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EFFECTS OF EXIT ORIFICE DIAMETER, SPRAY PRESSURE, AND SPRAY HEIGHT ON THE SPRAY CHARACTERISTICS OF AN AGRICULTURAL SWIRL NOZZLE

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ABSTRACT

This study investigated the impact of exit orifice diameter, spray pressure, and spray height on the spray characteristics of an agricultural swirl nozzle, utilizing image processing to identify optimal nozzle design and operating conditions that enhance atomization efficiency and improve spray performance. The research evaluated the effects of four orifice diameters (1, 2, 3, and 4 mm), four spray pressures (100, 150, 200, and 250 kPa), and three spray heights (40, 60, and 80 cm) on average droplet size, spray angle, and spray uniformity. The Nikon 750 JP, equipped with a 24.3-megapixel sensor, was used to capture spray patterns under varying operating conditions. Python-based algorithms were employed to analyze the spray patterns and quantify droplet distribution. The images processed reveal that Orifice diameters of 1 mm and 2 mm produce relatively smaller droplets (0.1295 mm and 0.0523 mm, respectively), while orifice diameters of

3 mm and 4 mm generate larger droplets (0.1569 mm and 0.1347 mm, respectively). Spray angle increases with increasing orifice diameter, from 10.59° at 1 mm to 42.07° at 4 mm. Spray uniformity improves as the orifice diameter increases from 1 mm to 3 mmm but drops slightly at 4 mm. Increase in spray pressure tends to decrease droplet size. The largest droplets were observed at 40 cm (0.1909 mm), with size decreasing significantly at 60 cm (0.1104 mm) and 80 cm (0.0529 mm). Spray height primarily influenced droplet size, with 60 cm being the optimal spray height, resulting in the most uniform spray coverage. Beyond 60 cm, uniformity declines, suggesting reduced precision at greater heights. These findings provide valuable insights for optimizing nozzle design and operating conditions to enhance spray performance and efficiency in agricultural applications.
Keywords: Agricultural swirl nozzle, Exit orifice diameter, Spray height, Spray pressure

INTRODUCTION

Accurate and efficient spray-delivery systems are vital for ensuring effective application of pesticides and nutrients while minimizing environmental impact and resource waste (Rahimi *et al*., 2024). Among the various components influencing spray performance, the design and operational parameters of spray nozzles are critical (Hosamani and Krishnamurthy, 2020). Swirl nozzles, which introduce a tangential flow to generate a hollow cone spray pattern, have gained popularity due to their ability to produce uniform droplet distribution and cover larger surface areas (Gao *et al*., 2011). One of the most influential design factors is the exit orifice diameter, which directly affects the velocity and volume flow rate of the spray. Similarly, spray pressure determines the energy available for atomization, which in turn impacts droplet size and spray dispersion. Additionally, the spray height, which is the vertical distance between the nozzle and the target, affects the travel time and dispersion of droplets, thereby influencing coverage uniformity and drift potential (Chen *et al*., 2020). Despite existing studies on nozzle performance, there is a limited comprehensive analysis of the interactive effects of these three parameters: exit orifice diameter, spray pressure, and spray height, particularly in the context of swirl nozzles adapted for agricultural use. This study aims to fill this gap by experimentally evaluating how variations in these parameters influence key spray characteristics, including droplet size, spray angle, and uniformity. The outcomes are expected to guide farmers, agricultural engineers, and policymakers in selecting and optimizing spraying systems for efficient and sustainable field applications.

Agricultural spray nozzles are critical components in pesticide application, influencing spray coverage, droplet size distribution, and drift potential. Recent experimental studies have focused on pressure swirl nozzles, which produce hollow cone sprays with fine atomization. Xue *et al.* (2023) investigated full-cone pressure swirl nozzles, analyzing droplet size, velocity, and liquid volume flux under varying Reynolds numbers, demonstrating the sensitivity of spray characteristics to operating conditions. Similarly, Han *et al.* (2024) conducted detailed experimental studies on pressure-swirl nozzles, focusing on flow rates and pressure drops relevant to industrial applications, which provided insights into the atomization mechanisms and spray morphology. Zhang *et al.* (2017) further investigated the effects of nozzle diameter and injection pressure on spray angle and morphology, confirming that nozzle geometry has a significant impact on spray behavior.

