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Evaluation of Agri-Drone Spray Pattern and Geometric Coverage Characteristics via a Spreadsheet Model and Zero Crosswind Testing

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Abstract

Agricultural drones or Agri-Drones can improve the efficiency of crop spraying operations, but their performance depends on the spray pattern and distribution of liquid across the target area. This study examines the spray pattern and geometric coverage of a flat-fan hydraulic nozzle in single-nozzle and two-adjacent-nozzle configurations using a controlled indoor test rig. A spreadsheet tool, EASYDist, is used to estimate theoretical spray width and coverage, and the estimates are compared with visually observed experimental patterns. The drone propellers are removed during the testing to eliminate rotor-induced downwash, and the tests were conducted without crosswind exposure. The measured experimental spray width is approximately 1.5 m for the single-nozzle configuration and 3.84 m for the two-nozzle configuration, with overlapping spacing of 0.98 m. The geometric overlap of 65.3% are measured based on the observed spacing. The estimated elliptical spray coverage areas of 0.1296 m² and 0.6739 m² for the single and two-nozzle configurations are recorded, respectively. These results provide an initial comparison between a simple geometric model and observed spray characteristics.

Keywords: Pesticide Spraying, Flat Fan Nozzle, Agricultural Drone, Smart Nozzle

Introduction

Agricultural drones or Agri-Drones, as shown in Figure 1, are playing an expanding role in applying pesticides and herbicides, as well as in direct-seeding crops. Their potential advantages include rapid deployment and reduce direct exposure of operators to spray materials. However, application effectiveness depends not only on flight

planning and vehicle control but also on how liquid is atomized and deposited on the target. Uneven deposition can leave parts of a crop under-treated while applying excessive liquid to other areas, reducing efficacy, and increasing the risk of off-target contamination [1], [2].

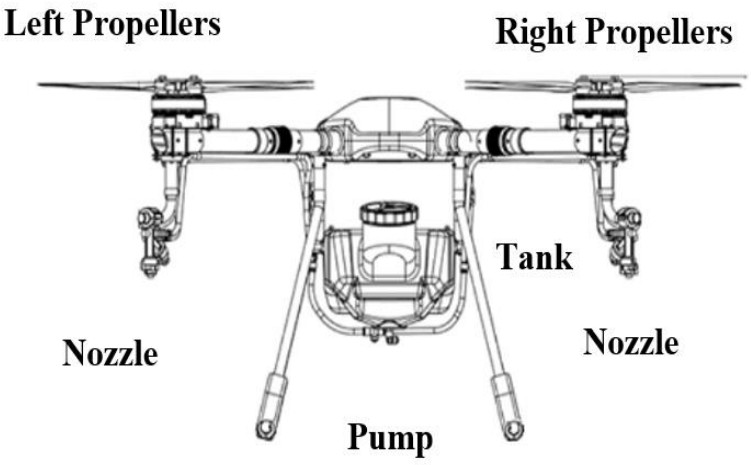


Figure 1. Agri-Drone in study.

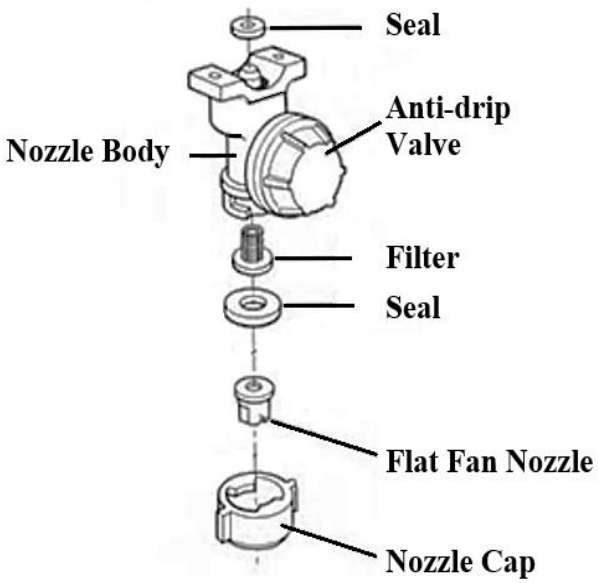


Figure 2. Hydraulic nozzle components [11].

Research on Agri-Drones has addressed flight control, communication, obstacle

avoidance, route planning, and spray-system performance. Nozzle characteristics remain important because nozzle type, pressure, flow rate, mounting orientation, and distance from the target influence spray angle, droplet formation, deposition, and drift [3]-[9]. A useful assessment should therefore distinguish the geometric footprint of a spray from the amount and uniformity of liquid actually deposited on a surface.

Hydraulic nozzles use liquid pressure to form a spray through a designed orifice. Common patterns include flat fan, hollow cone, full cone, and solid stream configurations [10]-[12]. A flat-fan nozzle produces a fan-shaped sheet of liquid and is often used for broadcast application. Its nominal spray width can be estimated from spray angle and nozzle-to-target distance, but the observed footprint also depends on pressure, nozzle condition, liquid properties, and the method used to identify the wet boundary. Accordingly, geometric estimates should be checked against measurements under documented operating conditions.

