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Comparison of Volumetric Distribution in Drone Spraying Considering Height, Application Volume, and Nozzle Type

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Abstract: The advancement of technology in agriculture has driven the use of drones for spraying, with their increasing adoption presenting challenges in calibration and volumetric distribution efficiency. This study aimed to evaluate the volumetric distribution of drone spraying by combining different operational parameters to determine spray swath and application uniformity. Experiments were conducted using a DJI T10 drone and a volumetric distribution table to assess the impact of different flight heights (2, 3, and 4 m), application volumes (8, 12, 16, and 20 L ha^{-1}), and nozzle types (FV 110 015, FL 110 010, and CO 080 010). Environmental conditions were monitored, and data were analyzed using histograms, analysis of variance (ANOVA) by F-test ($p \leq 0.05$), and the Scott–Knott test ($p \leq 0.05$) to group means. Results indicated that a lower application volume (8 L ha^{-1}) led to greater application uniformity and a narrower spray swath. Higher flight altitude (4 m) resulted in a wider spray swath and a normal distribution of spray deposition. Fine droplet nozzles (CO 080 010) enhanced uniformity, while very coarse droplets (FV 110 015) concentrated more volume in the center of the swath. Thus, using fine droplet nozzles (CO 080 010), lower application volume (8 and 12 L ha^{-1}), and higher flight altitude (4 m) as operational parameters maximizes drone spraying efficiency; however, this also increases drift potential.

Keywords: drone technology; operational parameters; UAV (unmanned aerial vehicle); spray swath; application uniformity; precision agriculture

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1. Introduction

Agriculture is one of the main pillars of the economy in several countries today, such as Brazil, where it represents approximately 16% of the gross domestic product (GDP) [1]. In recent years, agriculture has been revolutionized and automated, incorporating various precision agriculture techniques, primarily through the use of remotely piloted aircraft (RPA), commonly known as drones.

In Brazil, there are more than 188,000 drones registered in the national system, with 6235 used for agricultural spraying [2]. This technology has been expanding worldwide, with its application already exceeding 500 million hectares of agricultural land globally [3]. Spraying drones offer significant advantages over traditional methods, especially by providing access to non-mechanized areas, enabling spraying in flooded terrains [4,5], and facilitating operations in small plots where maneuvering ground sprayers and airplanes is challenging. They also enhance safety, convenience, mobility, and operational efficiency, while preventing crop damage in the field [6]. Additionally, drone spraying reduces operator exposure to chemicals and minimizes environmental impacts by lowering CO_2 emissions, decreasing water consumption, and optimizing pesticide use [3,7,8].

With the increasing adoption of spraying drones in agriculture, various studies have been reported in the literature, mainly demonstrating their effectiveness in pest and disease control using reduced spray volumes, as well as their potential to lower operational costs [9,10]. However, the efficiency of agricultural drone spraying depends on multiple factors, including flight height, speed, application volume, and nozzle type, particularly for crops such as cotton, soybeans, coffee, and fruit trees. Previous studies indicate that flight height directly affects droplet deposition and spray drift, with recommended heights between 1.0 and 2.5 m for different crops [11–13]. However, the optimal flight height and application volume depend on vegetation characteristics and environmental conditions, making it essential to define specific parameters for each application [9]. Additionally, flight speed can influence both deposition uniformity and coverage efficiency [14]. The proper nozzle selection also plays a crucial role in drift control, affecting volumetric distribution and spray penetration into the canopy [15,16].

These parameters can strongly influence the volumetric distribution pattern in drone applications. In ground spraying, volumetric distribution is affected by factors such as boom height and nozzle spray angle, which directly impact spray overlap and can interfere with the coefficient of variation [17,18]. Additionally, nozzle spacing and operating pressure also play a role in distribution uniformity [19]. However, some adjustments are not possible in drone spraying, such as operating pressure, which remains constant regardless of the application volume. This limitation further highlights the importance of understanding volumetric distribution and the coefficient of variation in drone-based spraying.

Understanding the volumetric distribution of spraying is essential to ensure efficient and safe pesticide application. Proper distribution improves plant coverage, enhancing pest and disease protection while preventing negative impacts on areas with excessive or insufficient product application. The volumetric distribution of ground-based spraying equipment is well established by standards such as International Organization for Standardization [20]. However, for drones, there are no specific regulations to evaluate volumetric distribution. This lack of regulation makes it impossible to determine whether drone applications result in under-dosed (ineffective) or over-dosed (wasteful and phytotoxic) areas based on application uniformity. Therefore, further research is essential to develop and validate a system that can serve as a foundation for new regulatory standards that is applicable under field conditions rather than in restricted, controlled environments [21,22].

Thus, given the growing adoption of spraying drones in agriculture and the lack of specific regulations to evaluate volumetric distribution, it is essential to investigate how different operational parameters influence droplet deposition. Considering that volumetric distribution and the coefficient of variation are key factors for spraying efficiency, this study hypothesizes that flight height, nozzle type, and application volume can significantly affect deposition uniformity and spray swath width. Therefore, this study aims to evaluate the impact of these operational parameters on drone spraying, providing insights that can contribute to the development of technical guidelines and optimize the use of this technology in the field.

2. Materials and Methods

Three different experiments were conducted to compare flight parameters, including application volume (L ha^{-1}), flight height (m), and nozzle types. Using a DJI Agras T10 spraying drone (DJI Sciences and Technologies®, Shenzhen, China), these three parameters were tested to assess their influence on the spray patternator developed by the authors.

The selected parameters were chosen due to their impact on commercial crops and fruit trees [23–26]. Modifying these parameters directly affects droplet deposition and spray swath width.

2.1. Drone Characteristics

The drone used in the experiments was the DJI Agras T10 (SZ DJI Technology Co., Ltd., Shenzhen, China), an advanced model designed for agricultural applications. It features a spray tank with an 8 L capacity and a nominal takeoff weight of 24.8 kg. The T10 drone has a maximum flight speed of up to 10 m s^{-1} and an operational efficiency of up to 6 ha h^{-1}.