In the context of agricultural applications, Harikant *et al*. (2023) reviewed adjustable flow and rotating spray nozzles, emphasizing their potential to enhance spray uniformity and reduce drift through controlled fluid dynamics and spray motion. Their work highlights the importance of innovative nozzle designs in overcoming the limitations of conventional nozzles, enabling precise and efficient spraying. Optimization studies, such as those by Kumar *et al.* (2020), have evaluated nozzle characteristics, including pressure and height, to improve discharge rate, spray angle, and uniformity across different sprayer types. Their findings indicate that operating parameters have a significant influence on spray performance and that specific combinations of pressure and nozzle height yield optimal results for various sprayers. Çetin *et al.* (2019) conducted a study on the determination of spray angle and flow uniformity of spray nozzles with diverse hydraulic spray nozzles at different spray pressures with the aid of image processing operations based on the indices of spray images, which were obtained with a digital camera to verify spray patterns and spray angles using different image processing software for analysis. The study found that the pattern of spray captured using the image processing method was homogeneous, with uniformity of flow achieved through the line-profile method. Their study concluded that the pressures of spray had a significant impact on spray angles, with $p < 0.05$ for all spray nozzles.

MATERIALS AND METHODS

Experimental material and setup

The experimental setup incorporated several essential components to ensure precise data collection and analysis. A Nikon 750 JP camera, featuring a 24.3-megapixel resolution, was used to capture high-resolution images with excellent detail and dynamic range. The camera is capable of continuous shooting at a rate of up to 6.5 frames per second, making it suitable for documenting rapid spray events. To ensure image stability and eliminate motion blur during capture, the camera was mounted on a tripod stand, which provided a secure and steady base throughout the experimental process. A custom-designed test rig was utilized to support the experimental evaluation of the swirl nozzles. This rig provided controlled testing conditions, enabling the accurate assessment of nozzle performance. Water was used as the testing fluid in this study, chosen for its consistency, availability, and suitability for evaluating the atomization and spray characteristics of agricultural nozzles under controlled laboratory conditions (Ou et al., 2024).

Description of swirl nozzle

The swirl nozzle (Figure 1) consists of the nozzle body or sleeve. This swirl element is a cylindrical plug that has a helical liquid passage groove mounted on it, the orifice disk with a nozzle exit orifice, the hexagonal nut acting as a securing cap for the orifice disk, a swirl chamber, a pair of tapered roller bearings, a rubber gasket seal, and an end cap at the other end of the nozzle. The nozzle was connected to a supply line through the tangential inlet port. The securing cap of the nozzle holds the exit orifice securely in place. The securing cap features a hexagonal body and a screw thread on the interior part, facilitating easy removal and installation of the orifice plate with the use of a specially fabricated open-end wrench (flat spanner). One ball bearing is located on the upper nozzle body, while the second bearing is located in the lower nozzle body. This arrangement enables the cantilevered swirl element to rotate freely within the upper nozzle body when actuated by the inflowing pressurized liquid stream entering the nozzle through the tangential inlet port.

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Experimental Procedure

The experiment was conducted in a controlled laboratory environment to observe and analyze the behavior of the spray pattern. A Nikon D750 DSLR camera was used for high-speed image capture to determine the key spray characteristics, including droplet size, spray angle, and uniformity through image processing techniques. The camera was securely mounted on a tripod stand and configured with a high shutter speed of up to 1/14,000 seconds to accurately freeze and document the motion of the spray. To ensure optimal visibility and image clarity, appropriate lighting was provided using a combination of artificial light sources. The collected images were transferred to a personal computer for image analysis using Python source code to determine droplet sizes, spray angle, and spray uniformity.

Experimental Design and Statistical Analysis

The study considered three independent variables: nozzle exit orifice diameter at four levels (1, 2, 3, and 4 mm), operating pressure at four levels (100, 150, 200, and 250 kPa), and spraying height at three levels (40, 60, and 80 cm) randomized using Optimal design of design expert (Version 13). The data obtained from the experiment were analysed using the Statistical Package for the Social Sciences (SPSS) software. The Duncan multiple range test was used to separate the means of spray characteristics and mean plot were used to identify the relationships between nozzle exit orifice diameter, operating pressure, and spraying height, as well as their effects on spray characteristics.