Literature review

Agri-Drones have revolutionized the way farming operations are conducted, particularly in the realm of spraying pesticides, herbicides, and fertilizers. These unmanned aerial vehicles (UAVs) are equipped with specialized nozzles that allow for precise control over the application of chemicals, optimizing their effectiveness while minimizing waste and environmental impact. The key aspects that determine the success of drone spraying include the nozzle spray pattern, coverage, distribution, drift, and droplet size, all of which are interrelated and contribute to the overall efficiency of the spraying process. A wide visible coverage does not necessarily indicate uniform deposition, and a geometrically overlapping coverage does not by itself prove that the target receives a uniform application rate. This study focuses on the first-stage geometric assessment of spray pattern and coverage.

1.1 Spray pattern

The nozzle spray pattern is a fundamental element of drone spraying technology, as it determines how the liquid is dispersed over the target area. This pattern is influenced by various factors, including the type of nozzle used, the pressure of the liquid, and the speed and altitude of the drone. Different spray patterns are suitable for different applications; for instance, a fan spray pattern is often used for broad coverage, spreading the liquid in a wide, flat distribution ideal for evenly treating large, open fields. The flat fan nozzle is commonly employed for herbicide broadcast spraying, producing a flat fan spray pattern. Example of commonly available spray angle at 40°, 25°, and 10° are shown in Figure 3, with respective triangular pattern. Standard flat-fan nozzles typically operate in an ideal range of 2–3 bar [13]. On the other hand, a cone spray pattern may be employed when more concentrated application is needed, such as targeting specific plants or areas within a crop. The hollow cone design, with a concentrated ring-shaped coverage, and the full cone design, with a concentrated circular coverage can exhibit spray angles ranging between 30°-170° [14], with recommended operating pressures of 1-3 bar for full cone and 3-7 bar for hollow cone [15].

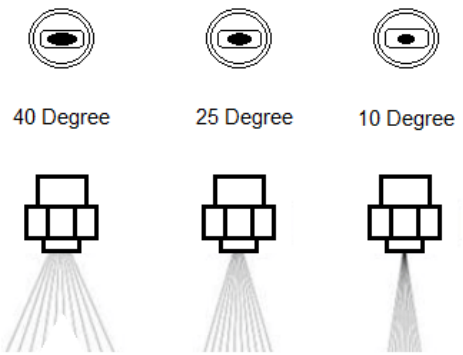


Figure 3. Nozzle Spray Pattern.

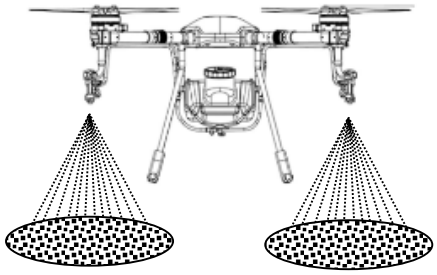
Cone nozzles find extensive use in foliage spraying because their droplets approach leaves from multiple directions. Other than the flat fan and cone nozzle, the solid stream nozzles represent a distinct type of hydraulic nozzle, utilizing hydraulic pressure to eject liquid. These nozzles shape the fluid into a cohesive, round jet by forcing it through a specially designed orifice. Consequently, the designated spray angle for these nozzles is considered to be 0°. Solid stream nozzles find application in various scenarios, including spot weed treatment or herbicides. It is also suitable for tasks such as cleaning, cutting, and liquid recycling. The ability to adjust the spray pattern dynamically as the drone flies over the field is one of the significant advantages of using drones for agricultural spraying. This flexibility allows for a tailored approach to crop management, where the spray pattern can be optimized for varying conditions within the same field, such as differences in crop density, topography, or susceptibility to pests and diseases. Additionally, advanced drones can be equipped with multiple types of nozzles that can switch between different spray patterns mid-flight, further enhancing their versatility and effectiveness.

1.2 Spray Coverage

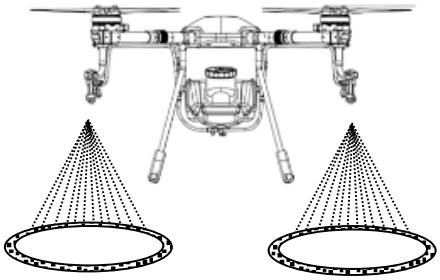
Coverage, the second crucial factor, refers to the extent of the area that the drone can treat effectively in a single pass. The goal of any spraying operation is to achieve uniform coverage across the entire field, ensuring that every part of the crop receives the necessary treatment. Inconsistent coverage can lead to uneven growth, with some areas being over-treated while others are under-treated, which can negatively impact crop yields and quality. Nozzle spray coverage refers to the pattern and manner in which a liquid is dispersed when it is ejected from a nozzle. This coverage can vary widely depending on the design and type of nozzle, the pressure and flow rate of the liquid, and other factors. The coverage can vary significantly based on the nozzle design, liquid pressure, and flow rate, influencing the effectiveness of the application, as shown in Figure 4. Key aspects include the spray pattern, which can be conical, fan-shaped, or a concentrated jet, each serving different purposes from broad coverage to targeted applications.

The spray angle determines the area covered, with wider angles dispersing liquid over a larger area at lower intensity, while narrower angles provide more focused,

intense sprays. Droplet size coverage is also crucial, as different applications require varying droplet sizes; for instance, fine mists are ideal for humidification, while larger droplets are necessary for irrigation. Uniformity of the spray ensures consistent coverage, essential in applications like pesticide spraying and surface coating. Additionally, the flow rate, which can often be adjusted, controls the volume of liquid dispensed over time, impacting the application's efficiency and effectiveness.



Flat Fan Nozzle



Hollow Nozzle

Figure 4. Spray coverage shapes.

