 | 204±4 |
| **Green nozzle type (XR110015VS)** | | | | | | |
| **Point (m)** | **Dv0.1 (µm)** | **Dv0.5 (µm)** | **Dv0.9 (µm)** | **Vol. D (µl/cm²)** | **Coverage (%)** | **Dep. D (Dep/cm²)** |
| -1.5 | 66±6.09 | 68±15.50 | 70±24.40 | 0.20±0.06 | 14.20±2.92 | 1,115±111 |
| -1.0 | 51.30±4.74 | 66±15.10 | 83±29 | 0.26±0.07 | 14.40±2.95 | 1,126±112 |
| -0.5 | 62.20±5.74 | 96.10±21.90 | 137±47.70 | 0.30±0.08 | 15.10±3.10 | 1,283±128 |
| 0 | 64±5.91 | 81.30±18.60 | 111±38.70 | 0.43±0.12 | 16.10±3.30 | 1,355±135 |
| 0.5 | 63.90±5.89 | 109±24.80 | 190±66.40 | 0.42±0.12 | 20.90±4.28 | 1,388±139 |
| 1.0 | 70±6.46 | 114±26 | 177±61.60 | 0.49±0.14 | 22.30±4.58 | 1,350±135 |
| 1.5 | 61±5.63 | 97.10±22.20 | 131±45.80 | 0.38±0.11 | 14±2.88 | 1,116±111 |
| Mean±SD | 62.60±11.30 | 90.20±24.20 | 128.40±61.60 | 0.35±0.15 | 16.70±5.60 | 1,248±140 |

*Note*. Dep. D = Deposition density; Vol. D = Volumetric deposition

Table 4
*The* t*-test result for all paired parametric data for both nozzles*

| | Parameter | | | | | |
|---|---|---|---|---|---|---|
| | **Dv0.1 (µm)** | **Dv0.5 (µm)** | **Dv0.9 (µm)** | **Vol. D (µl/cm²)** | **Coverage (%)** | **Dep. D (Dep/cm²)** |
| *t*-value | 7.63 | 6.95 | 11.06 | 2.77 | -6.97 | -27.62 |
| *p*-value | 0.00026*** | 0.00044*** | 0.00003*** | 0.032** | 0.00044*** | 0.00001*** |

*Note*. Dep. D = Deposition density; Vol. D = Volumetric deposition**;** ** = 0.05 significant level; *** = 0.01 significant level

Table 5
*Result for droplet size distribution*

| Nozzle type | Dv0.1 (µm) | Dv0.5 (µm) | Dv0.9 (µm) | CV (%) | Spray quality* |
|---|---|---|---|---|---|
| White | 149±49 | 261±103 | 363±86 | 85 | Medium |
| Green | 62.62±11.30 | 90.20±24.20 | 128.40±61.60 | 27 | Very fine |

*Note*. CV = Coefficient of variation; * Droplet classification standards for > 3 bars (ASABE, 2009)

for applications needing minimized drift and focused spraying of bio-fertilizer in targeted areas. Meanwhile, the green nozzle's fine and uniform droplet pattern is ideal for achieving consistent coverage over broader areas, beneficial in foliar applications. However, the green nozzle's smaller droplets could be prone to drifting in windy conditions, requiring careful management to ensure optimal efficacy. The findings for XR11008VS and XR110015VS align with previous literature that identifies larger droplets as beneficial for reducing drift and improving deposition on target areas, particularly for pesticide applications (Miller & Ellis, 2000). However, these larger droplets may reduce coverage uniformity compared to finer sprays, as observed in our study. On the other hand, finer sprays, like those generated by XR110015VS, are associated with higher deposition rates and better coverage (Nuyttens et al., 2007). Nonetheless, fine sprays have a higher drift potential, particularly under windy conditions (Ferguson et al., 2016). Figure 6, displaying droplet size distribution across a 6 m swath width, demonstrates how finer droplets can achieve high coverage but are susceptible to environmental factors such as wind. Therefore, selecting a nozzle type should balance spray quality, coverage needs, and environmental considerations to optimize application effectiveness (Pascuzzi et al., 2017; Salyani et al., 2013).