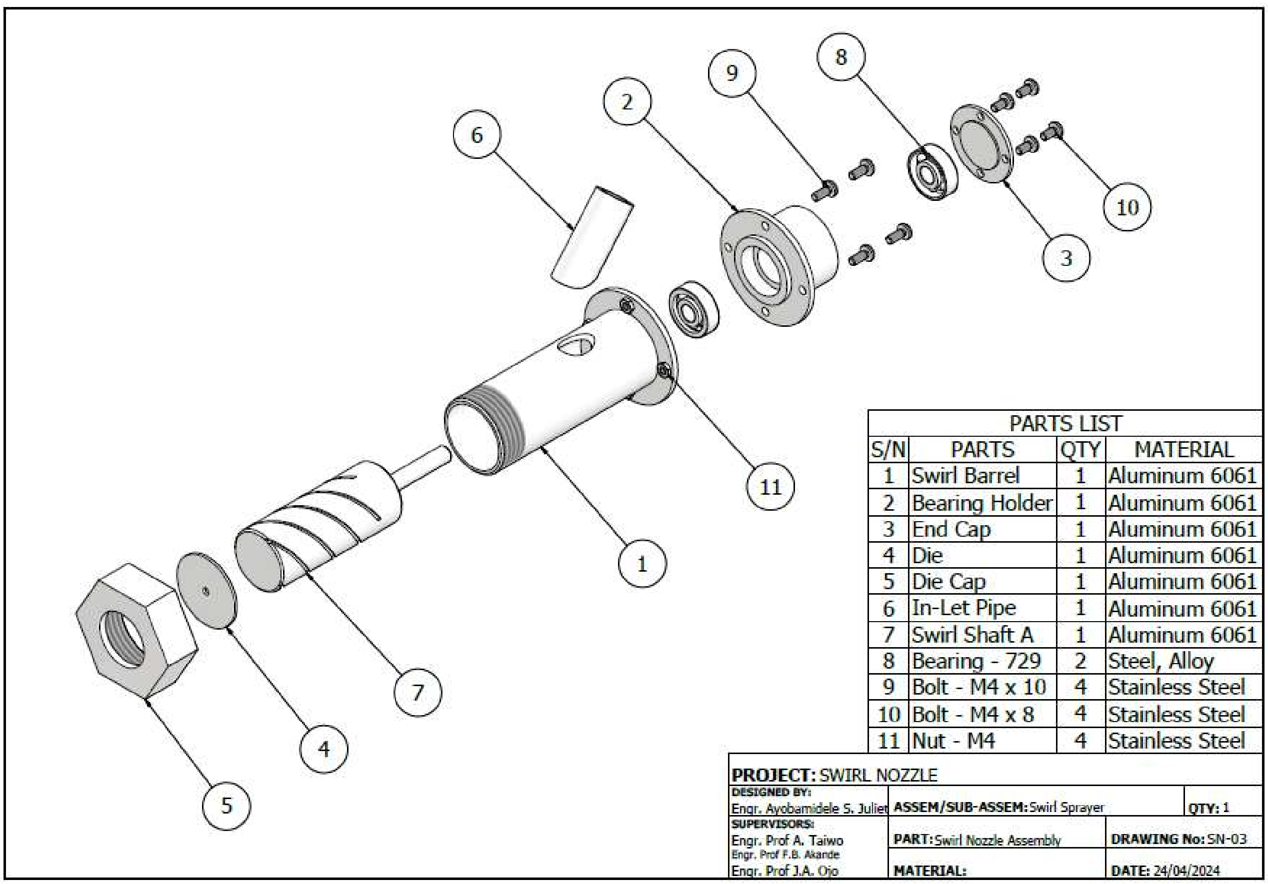

Figure 1: Exploded diagram of the Swirl Nozzle

RESULTS AND DISCUSSION

Result of Spray Characteristics

The results of spray characteristics arranged using Duncan Multiple Range (DMR) method is presented in Table 1. From the table of results, it is shown that orifice diameter has the most significant impact on both spray angle and spray uniformity, with larger diameters producing wider spray angles and more uniform spray patterns. While spray pressure tends to improve spray uniformity slightly, it has no significant effect on droplet size or spray angle. The spray height exhibits a trend in which droplet size decreases as height increases, and spray uniformity peaks at an intermediate height of 60 cm; however, these differences are not statistically significant. Overall, larger orifices consistently yield wider spray angles and improved uniformity, while droplet size remains relatively unchanged. Higher spray pressure enhances uniformity but has a limited influence on droplet size and spray angle within the tested range. Additionally, a spray height of 60 cm provides the best balance between spray angle and uniformity, whereas increasing height generally leads to smaller droplet sizes. These findings align with the study by Santosh et al. (2023), which reported that droplet size decreases with increasing pressure, spray uniformity improves with higher pressure, and spray angle varies according to nozzle height. Figure 2 shows spray images taken at different height, orifice diameter, and spray pressure combinations

Table 1: Result of spray characteristics arranged using DMR method

	Average droplet size	Spray angle	Spray uniformity
Orifice diameter			