Spray coverage is also the dispersion of spray flow in the direction of the spray width [16]. Environmental conditions, such as wind, temperature, and humidity, significantly impact spray coverage. Wind can cause drift, dispersing droplets away from the target area and leading to uneven application. Temperature and humidity influence evaporation rates, affecting how droplets adhere to plant surfaces. Spraying during calm weather conditions or using drift-reducing agents can help maintain uniform coverage and minimize environmental impact.

Agri-Drones can be programmed with precise flight paths that consider the size and shape of the field, as well as any obstacles that may be present, such as trees or buildings. By flying at a consistent altitude and speed, drones can maintain a uniform

distance from the crop canopy, which is essential for even coverage. Moreover, drones equipped with GPS and other positioning technologies can ensure that there is minimal overlap or gaps between passes, further enhancing the efficiency of the spraying operation. In large or irregularly shaped fields, drones can adapt their flight patterns to ensure that every section is adequately covered, something that would be difficult, if not impossible, to achieve with traditional ground-based spraying equipment.

1.3 Spray Distribution

Distribution is closely related to coverage but focuses specifically on how evenly the sprayed liquid is spread across the target area, as shown in Figure 5. Achieving uniform distribution is critical for maximizing the effectiveness of the applied chemicals, as uneven distribution can result in some parts of the crop receiving too much chemical while others receive too little.

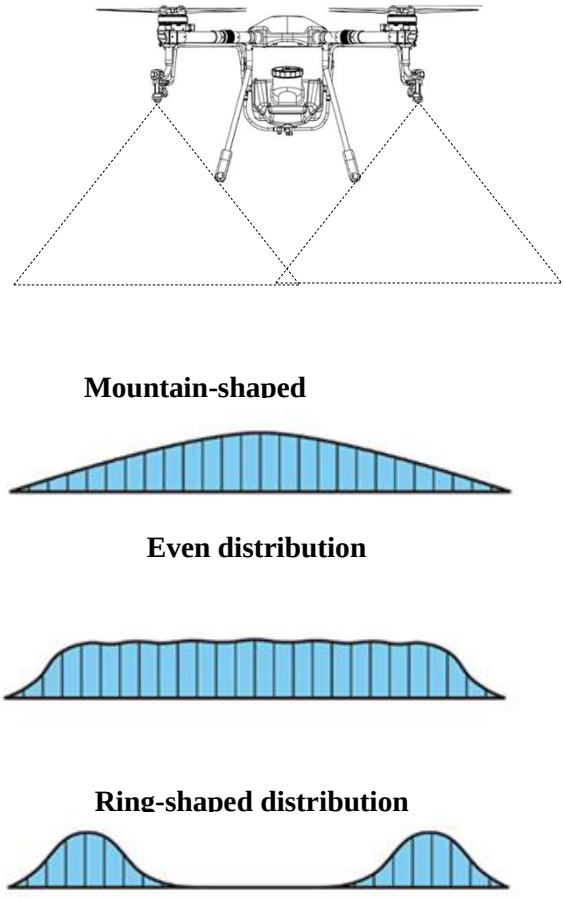


Figure 5. Spray distribution shapes [16].

This can lead to areas of the field that are over-treated, potentially causing damage to the plants or contributing to chemical runoff, while other areas may remain untreated, leaving the crop vulnerable to pests and diseases. The precision with which agricultural drones can control distribution is one of their most significant advantages. By adjusting the flow rate and spray pattern in real-time based on the drone's speed, altitude, and the

specific needs of the crop, drones can ensure that the liquid is distributed evenly across the entire field. This level of control is particularly important in precision agriculture, where the goal is to apply the right amount of chemical at the right place and time, thereby reducing waste and minimizing environmental impact. Advanced drones are equipped with sensors that monitor the distribution of the spray in real-time, allowing for immediate adjustments to be made if any inconsistencies are detected. This ensures that every part of the crop receives the optimal amount of treatment, leading to more uniform growth and higher overall yields. Spray is evenly distributed across the width [17]. Some applications impose the use of multiple nozzles simultaneously, emphasizing the critical need for an even liquid coverage. The variability in spray coverage is influenced by factors like spray height, pressure, and the specific type of nozzle employed. For example, flat fan nozzles generate a strip of spray that tapers at each end, requiring overlapping for uniform distribution.

1.4 Spray Drift

Spray drift, as shown in Figure 6, is a phenomenon where droplets are physically moved from the intended target to unintended places during the spray operation or for a brief period afterward because of intricate field environmental factors like a downwash or crosswind influence.

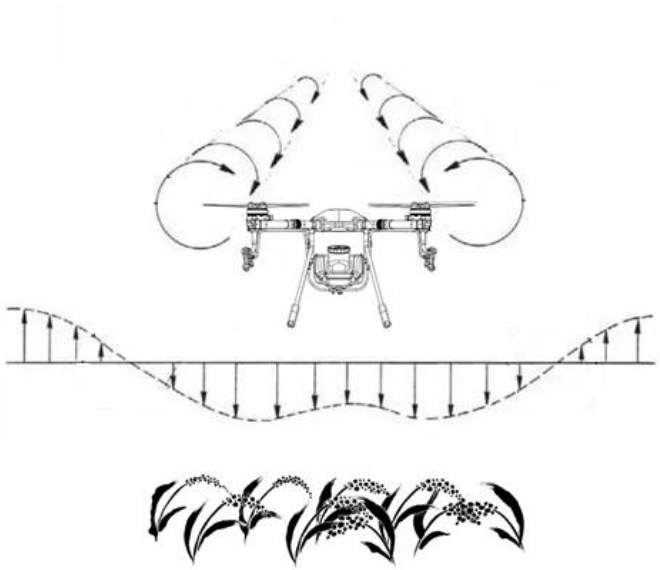


Figure 6. Spray drift due to crosswind and downwash.