The drone's spraying system is equipped with two diaphragm pumps, with pressure automatically adjusted by the equipment between 2.0 and 4.5 kg cm^{-2}, making it impossible to manually adjust the pressure during or before an operation. Each pump controls two nozzles, allowing for efficient spraying tailored to field requirements. The system has a maximum flow rate of 1.5 L min^{-1}, with a flow meter accuracy of approximately 2%. The effective spraying range varies from 1.5 to 3.0 m (with two nozzles) to 3.0 to 5.5 m (with four nozzles), ensuring wide and consistent coverage [27].

Additionally, the T10 drone is equipped with a spherical radar, providing omnidirectional environmental awareness, allowing the drone to intelligently detect and avoid obstacles. It also enables stable flights in challenging terrains, such as sloped areas. This combination of technologies ensures a safe and efficient operation, adapted to various agricultural conditions.

2.2. Characteristics of the Spray Patternator

For the evaluation of the volumetric distribution of spraying performed by drones, a low-cost system was developed using readily available materials, allowing it to be built anywhere without the need for advanced technology or machinery to assemble the structures.

The volumetric distribution evaluation system was designed with dimensions of 5.30 × 4.30 m, using rectangular fiberglass sheets. A total of ten fiberglass sheets (2.44 × 1.10 m each) were used to construct the spray patternator. To prevent liquid loss between the grooves of the sheets, they were overlapped and fixed. For distribution assessment, 31 collection cups were placed at the front edge of the table, spaced 0.17 m apart. These cups were used to collect the sprayed liquid (water with adjuvant) and analyze the distribution across each spacing.

The support structure for the fiberglass sheets was assembled using wood at different heights, allowing the sprayed liquid to flow into the glass containers. Each support structure was spaced 1.30 m apart, with the highest one at 0.95 m, the second at 0.60 m, the third at 0.35 m, and the fourth at 0.20 m from the ground, forming different angles (75 and 83°) (Figure 1).

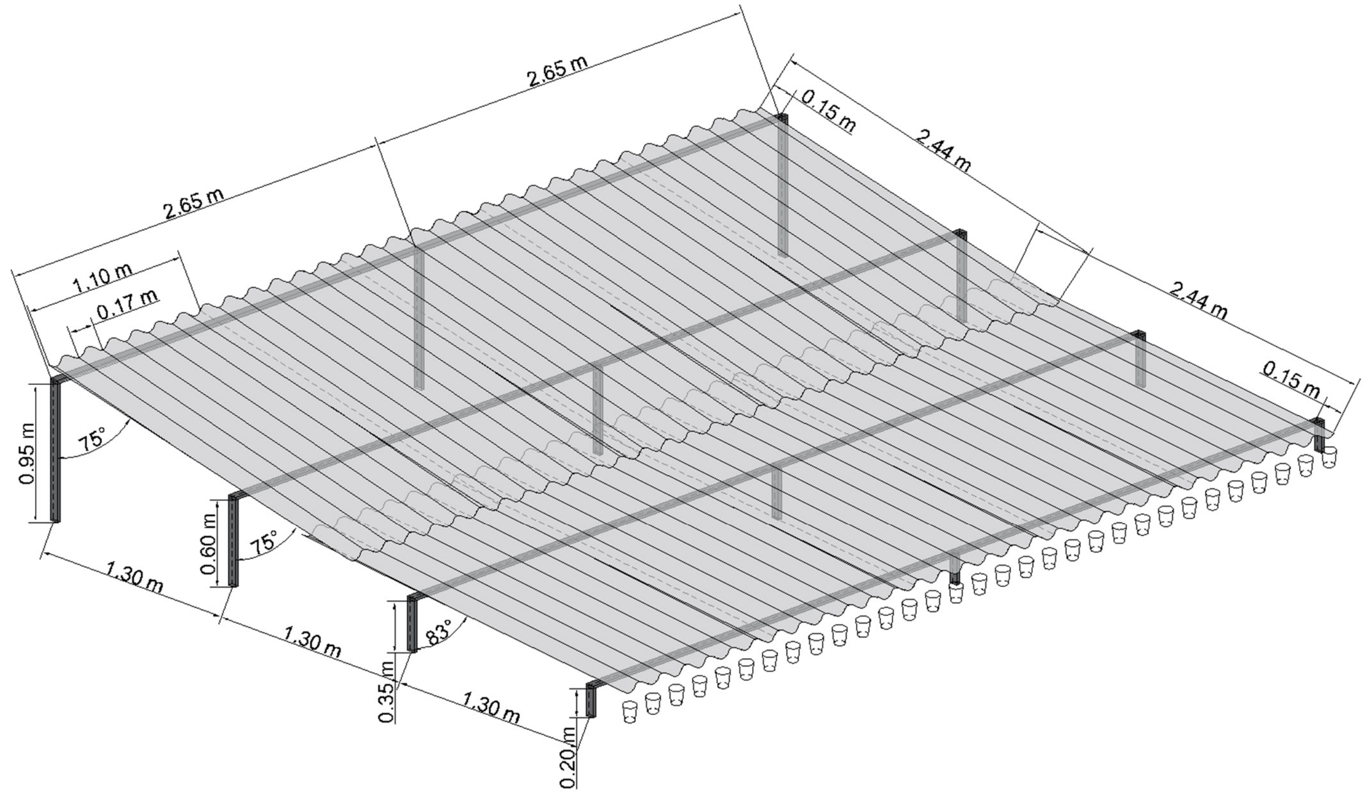

Figure 1. Illustration of the spray patternator for the spraying drone, side view with the respective spacings and heights of each slat and stake in meters.