1	0.0544^{a}	21.1120^{a}	2.5900^{a}
2	0.0371^{a}	30.8750^{ab}	6.1000^{b}
3	0.0547^{a}	39.4050^{b}	6.9625^{b}
4	0.0526^{a}	52.9925^{c}	5.8125^{b}
Spray pressure			
100	0.0532^{a}	33.1725^{a}	3.2250^{a}
150	0.0488^{a}	33.7920^{a}	4.9600^{a}
200	0.0513^{a}	36.4350^{a}	6.2250^{a}
250	0.0470^{a}	37.8150^{a}	6.4625^{a}
Spray height			
40	0.0688^{a}	32.4317^{a}	4.3167^{a}
60	0.0449^{a}	38.6050^{a}	6.3333^{a}
80	0.0335^{a}	34.4860^{a}	4.9100^{a}

Means with the same letter(s) are not significantly different from each other. ($p \leq 0.005$)

Figure 2: Spraying pattern of the nozzle at different heights

Effect of Orifice Diameter on Spray Characteristics

A. Average droplet size

The graph in Figure 3 highlights that an orifice diameter of 2 mm is optimal for achieving the smallest average droplet size, which is advantageous in applications requiring fine misting or uniform coverage. This observation aligns with the findings of Karabey and Tanış (2024), who noted that intermediate orifice diameters typically produce more favorable droplet size distributions compared to very small or large diameters.

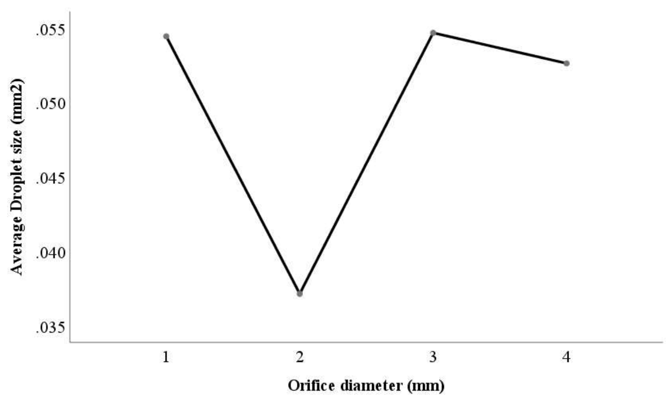

Figure 3: Effect of orifice diameter on average droplet size

B. Spray angle

Figure 4 shows that as the orifice diameter increased, the spray angle became wider steadily and consistently, indicating a strong and direct relationship between these variables. Therefore, in practical applications, selecting a nozzle with a larger orifice diameter will result in a broader spray pattern. This observation is consistent with the findings of Zheng et al. (2020), who also reported that increasing orifice diameter contributes to a wider spray angle and enhanced spray uniformity.