## Droplet Deposition Density

Table 3 and Figure 7 present data on deposition density (Dep/cm²) for the white (XR11008VS) and green (XR110015VS) nozzles across various sampling points. The green nozzle exhibits a consistently higher deposition density, peaking around 1,400 Dep/cm², particularly between the -0.5 to 1.0 m sampling points. This indicates that the green

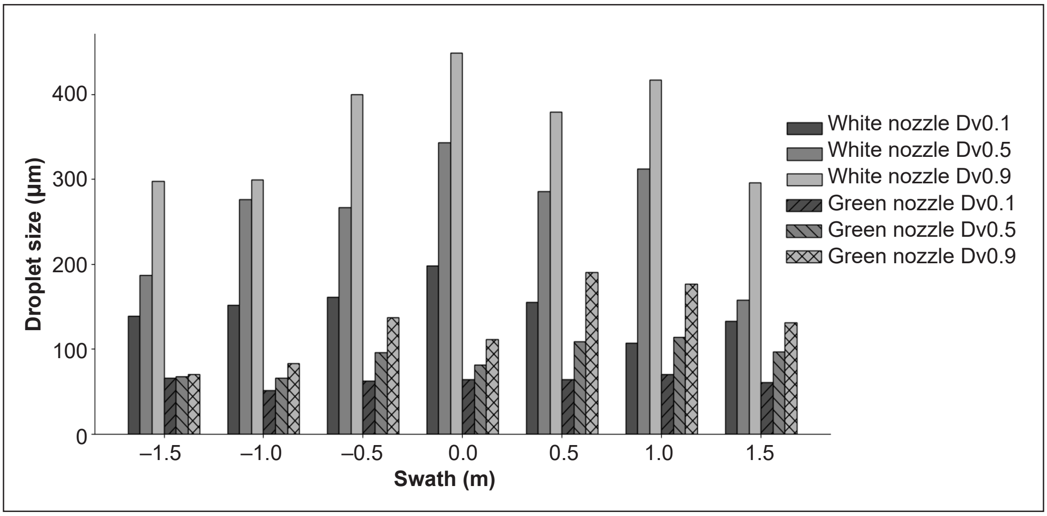


*Figure 6*. Droplet size distribution across a 6 m swath at 0.5 m intervals for all nozzles at Dv0.1, Dv0.5, and Dv0.9, respectively

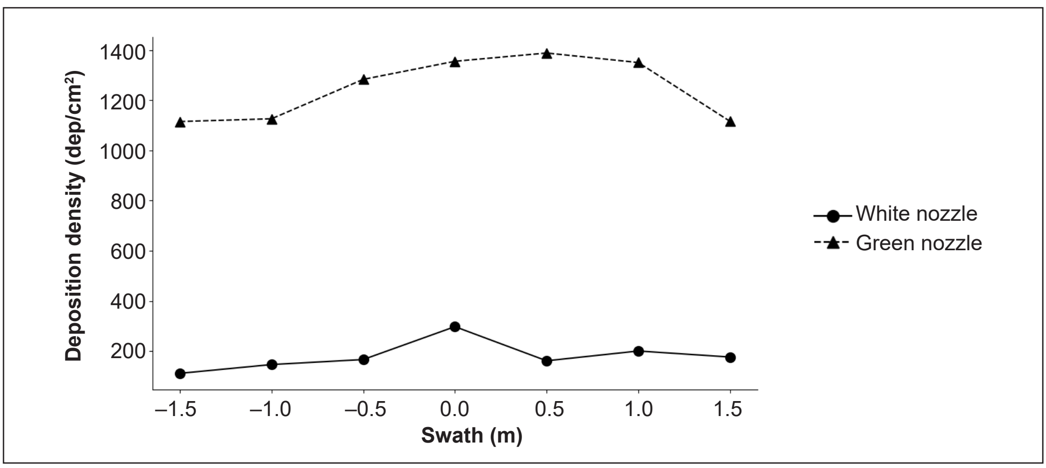


*Figure 7*. Mean deposit density

nozzle achieves greater deposition density across the swath width, which may enhance coverage and pesticide efficacy. In contrast, the white nozzle has a lower deposition density, fluctuating between approximately 100 and 300 Dep/cm², with its peak near the center point (0 m) at around 300 Dep/cm². Table 3 provides further detail, showing the green nozzle has a much higher average deposition density of 1,248±140 Dep/cm² compared to the white nozzle's 204±94 Dep/cm². This significant difference, supported by the *t*-test results in Table 4 ($t$ = -27.62, $p$ < 0.01), highlights the green nozzle's superior performance in deposition density. However, this comes with the trade-off of potentially increased drift due to finer droplets, as suggested by other studies (Grella et al., 2023; Nuyttens et al., 2007).

The results align with existing research on nozzle performance and droplet deposition density, crucial for effective pesticide application. Higher deposition density, as observed with the green nozzle (XR110015VS), can enhance coverage and improve pesticide efficacy by ensuring a more uniform application on target surfaces. Recent studies indicate that nozzles producing finer droplets typically yield higher deposition densities, improving coverage but potentially increasing drift risk due to smaller droplet size (Shan et al., 2021; Srinivasarao et al., 2021). However, finer droplets, while improving target coverage, can lead to off-target movement, particularly in windy conditions (Grella et al., 2023). In contrast, the white nozzle (XR11008VS) produces coarser droplets with lower deposition density, which can improve precision by reducing drift (Shan et al., 2021). This suggests that the white nozzle may be more suitable for applications where drift reduction is prioritized over maximum coverage density. The *t*-test in Table 4 confirms the significant difference between the nozzles' deposition densities, supporting the green nozzle's use in situations where maximum coverage is essential (Srinivasarao et al., 2021).