2.3. Experiment I

Considering that application volume combined with flight height can alter the spray distribution pattern [28], this experiment aimed to evaluate the impact of different flight heights and application volumes on volumetric distribution and spray swath. A total of 12 treatments were tested in a two-factor factorial design, with four spray volumes (8, 12, 16, and 20 L ha^{-1}) and three flight heights (2, 3, and 4 m), each with three replications in a randomized block design. The center of the spray patternator was used as a reference to ensure consistency across treatments. In all experiments, the drone sprayed the liquid on the distribution table for 3 min, after which the collected liquid was measured using a graduated cylinder.

The flow rate of each nozzle was not considered as a variable in this study, since when using different application volumes with drones, the flow rate is automatically adjusted, making standardization difficult due to the number of nozzles activated for each selected volume. In all tested volumes, four nozzles were activated, except for the 8 L ha^{-1} volume, which used two nozzles, resulting in a flow rate of 0.71 L min^{-1}. For the other spray volumes (12, 16, and 20 L ha^{-1}), four nozzles were used, providing flow rates of 1.20, 1.42, and 1.79 L min^{-1}, respectively.

2.4. Experiment II

Knowing that the nozzle type can alter the spray distribution pattern, as well as the height at which the spraying is performed [29], this experiment aimed to evaluate the volumetric distribution profile by combining different flight heights with fan- and cone-type nozzles.

The spray nozzles used in this study were an FV 110 015 fan-type nozzle with a 110° spray angle and a flow rate of 0.57 L min^{-1}, an FL 110 010 fan-type nozzle with a 110° spray angle and a flow rate of 0.38 L min^{-1}, and a CO 080 010 cone-type nozzle with an 80° spray angle and a flow rate of 0.38 L min^{-1}. These nozzles differ mainly in droplet size and flow rate, which are key factors influencing product deposition and drift potential.

The FV 110 015 nozzle (Jacto, Pompéia, SP, Brazil) has a higher flow rate and produces very coarse droplets, making it more suitable for soil-applied herbicides as it reduces drift. The FL 110 010 nozzle (TeeJet Technologies, Springfield, IL, USA) generates fine droplets and is widely used due to its balance between coverage and drift control. The CO 080 010 nozzle (TeeJet Technologies, Springfield, IL, USA) has a smaller spray angle and a lower flow rate, resulting in fine droplets, which enhance crop coverage but pose a higher drift risk under unfavorable conditions.

The classification of these nozzles according to the American Society of Agricultural and Biological Engineers (ASABE) [30], including their respective volumetric median diameters (VMDs), is presented in Table 1.

Table 1. Types of nozzles used in this study with their respective flow rates, spray angles, colors, volumetric median diameters, and droplet spectrum classifications.

Nozzle Type	Flow Rate (L min^{-1})	Spray Angle (°)	Color	VMD (µm)	Classification
FV 110 015	0.57	110	Green	404–502	Very Coarse
FL 110 010	0.38	110	Orange	106–235	Fine
CO 080 010	0.38	80	Orange	106–235	Fine

Similarly to Experiment I, the same flight heights (2, 3, and 4 m) were used, with a standardized application volume of 12 L ha^{-1} for all tested nozzle type combinations. The experiment was conducted with three replications in a two-factor factorial design (nozzle types × flight heights) within a randomized block design.

2.5. Experiment III

Since application volume can alter the spray distribution pattern [28], primarily by affecting operating pressure and droplet formation, and considering that nozzle type also influences spray distribution in applications using hydraulic nozzles [29], the third experiment evaluated the impact of different spray nozzle and application volume combinations on volumetric distribution and spray swath width.

Thus, the three spray nozzle types previously reported in Experiment II (FV 110 015, FL 110 010, and CO 080 010) were combined with three application volumes (12, 16, and 20 L ha^{-1}). Each treatment included three replications, forming a two-factor factorial design within a randomized block design. As mentioned in the previous experiments, the flight height was standardized at 3 m, with the spraying system activated for 3 min and the equipment positioned at the center of the spray patternator.

2.6. Measurement of Weather Conditions

The meteorological conditions were measured before, during, and after each application for all treatments using a digital thermo-hygrometer (AKSO, São Leopoldo, RS, Brazil), which provided data on temperature (°C) and relative humidity (%). Simultaneously, wind speed (km h^{-1}) was measured using a digital anemometer (AKSO, São Leopoldo, RS, Brazil). The equipment was positioned 5 m from the experimental area. Whenever the conditions were irregular or unfavorable, the application was postponed until environmental conditions stabilized—specifically, temperature between 20 and 30 °C, relative humidity between 70 and 90%, and wind speed below 10 km h^{-1}.

2.7. Analyzed Variables and Data Processing

For the experiments, a spray mixture was prepared containing water and 20 mL of the drift-reducing and wetting adjuvant Vitaphix Power (Satis Indústria e Comércio Ltda., Araxá, MG, Brazil). This additive was used to enhance droplet deposition on the spray patternator and facilitate liquid runoff into the collectors. After each replication, a waiting period of approximately 10 min was observed to ensure complete runoff of the mixture. Subsequently, a graduated cylinder (2 mL precision) was used to measure the collected volumes at each position. This same procedure was followed for all treatments, ultimately determining the volumetric distribution and the collected volume (mL) at each position.

The collected values at each position were used to calculate the spray swath width (meters) by multiplying the positions with collected volume by the distance (0.17 m). On the other hand, to measure application uniformity, the coefficient of variation (CV%) (1) was calculated by comparing each position and the overall treatment.

$$\text{CV\%} = \left(\frac{\text{Standarddeviation}}{\text{Mean}}\right) \times 100 \tag{1}$$

These evaluated parameters were compared using histograms and bar plots to understand the spray distribution pattern. Subsequently, an analysis of variance (ANOVA) was performed for spray swath width and CV% by F-test ($p \leq 0.05$). Significant values found were grouped using the Scott–Knott test ($p \leq 0.05$). All analyses were conducted using the R Studio program (R 4.4.1. Project for Statistical Computing, 2025).