According to studies, spray drift caused by drone spray is also a significant factor to consider, although market preferences tend toward the design of the drone as well. These concerns are reaffirmed by Heidary et al. [18], who state that spray drift continues to be major obstacle in the spray application industry. Drift droplets pose a risk to sensitive crops, contaminate the environment, and endanger the health of people and animals. Drift can be divided into two distinct categories: vapor drift, which is associated with the process of volatilization, and particle drift, which refers to the movement of spray particles during or after pesticide application [19]. The crosswind

speed, boom height, downwash distance, and droplet size can all affect the spray drift. Agriculture drones are designed to minimize drift through precise control of the spraying process. For instance, by flying at a lower altitude, drones can reduce the distance that droplets must travel before reaching the crop, thereby minimizing their exposure to wind. Some drones also feature wind sensors that allow them to adjust their flight path or pause spraying if wind conditions become too unfavourable.

1.5 Spray Droplets

Droplet size is another critical factor that affects both the coverage and effectiveness of the spray. The size of the droplets produced by the nozzles determines how well the spray adheres to the crop and how deeply it penetrates the canopy. Smaller droplets, as shown in Figure 7, tend to provide better coverage and can reach more areas of the plant, including the undersides of leaves and the lower parts of the stem.

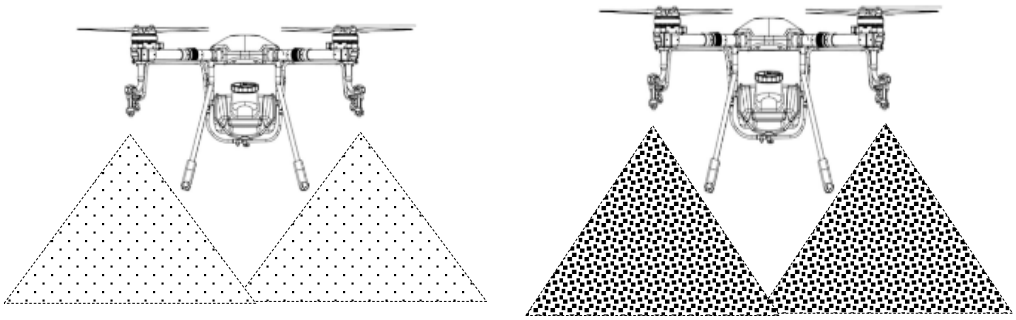


Figure 7. Spray droplets.

However, these smaller droplets are also more prone to drift, especially in windy conditions. Conversely, larger droplets are less likely to drift and can provide more targeted application, but they may not cover as large an area or adhere as well to the plant surfaces. The ability to control droplet size is one of the key features of advanced agricultural drones. By adjusting the pressure and flow rate of the liquid, as well as the design of the nozzle, drones can produce droplets of the desired size for the specific application. This allows for a more customized approach to spraying, where the droplet size can be optimized for the type of crop, the stage of growth, and the prevailing environmental conditions.