## Percentage Coverage

Table 3 and Figure 8 reveal that the green nozzle (XR110015VS) consistently achieves a higher percentage coverage than the white nozzle (XR11008VS) across all sampling points. Specifically, the green nozzle reaches peak coverage at around 22% at the 1-m mark, while the white nozzle's coverage tops out at approximately 12% at 0 m. This suggests that the finer droplets from the green nozzle deliver more extensive and uniform coverage compared to the coarser droplets produced by the white nozzle. This finding is consistent with Zhang et al. (2024), who noted that finer droplets typically enhance target coverage due to their larger surface area, which improves adhesion on leaf surfaces. Such coverage is particularly advantageous when uniform pesticide distribution is essential for effectiveness.

Hunter et al. (2019) also found that equipment speed influences coverage, with the best results at lower speeds. At a speed of 7 m/s, they recorded coverage of 22, 16, and 13% for Air Induction Extended Range (AIXR), Extended Range (XR) flat-fan, and the Turbo TeeJet® Induction (TTI) nozzles, respectively. Similarly, flow rate impacts coverage; Nansen et al. (2015) observed up to 10% coverage at flow rates between 30 and 40 L/ha, indicating that both speed and flow rate adjustments can enhance coverage in field applications.

However, the increased coverage with finer droplets has a downside. Nuyttens et al. (2007) emphasized the heightened drift potential of fine droplets, especially in windy conditions. The green nozzle's higher coverage percentage, while beneficial for thorough application, could increase the risk of off-target drift compared to the white nozzle, which produces coarser droplets that offer better drift control. Thus, the recommendation on the timing for the spraying application is crucial to avoid the drift or off-target spray droplets.

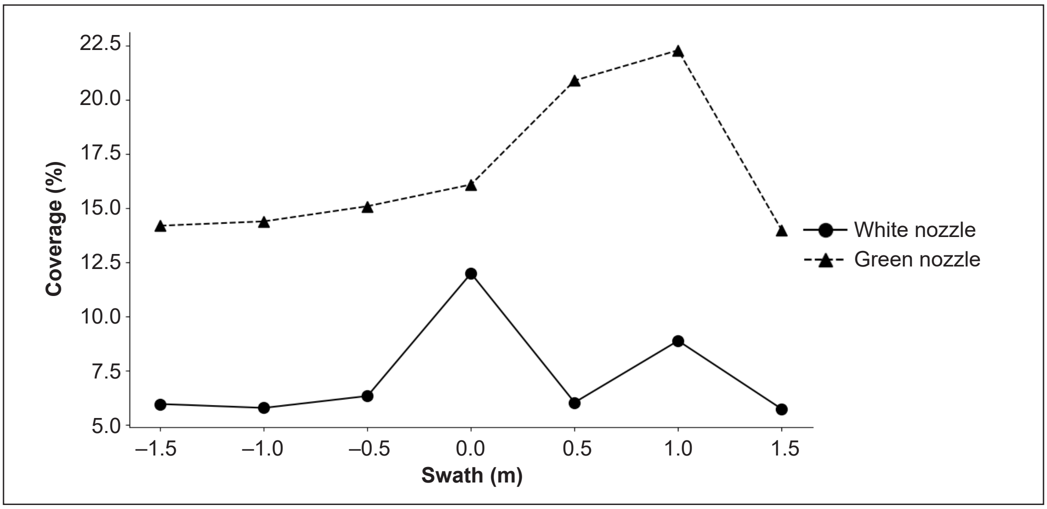


*Figure 8*. Mean percentage coverage from both nozzles

## Drift

The ISO 22866:2005 standard (International Organization for Standardization [ISO], 2005) recommends measuring spray drift up to 50 m downwind from the swath edge. However, studies such as Xue et al. (2014) found that 90% of the drift was captured within 8 m when a UAS operated at 5 m height under 2 m/s wind conditions. This study and the results presented in Table 6 highlight the differences in spray drift deposition between the green and white nozzles at varying distances from the swath edge, along with the corresponding meteorological conditions during each test run. At the closest measurement point (1.5 m), the white nozzle deposited significantly more spray (1.60 µl/cm²) than the green nozzle (0.49 µl/cm²) ($t$ = -9.093, $p$ = 0.001). This suggests that the white nozzle's coarser droplets settle more rapidly, reducing the likelihood of drift under moderate wind conditions (2.05 m/s). The significantly higher deposition at this near-field location indicates its suitability for applications requiring localized spray coverage. However, as the distance increased, the green nozzle exhibited greater deposition than the white nozzle. At 6.5 m, the green nozzle deposited 0.258 µl/cm², whereas the White nozzle deposited 0.165 µl/cm² ($t$ = 5.305, $p$ = 0.006). By 10.5 m, this trend became more pronounced, with the green nozzle (0.140 µl/cm²) significantly outperforming the white nozzle (0.026 µl/cm²) ($t$ = 11.779, $p$ = 0.000). The higher drift potential of the green nozzle is likely due to its finer droplets, which remain airborne for longer durations, increasing the likelihood of mid-range deposition. At 20.5 m, both nozzles exhibited reduced deposition, but the green nozzle still showed slightly higher values (0.0161 µl/cm²) than the white nozzle (0.0090 µl/cm²) ($t$ = 4.041, $p$ = 0.016). This indicates that even at long distances, the finer droplets from the green nozzle continue to contribute to drift, reinforcing its potential for broader area coverage.