3. Results and Discussion

The meteorological conditions recorded during the treatments did not present any critical factors within the evaluation period. The observed conditions included a minimum temperature of 21.2 °C and a maximum of 29.7 °C, with relative humidity ranging from 59 to 78%, and wind speed either absent or reaching up to 0.3 m s^{-1}. The flight operations were conducted between 07:00 and 10:00 AM and between 05:00 and 08:00 PM. The selection of these time periods ensured favorable spraying conditions, maintaining relative humidity above 55%, wind speed between 2 and 10 km h^{-1}, and temperatures ranging from 20 to 30 °C [31].

3.1. Volumetric Distribution

The volumetric distribution of spraying, considering different combinations of flight height (2 m, 3 m, and 4 m) and application volume (8, 12, 16, and 20 L ha^{-1}), exhibited different behaviors among treatments (Figure 2). It was observed that as flight height increased (3 and 4 m), the aerodynamic effect of the downward airflow generated by the drone's motors influenced the spray pattern, leading to a more uniform distribution. Additionally, higher application volumes resulted in greater deposition at the center of the spray swath, suggesting better target surface coverage compared to lower volumes (8 L ha^{-1}). These findings align with previous studies, which emphasize the importance of adjusting flight height and application volume to optimize spray distribution and minimize losses due to drift [11,12].

When the spray nozzles were tested in combination with flight heights (Figure 3), the results indicated variations in the deposition pattern among the tested nozzles. Some models, such as FV 110 015, showed a higher concentration of spray solution in the central region of the swath, whereas others, like FL 110 010 and CO 080 010, provided a more uniform distribution across the sprayed area. Additionally, flight height influenced lateral droplet dispersion for all nozzle types, reinforcing the need for operational adjustments to ensure uniform spraying. The selection of the appropriate nozzle is a key factor in drone spraying, as it directly affects droplet size, deposition pattern, and drift reduction [15].

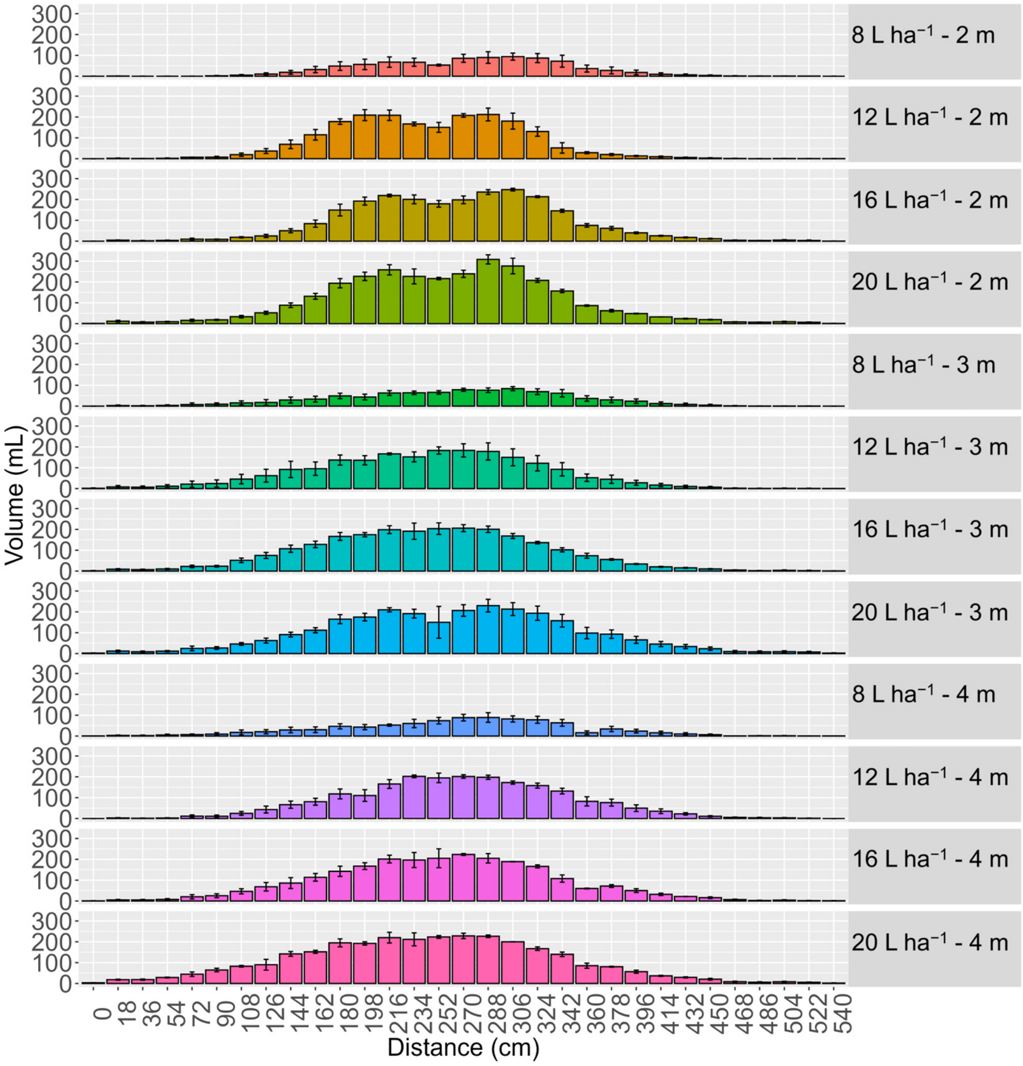

Figure 2. Volumetric distribution of the spraying drone with different application volumes (8, 12, 16, and 20 L ha^{-1}) and flight heights (2, 3, and 4 m) in Experiment I.

In the interaction between application volume and nozzle type in volumetric spray distribution (Figure 4), it was observed that higher application volumes (20 L ha^{-1}) resulted in greater total spray deposition, with higher central concentration and lower deposition variability. On the other hand, lower application volumes (12 L ha^{-1}) promoted a more homogeneous distribution but may have led to reduced coverage in the central area of the spray swath. Additionally, the distribution pattern was strongly influenced by the nozzle type, emphasizing the need for adjusting these variables together to optimize droplet deposition and minimize spraying variations. The FV 110 015 nozzle, which has a higher flow rate and produces very coarse droplets, showed greater concentration of collected volumes at the center of the swath for all application volumes.