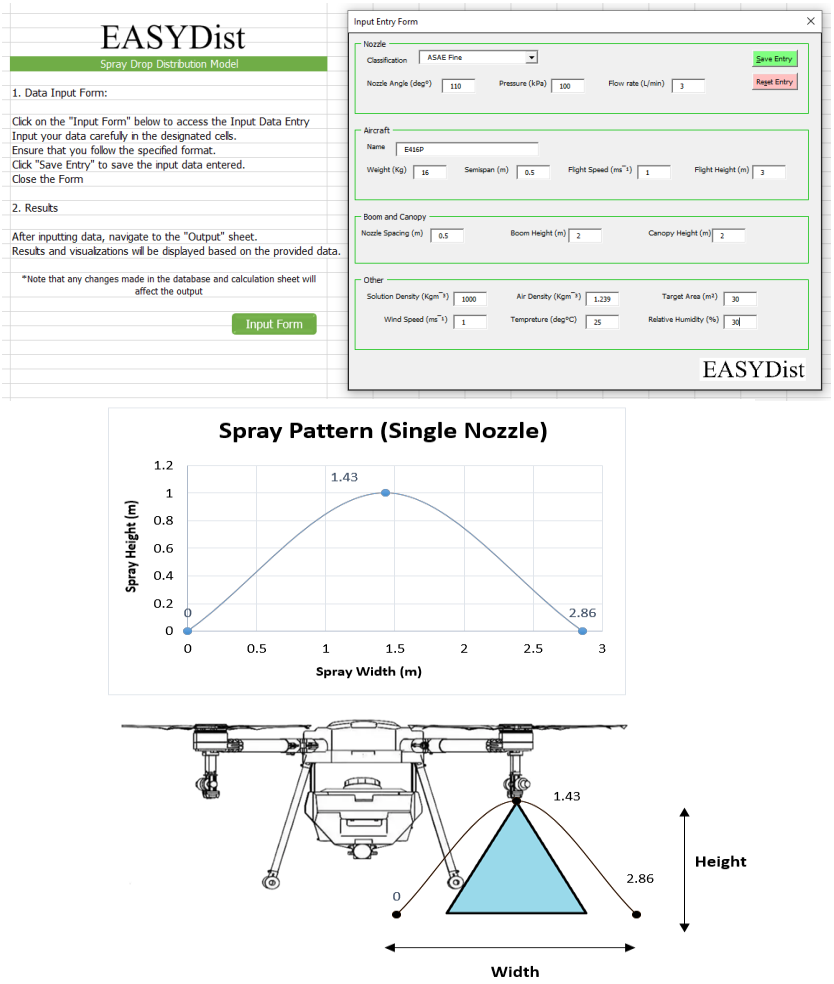
Methodology

The integration of these factors, nozzle spray pattern, coverage, distribution, drift control, and droplet size, into the operation of agricultural drones represents a significant advancement in the field of precision agriculture. This research focuses on a combined strategy of the simulation and experimentation of the nozzle's spray pattern and coverage simultaneously, under zero downwash influence.

Simulation parameter

In the simulation approach, two parameters, the spray pattern and coverage, are studied. The spray pattern is captured by using a camera and compared with a simulated pattern

using the EASYDist Ver 1 software, as shown in Figure 8. The software is a locally built spreadsheet model simulator which can be used to simulate the spray and coverage pattern of the nozzle.



2.1 Spray Pattern

Spray pattern is strongly correlated to the spray angle and spray height. The relationship among these factors is illustrated in Figure 9 below.

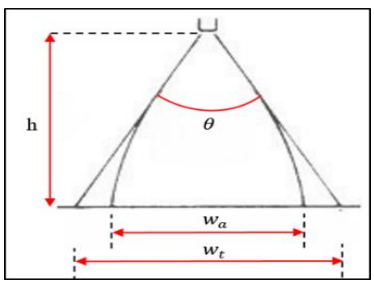


Figure 9. Spray pattern height and width

The theoretical spray width of the nozzle can be obtained by applying the trigonometry formula as shown in Equation (1),

$$w_{t(n=1)} = \tan\left(\frac{\theta}{2}\right) \times h \times 2 \quad (1)$$

where θ is the spray angle in unit of degree (°), w_t is the theoretical spray width (m) and h is the spray height (m). On the other hand, the actual spray pattern, w_a(m) can be obtained from the spray pattern as shown in Figure 10 and can usually be obtained by directly measuring the actual spray width.

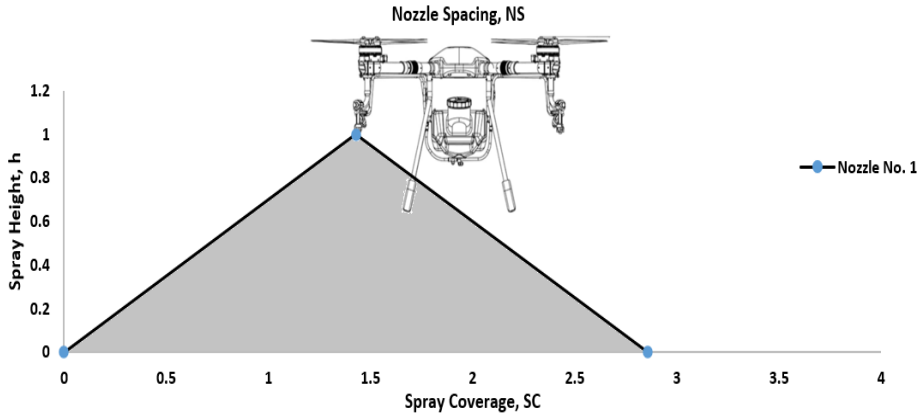


Figure 10. Spray width and coverage with a nozzle.

The actual spray width is usually influenced by factors such as nozzle type, spray height, pressure, and drone speed. A higher altitude or pressure typically results in a wider pattern, though this may increase the risk of drift and uneven coverage. Wind, temperature, and humidity also play a role, as they can affect droplet distribution. The optimal spray pattern width balances these factors to achieve efficient and uniform coverage while minimizing drift and off-target spray.

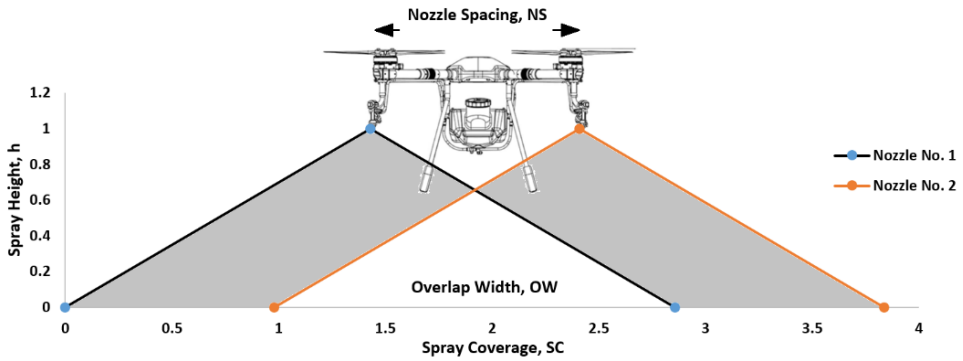


Figure 11. Spray width and coverage with two adjacent nozzles.