Table 6
*Average volumetric deposition of spray drift and standard deviation (in brackets) from spray nozzles along distance, and the metrological information*

| **Distance (m)** | **Volumetric deposition (µl/cm²) and standard deviation** | | ***t*-value** | ***p*-value** |
|---|---|---|---|---|
| | **Green nozzle** | **White nozzle** | | |
| 1.5 | 0.490 (0.023) | 1.600 (0.210) | -9.093 | 0.001 |
| 6.5 | 0.258 (0.011) | 0.165 (0.030) | 5.305 | 0.006 |
| 10.5 | 0.140 (0.016) | 0.026 (0.008) | 11.779 | 0.000 |
| 20.5 | 0.016 (0.003) | 0.009 (0.001) | 4.041 | 0.016 |
| Wind speed (m/s) | 1.400 (0.500) | 2.700 (0.300) | -3.862 | 0.018 |
| Temperature (°C) | 30.700 (1.500) | 33.500 (1.000) | -2.690 | 0.055 |
| R/H (%) | 65.500 (7.400) | 60.000 (10.000) | 0.671 | 0.537 |

*Note*. R/H = Relative humidity

These findings are consistent with Baetens et al. (2007), who found that smaller droplets tend to drift farther, and with Grella et al. (2017), who reported that nozzle type plays a critical role in drift variability.

Meteorological conditions also varied between the test runs. Wind speed increased from 1.4 m/s during the green nozzle test to 2.7 m/s during the white nozzle test ($t$ = -3.862, $p$ = 0.018). Additionally, temperature increased from 30.7 to 33.5°C ($t$ = -2.690, $p$ = 0.055), while relative humidity dropped from 65.5 to 60.0% ($t$ = 0.671, $p$ = 0.537). While these changes may have had some influence on spray drift, the overall trends suggest that nozzle design remained the dominant factor affecting deposition patterns. The finer droplets of the green nozzle were more susceptible to increased wind speed, which explains their greater deposition at mid-to-long distances.

For UAS-based bio-fertilizer application, these findings emphasize the need to balance targeted deposition and drift control. The white nozzle is more effective for near-field spraying, where rapid droplet settlement is desirable, while the green nozzle is better suited for mid-range deposition, enhancing overall spray coverage. Optimizing application efficiency may require the use of adjuvants to improve deposition, real-time meteorological monitoring to adjust spraying parameters dynamically (Jomantas et al., 2023), and careful nozzle selection to minimize drift while ensuring uniform crop coverage.

## CONCLUSION

The study compares two nozzles, XR11008VS (white) and XR110015VS (green), for spraying bio-fertilizer from a UAS, focusing on droplet size, deposition density, coverage, and spray drift. The white nozzle produces larger droplets (mean Dv0.5 of 261 µm) with a "Medium" spray quality, suitable for drift reduction and targeted delivery. In contrast, the green nozzle generates finer droplets (mean Dv0.5 of 90.2 µm) with a "very fine" spray quality, ideal for achieving uniform coverage. The green nozzle achieves a higher deposition density (mean of 1,248 Dep/cm²) but increases drift risk, especially under windy conditions, while the white nozzle's coarser droplets reduce drift potential but result in lower deposition density. Drift analysis shows that the white nozzle achieves higher near-field deposition, whereas the green nozzle's finer droplets exhibit a more gradual drift pattern, leading to similar deposition at extended distances.

Overall, although the white nozzle is effective for minimizing drift and targeted spraying, the green nozzle is preferable for paddy cultivation, where uniform and thorough bio-fertilizer coverage is critical for rice plant growth and yield. With proper management of environmental conditions to control drift, the green nozzle's ability to cover larger areas can optimize input usage, lower costs, and enhance overall agronomic and economic outcomes for farmers. Additionally, practical considerations such as lower maintenance requirements, cost-effectiveness, and compatibility with existing UAS systems further reinforce its suitability for modern rice farming operations.

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