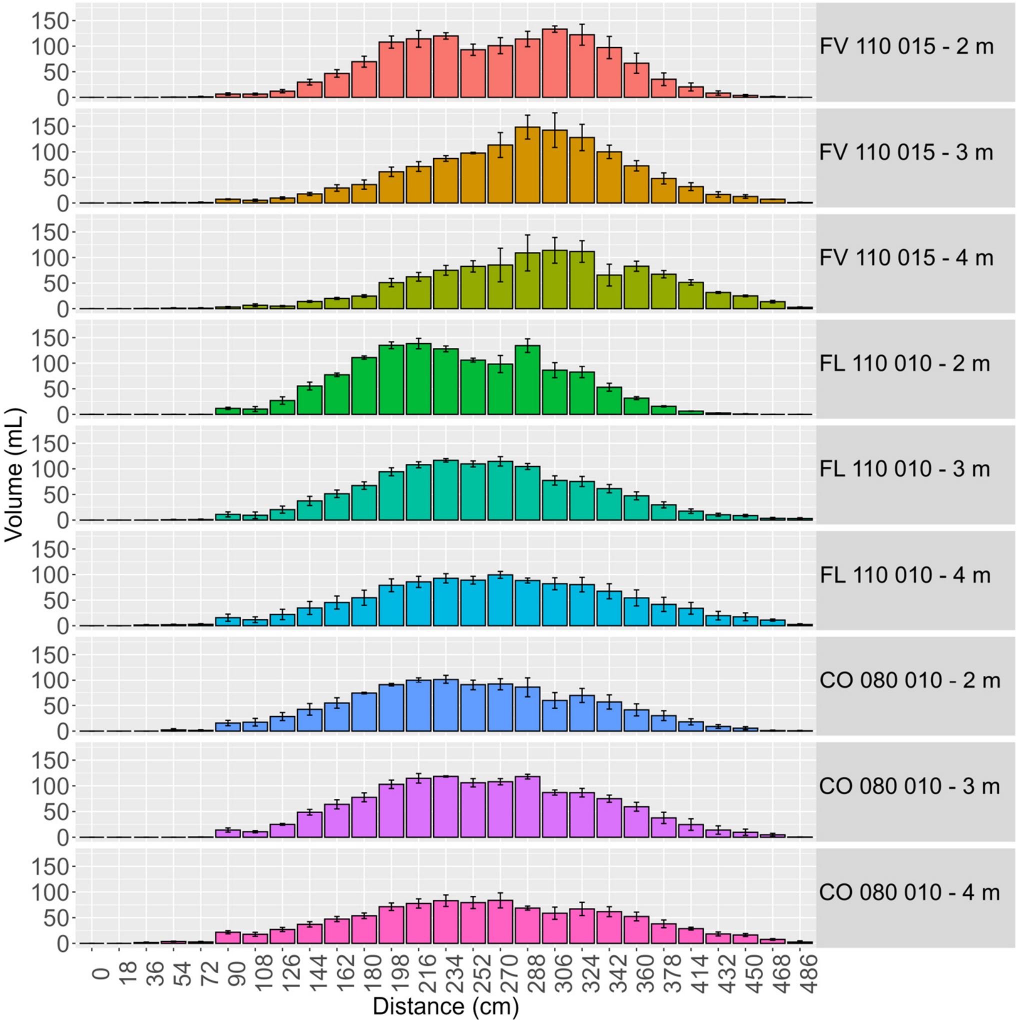

Figure 3. Volumetric distribution of the spraying drone with different nozzle types (FV 110 015, FL 110 010, and CO 080 010) and flight heights (2, 3, and 4 m) in Experiment II.

The results highlight the importance of selecting the appropriate flight height to optimize the uniformity of pesticide application by drones. In Experiment I, it was observed that a flight height of 2 m resulted in greater variation at the center of the spray swath, while heights of 3 and 4 m provided a more uniform distribution. This finding aligns with previous studies using flat-fan nozzles at a 1 m flight height, which reduced application uniformity [22]. This effect may be related to the flight dynamics of spraying drones and the interaction between the drone's airflow (downwash effect) and the distribution of the applied product.

When the flight occurs at a height of 2 m, the sprayed droplets become more susceptible to air turbulence due to their proximity to the target. This turbulence can lead to less uniform product dispersion, resulting in greater variation at the center of the spray swath. This phenomenon is known as the downwash effect, a downward airflow generated by the rotation of the drone's propellers, which is considered one of the main factors influencing droplet distribution and deposition [32,33].

Additionally, product dispersion tends to be wider at lower flight heights due to increased turbulence and reduced airflow stability near the target. This compromises the homogeneity of distribution, especially in the center of the spray swath. As flight height increases, dispersion becomes more stable since the airflow generated by the drone weakens before reaching the ground, reducing its impact on droplet distribution [34]. Another important factor to consider is that fine droplets, when affected by an increased downwash effect, become susceptible to collision and the formation of coalescent droplets, which in some cases can hinder droplet penetration into the plant canopy.