In the case of two adjacent nozzles used in the drone's configuration, as shown in Figure 11, an overlapping might also occur, and this can be calculated by determining the theoretical overlap width, *OW*, as shown in Equation (2),

$$Overlap\ width, OW = w_{t(n=1)} + w_{t(n=2)} - NS \quad (2)$$

where *NS* denotes as nozzle spacing (m). Therefore, proper overlap is essential for consistent coverage, as insufficient overlap can lead to gaps in the sprayed area, while excessive overlap may cause over-application. The overlap width depends on factors such as nozzle spray angle, flight altitude, and drone speed. Typically, a 30-50% overlap is used to compensate for variability in spray distribution due to wind, nozzle type, or changes in terrain. Adjusting these factors ensures even coverage across the entire field. Further consideration is required for the two adjacent nozzles due to the overlapping. It is crucial to determine the percent overlap between the nozzles to ensure the consistent coverage along the boom. Then, insert it into the equation below to determine the adjacent theoretical pattern as presented in Equation 3,

$$w_{t(n=2)} = (2 \times w_t) - Overlap\ width \quad (3)$$

Hence, the percent overlap can be formulated into Equation (4) below,

$$Percent\ overlap\ (\%) = \frac{Overlap\ width}{ns} \times 100 \quad (4)$$

The spray width of each individual nozzle, $w_{a_{single}}$ must be determined by derived Equation (3) to find the overlap width, which produces the formula shown in Equation (5) below,

$$w_{a_{single}} = w_{a_{adj}} - ns \quad (5)$$

2.2 Spray Coverage

The spray coverage is described as the dispersion of the spray flow in the direction of the spray width. The area coverage can be obtained by calculating the area of the spray pattern. In the case of a flat fan nozzle, the coverage is represented in the elliptical shape as exhibited in Figure 12. Therefore, the area of the ellipse can be calculated by using Equation (6).

$$A_{elliptical} = \pi ab \quad (6)$$

Where a is the length of semi major axis and b is the length of semi minor axis. Both values are expressed in unit of meters (m).

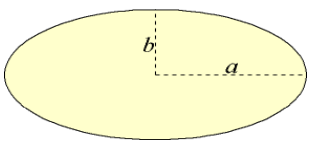


Figure 12. Area of ellipse

Both spray width and coverage can be represented by respective axis. Thus, from front and above view, the spray coverage can be represented in Figure 13.

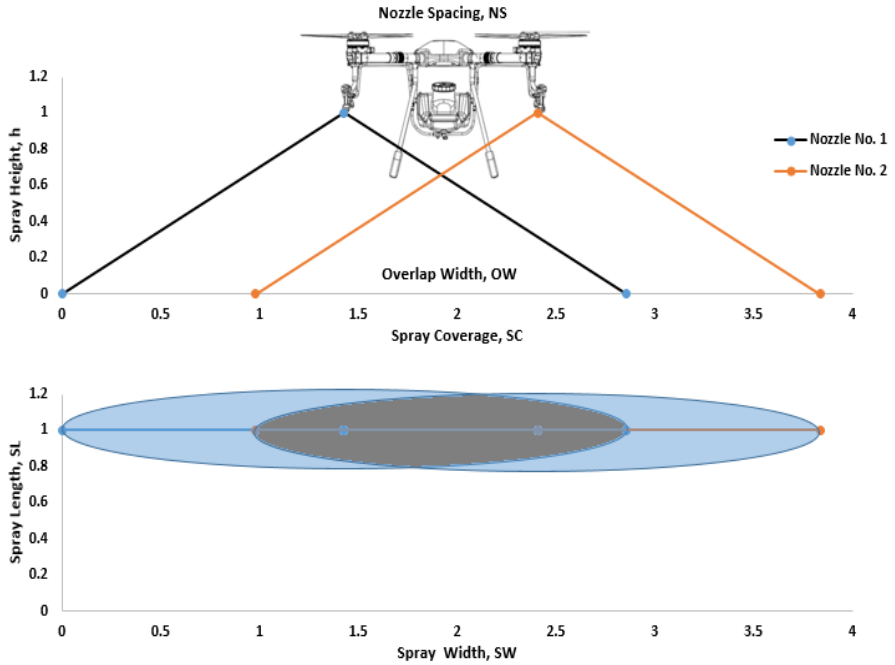
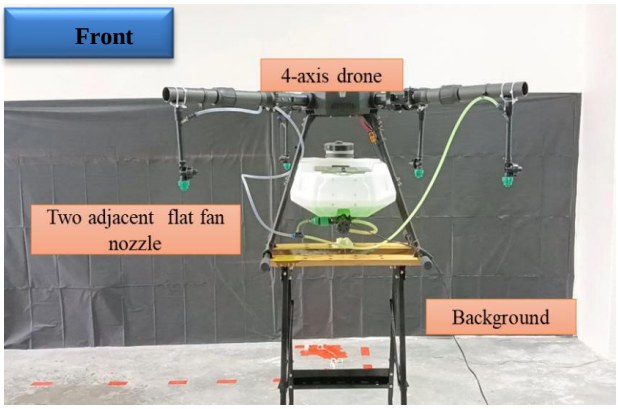


Figure 13. Spray width and coverage with two adjacent nozzles.

Experiment parameter

The experiment was conducted with a test rig setup of an agricultural drone with different nozzle configuration tested in a controlled indoor environment. The test rig involved the use of a 4-axis agricultural drone, a 16 L tank, and hydraulic nozzle of different orientation. A flat fan nozzle is used and positioned at the end of the arm in a vertically suspended position for either a single or two adjacent nozzles configurations, as shown in Figure 14. A water pump is linked to the piping system that provides water flow from the tank to the nozzles. The propellers are dismantled from the drone to avoid unnecessary accident during the experiment, and to let out any disturbance in the form of unwanted downwash effect at this stage of experiment.