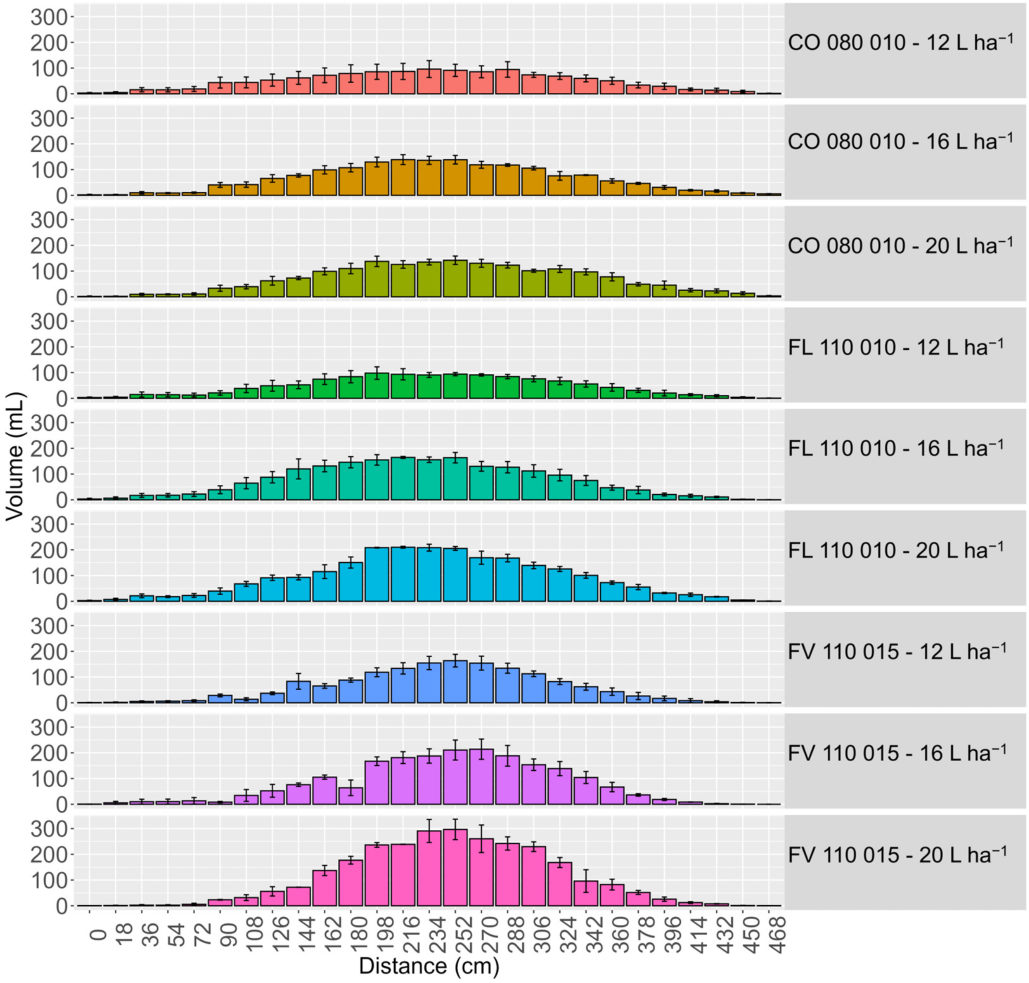

Figure 4. Volumetric distribution of the spraying drone with different nozzle types (CO 080 010, FL 110 010, and FV 110 015) and application volumes (12, 16, and 20 L ha^{-1}) in Experiment III.

In addition to the mentioned effect, hydraulic nozzles such as the flat-fan nozzle (FL 110 010) are spaced 1.5 m apart and operate with a 110° spray angle. At low flight altitudes, the downwash effect is more pronounced, especially on finer droplets, which can alter the flow direction and cause gaps in the central area of the spray swath, as observed in Experiment II. This issue becomes even more critical in fruit crop applications, which require a higher concentration of droplets in the middle or inner parts of the plants. In these cases, the wide spacing between nozzles and droplet drift compromise application efficiency.

Each drone model may exhibit specific dispersion patterns, and adjustments in the spraying system can optimize distribution at higher altitudes [22]. However, spraying at excessive altitudes can compromise product penetration into the plant canopy due to the reduced force of the airflow, which is a crucial factor in perennial crops. Additionally, environmental factors such as wind and temperature can intensify drift and evaporation, ultimately affecting application efficacy [35,36].

In Experiment II, wind speed directly influenced the application, resulting in significantly higher collected volumes in the cups positioned on the right side of the spray patternator compared to those on the left side. An increase in wind speed enhances droplet drift, requiring the use of larger droplets to mitigate drift, especially under wind conditions similar to those observed in this study.

In Experiment III, when using the FV 110 015 nozzle, which produces very coarse droplets, the highest collected volumes were observed in the central region of the spray swath. This result is attributed to the greater weight of the droplets, which reduces drift under stronger wind conditions. Additionally, increasing the spray volume led to a higher droplet density per unit area, promoting a more uniform product distribution over the plants. This improvement enhances coverage and reduces application gaps under field spraying conditions, contributing to better product penetration [23,37].

With a distribution pattern approaching a normal distribution, drone spraying, regardless of application volume, nozzle type, and flight height, proved to be more suitable for band applications, requiring overlapping spray passes to ensure complete coverage of the treated area.

3.2. Spray Swath Width

The second analyzed variable, spray swath width, varied among the experiments. Regarding spray volume, a directly proportional relationship was observed with swath width, meaning that increasing the application volume contributed to a wider spray swath, as evidenced by distribution at different flight heights in Experiment I (Figure 5). However, when application volumes and nozzle types were combined (Experiment III), no significant differences in spray swath width were observed (Figure 5).

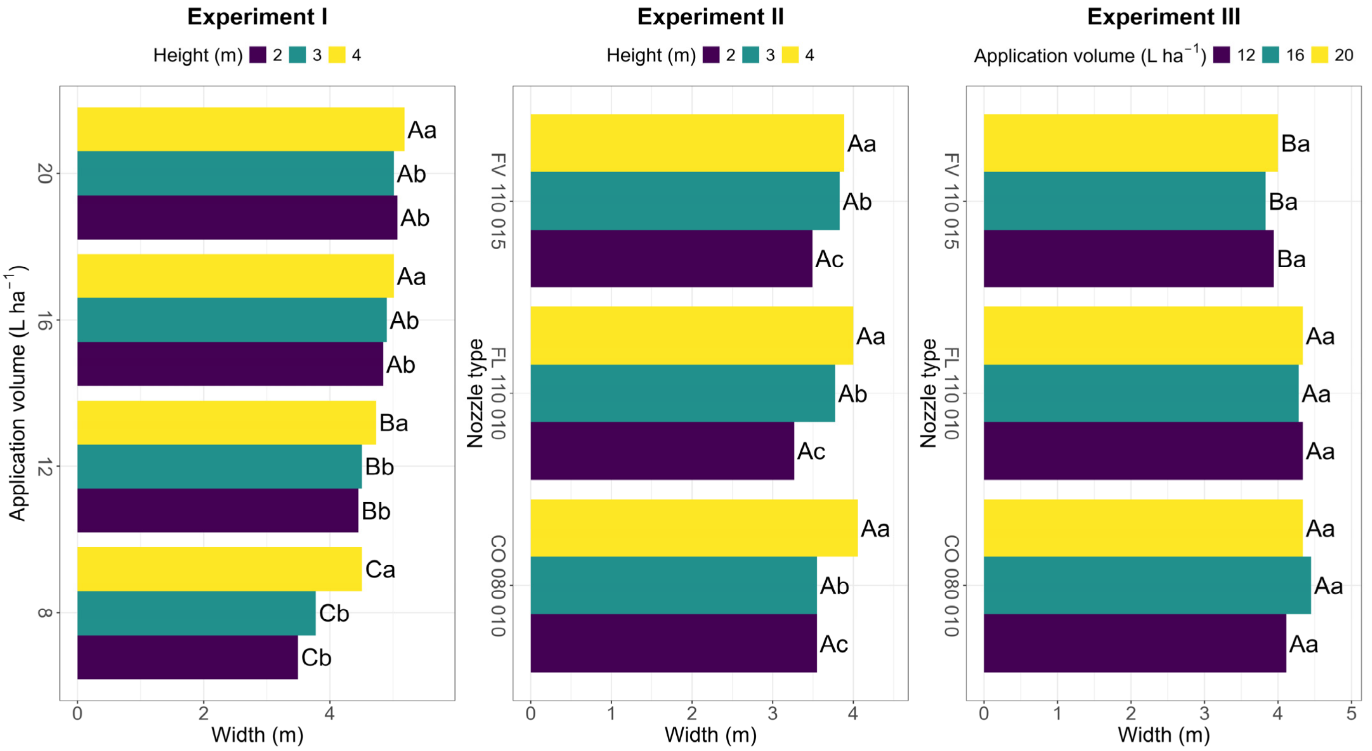

Figure 5. Spray swath width of the spraying drone for different combinations of operational parameters. Uppercase letters compare Factor 1, which refers to application volume in Experiment I, and nozzle type in Experiments II and III. Lowercase letters compare Factor 2, which refers to flight height in Experiments I and II, and application volume in Experiment III.

When varying the nozzle types, the fine droplets produced by the FL 110 010 and CO 080 010 nozzles resulted in a greater spray swath width, regardless of the application volume (Experiment III). It is important to highlight that no significant differences in spray swath width were observed when different nozzle types were combined with different flight heights (Experiment II) (Figure 5).

Nevertheless, it is worth noting that there was a significant increase in spray swath width at a flight height of 4 m, regardless of nozzle type (Experiment II), as well as with increases in application volume (Experiment I) (Figure 5).

These results reveal that the increase in spray swath width is related to the system pressure and nozzle type. That is, when application volume increases, the pressure exerted by the system on the nozzles also increases, leading to a wider spray angle [22]. Additionally, the production of fine droplets, particularly with orange-labeled nozzles, makes them more susceptible to dispersion due to the downwash effect, further expanding the working swath [22,32].

Additionally, when analyzing uniformity, excessive application volumes can cause greater variations in the system, resulting in lower uniformity. To control this effect, adjusting flight height along with other operational parameters is an effective strategy for achieving optimal spraying [22,38,39].

These results highlight the complexity of the interaction between flight height, application volume, nozzle type, and spray swath width. While in some specific cases, significant differences were observed ($p < 0.05$), whereas in other cases, variations were not as pronounced. This variability reinforces the importance of considering multiple factors when optimizing drone spraying efficiency and its relationship with treated area coverage. Moreover, these findings indicate the need for further studies to maximize the operational efficiency of spraying drones.

3.3. Coefficient of Variation

The third evaluated metric was the coefficient of variation (CV%). The experiments showed different values for each analyzed parameter. In Experiment I (Figure 6), with an application volume of 8 L ha^{-1}, in Experiment II, using the hollow cone nozzle (CO 080 010), and in Experiment III, using the hollow cone nozzle (CO 080 010) with an application volume of 12 L ha^{-1}, the lowest CV% values were observed, indicating higher application uniformity.

When comparing application volumes, it was found that higher volumes increased CV%, as observed for 16 and 20 L ha^{-1} in Experiments I and III, respectively, reducing application uniformity. However, flight heights did not influence uniformity, as observed in Experiments I and II.

When these parameters were associated with nozzle types, it was observed that nozzles producing fine droplets (CO 080 010 and FL 110 010) had the lowest CV% values, according to Experiments II and III. Thus, the hollow cone nozzle (CO 080 010) stood out as the most efficient in terms of low CV%, and when combined with low application volumes (12 L ha^{-1}), the lowest CV% values were recorded (Figure 6). On the other hand, nozzles producing very coarse droplets (FV 110 015) had the highest CV% values, meaning that uniformity was reduced when this nozzle type was used.

Despite the impact of the parameters on droplet distribution and CV%, no significant results were observed for flight height. Thus, the present study suggests that deeper insights could be obtained if the three-way interaction between parameters were analyzed. However, when an additional parameter is introduced (droplet size or spray nozzle type), new challenges arise, as multiple parameter selections occur simultaneously during applications.

These results highlight the complex interaction between flight height, application volume, and spraying dynamics, factors that directly affect the uniformity of product distribution [23]. Although our experiment did not show significant differences in CV% for different flight heights, it is well known that increasing flight height contributes to a higher drift potential [23], which negatively impacts spraying efficiency.