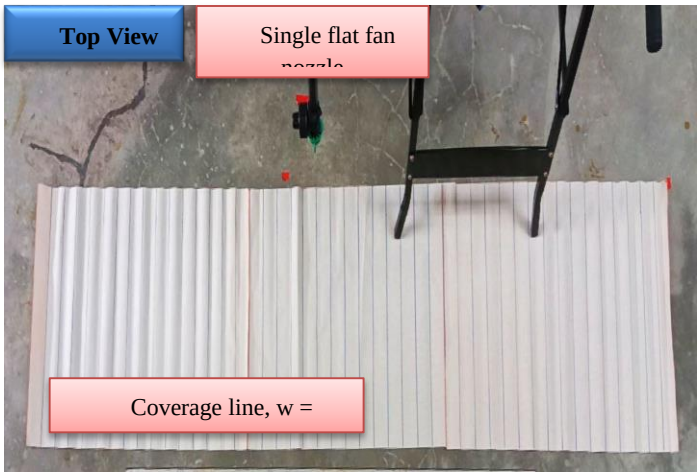


Figure 14. Front and top view of the experiment setup.

Results and Discussions

Spray Pattern Analysis

This experiment specifically examines the spray pattern and spray coverage of the flat fan nozzle under single and two adjacent nozzles configuration and setup orientations without external factors such as downdraft and crosswind. Based on Figure 15, a frontal view of the spray patterns generated by the flat fan nozzle for both configurations reveal a well-defined fan shape. The droplets exhibit a fine size and are distributed across a wide angular range.

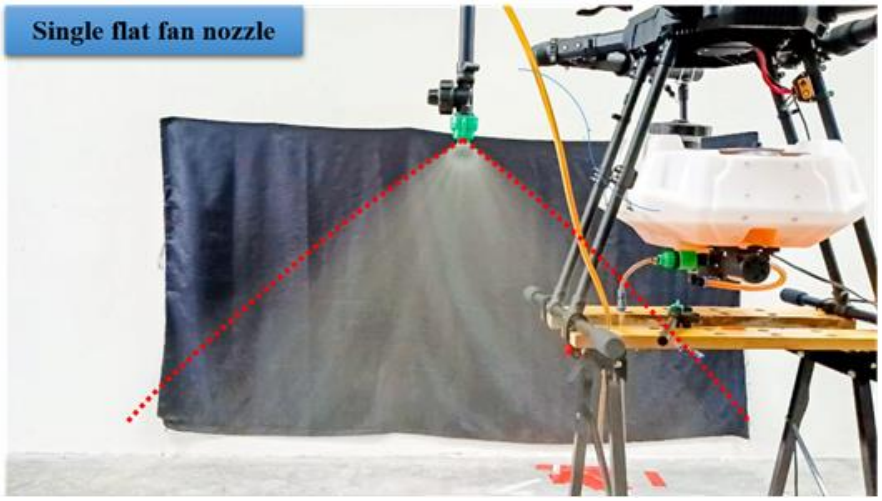


Figure 15. Spray pattern of single nozzle.

By referring to Figure 15, in a single nozzle configuration setup, the actual spray coverage, w_{a_s} obtained is 1.5m m, as shown in Figure 16 below.

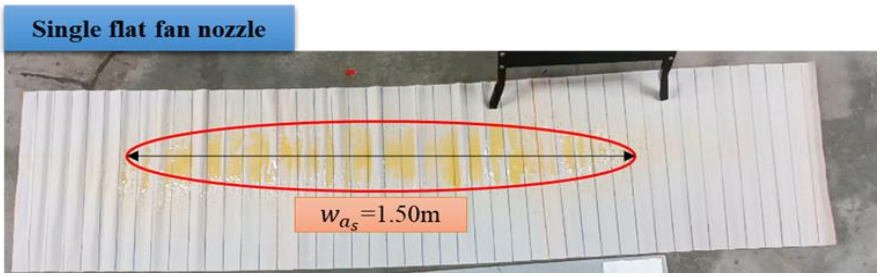


Figure 16. The actual spray coverage of single nozzle.

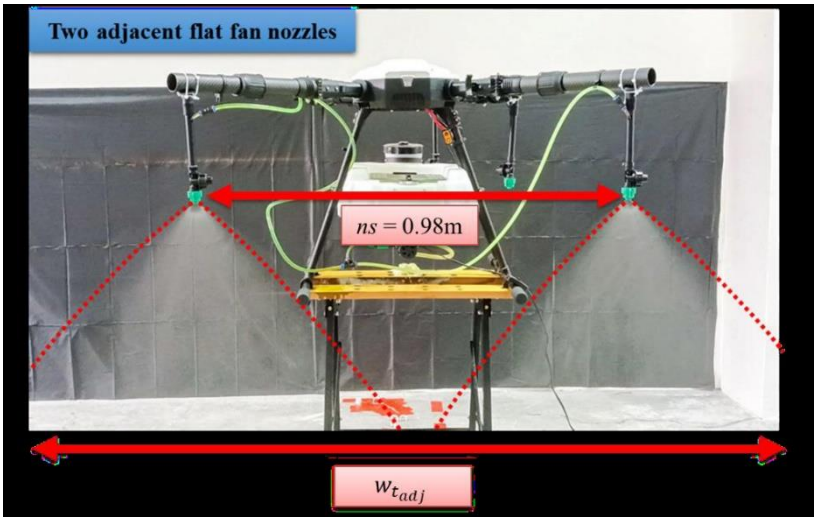


Figure 17. Spray pattern of two adjacent nozzles configuration.

In the two-nozzle configuration, the nozzle spacing, ns again play important role in determining the adjacent theoretical pattern, $w_{t_{adj}}$, which valued at 0.98 m. In the experiment, the actual spray coverage, $w_{a_{adj}}$ obtained is 3.84 m, as shown in Figure 18.

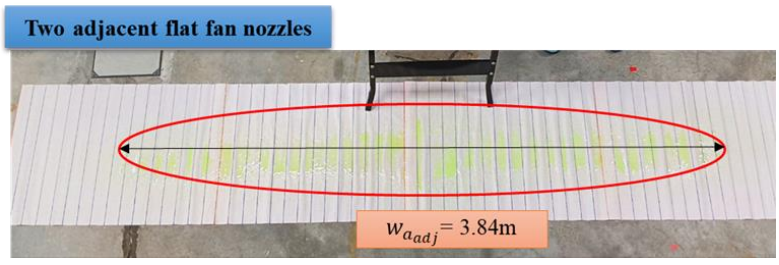


Figure 18. The actual spray coverage of two adjacent nozzles.

Spray Coverage Analysis

Spray coverage experiment highlights the spray pattern's shape and the area coverage of droplets from a top-down perspective. The percent overlap between the two nozzles can be found, which determines how much area covered by the spray from the two nozzles. The obtained percent overlap is 65.3%, indicating that each adjacent nozzle contributes half of the overlapping area, which corresponds to 32.7%. Nevertheless, a minimum overlap of 100% is recommended for flat fan nozzles to ensure optimal coverage. This ensures that both nozzles spray the entire area under the boom uniformly.

Based on the calculated overlap width, it implies that certain areas may be unsprayed, indicating insufficient atomization coverage. This problem may be occurred due to the limitation of the spray height because it also plays important role to achieve 100% overlap. Besides, the area coverage is calculated to determine the coverage obtained on the sprayed surfaces. The area coverage can be measured by taking into account the measured value of a and b, based on the semi length of major axis and minor axis, respectively, as shown in Figure 19 and Figure 20 below. Hence, the area coverage for single nozzle, A_{single} and two adjacent nozzles, $A_{adjacent}$ are estimated to be of 0.1296 m^2 and 0.6739 m^2, respectively.

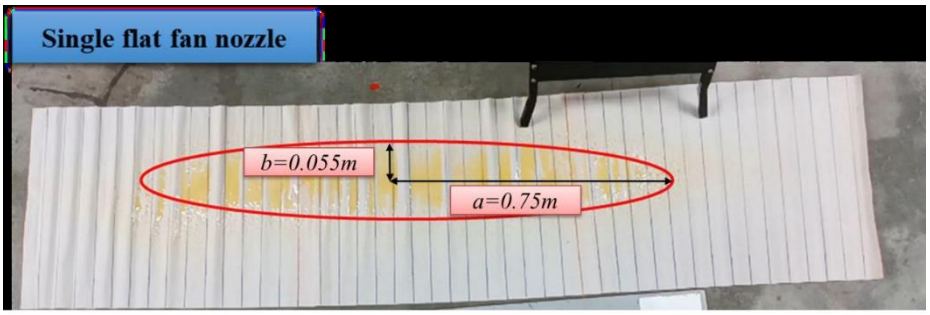


Figure 19. Spray area coverage for single flat-fan nozzle.

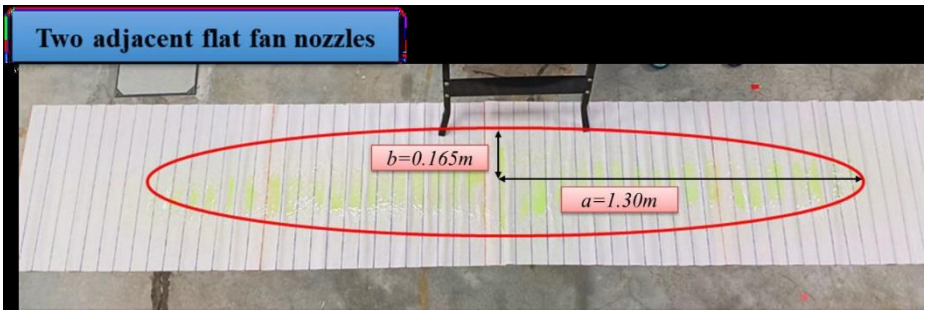


Figure 20. Spray area coverage for two adjacent flat-fan nozzles.

Conclusion

This study presents a preliminary geometric assessment of a flat-fan nozzle mounted on an Agri-Drone frame under indoor conditions without crosswind or rotor downwash exposure. The spray width is recorded as approximately 1.5 m, for the single-nozzle configuration and 3.84 m for the two-nozzle configuration, with the nozzle spacing of 0.98 m. It also noted that a 65.3% geometric overlap is recorded for the two-nozzle configuration. An estimated coverage areas of 0.1296 m² and 0.6739 m² are also recorded for the single and two-nozzle configuration, respectively. The observed fan-shaped patterns provide a qualitative comparison with the spreadsheet model.

Acknowledgement

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