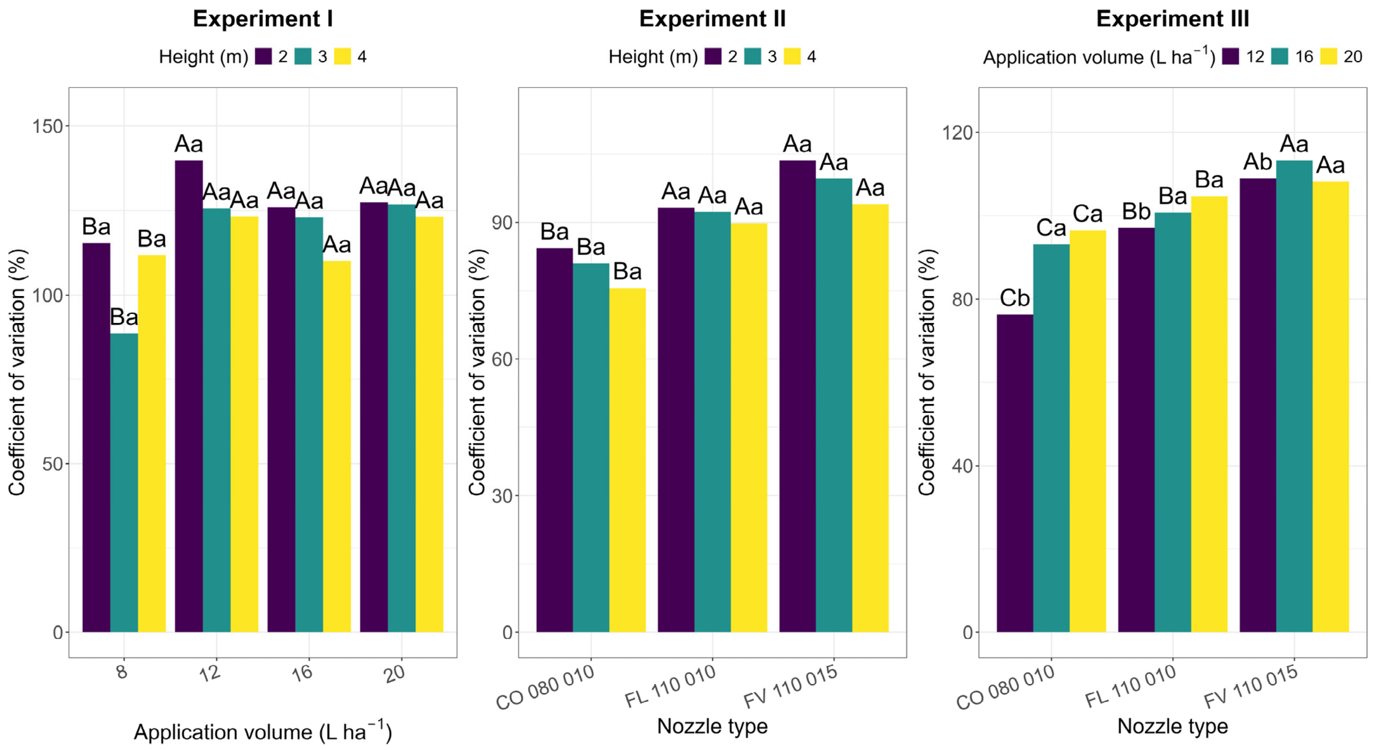

Figure 6. Coefficient of variation (CV%) of the volumetric distribution of the spraying drone for different combinations of operational parameters. Uppercase letters compare Factor 1, which refers to application volume in Experiment I, and nozzle type in Experiments II and III. Lowercase letters compare Factor 2, which refers to flight height in Experiments I and II, and application volume in Experiment III.

Additionally, high CV% values are frequently observed in agricultural spraying operations. Various studies using low application volumes report high CV% values, which are also attributed to environmental conditions in the field during spraying [21,40,41]. This variability poses a challenge for research, making it difficult to precisely determine the overlap in the total sprayed area. This aspect highlights the need for improvements in calibration techniques and operational control, as well as the consideration of environmental conditions, to ensure better results.

Regular drone calibration, performed on a dedicated calibration table, is a key strategy to optimize product use, minimizing waste and reducing operational costs. This practice is crucial for the sustainability of agricultural operations, as precise calibration prevents both under-application and over-application of products, ensuring greater efficiency in crop management and reducing undesirable environmental impacts. Thus, the use of a spray patternator for drones is directly linked to efficiency, quality, compliance, and the economic viability of agricultural spraying operations.

4. Conclusions

In this study, we evaluated the spray swath, uniformity, and volumetric distribution of a spraying drone under different configurations—nozzle types, application volumes, and flight heights—using a spray patternator.

Our results indicate that flight height does not influence uniformity but is directly proportional to spray swath width. In contrast, higher application volumes, such as 20 L ha^{-1}, increase the spray swath width but reduce uniformity.

When nozzle type was also considered, the hollow cone nozzle, such as the CO 080 010, showed the best overall performance, producing fine droplets that are efficiently carried by the downwash effect. However, as observed in Experiments II and III, increasing the flight height to 4 m or the application volume to 20 L ha^{-1} can make these fine droplets more susceptible to drift.

Additionally, the volumetric distribution tests highlight those operational parameters—flight height, application volume, and nozzle type—constantly interact with each other and with environmental conditions. Therefore, evaluating any parameter in isolation is not sufficient to optimize spraying applications.

Therefore, adopting a nozzle that produces fine droplets (such as the CO 080 010), combined with lower application volumes (such as 8 and 12 L ha^{-1}) and a higher flight height (4 m), contributes to increasing the efficiency of drone spraying; however, this combination may also raise the risk of drift.

These insights reinforce the importance of a holistic approach, considering multiple operational factors to achieve efficient and precise aerial spraying.

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