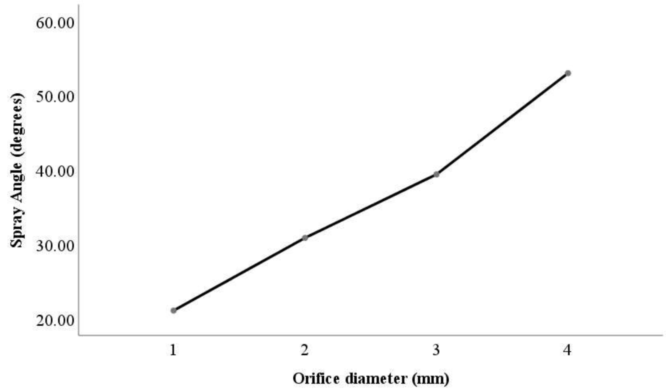

Figure 4: Effect of orifice diameter on spray angle

C. Spray uniformity

The graph in Figure 5 illustrates the relationship between orifice diameter and spray uniformity, where uniformity is expressed as a percentage. As orifice diameter increases from 1 mm to 3 mm, spray uniformity improves steadily, reaching a peak at 3 mm. This trend indicates a decrease in the coefficient of variation (CV), signifying more consistent droplet distribution and reduced variability across the spray pattern. However, at 4 mm, a slight decline in spray uniformity is observed, implying a modest increase in CV. This suggests that beyond a specific orifice diameter, the spray pattern becomes less uniform—possibly due to the formation of coarser droplets, weakened swirl intensity, or increased turbulence, which may disrupt even coverage. These observations are consistent with the findings of Chen et al. (2020) and Boel et al. (2020), who reported that increasing orifice diameter generally enhances spray distribution and cone angle up to an optimal point, after which uniformity plateaus or declines due to destabilization of the spray cone and droplet coalescence. Therefore, an orifice diameter of 3 mm appears to offer the best balance between flow rate and uniform coverage, as reflected by the lowest CV and highest spray uniformity in this study.

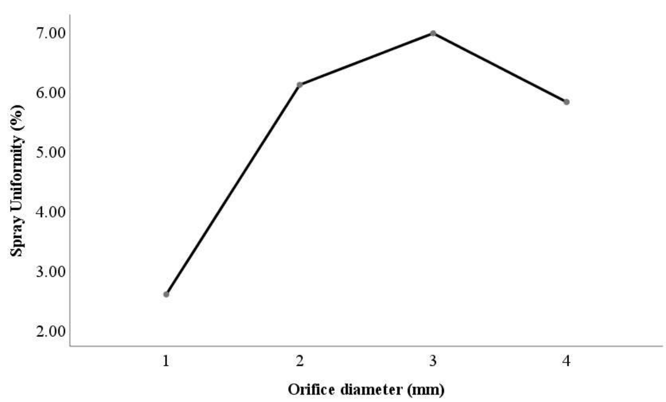

Figure 5: Effect of orifice diameter on spray angle

3.3 Effect of Spray Pressure on Spray Characteristics

A. Average droplet size

The graph shown in Figure 6 indicates that spray pressure has a variable effect on the average droplet size. Generally, increasing spray pressure tends to reduce droplet size, consistent with the principle that higher pressures promote finer atomization. However, the observed increase in droplet size at 200 kPa suggests that other factors, such as nozzle dynamics or fluid properties, may influence droplet formation at certain pressure levels. This pattern aligns with the findings of Anacleto *et al.* (2021), who reported that while higher spray pressures usually result in finer droplets, intermediate pressures can sometimes produce variable outcomes depending on the nozzle type and liquid characteristics.

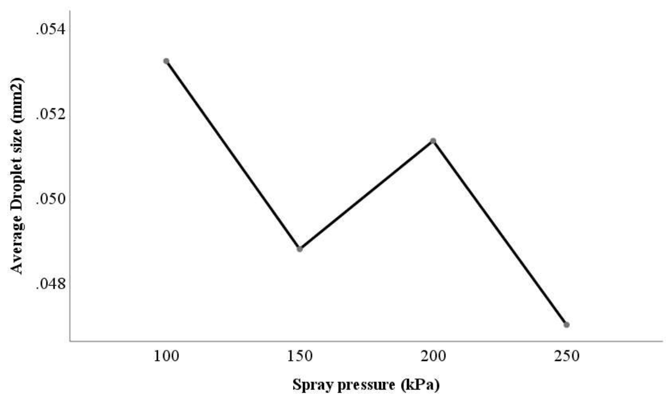

Figure 6: Effect of orifice diameter on spray angle

B. Spray angle

The graph in Figure 7 shows that increasing spray pressure resulted in a broader spray angle. This finding aligns with Santosh et al. (2023), who reported that higher spray pressure results in a broader spray angle, thereby improving coverage in agricultural spraying systems.

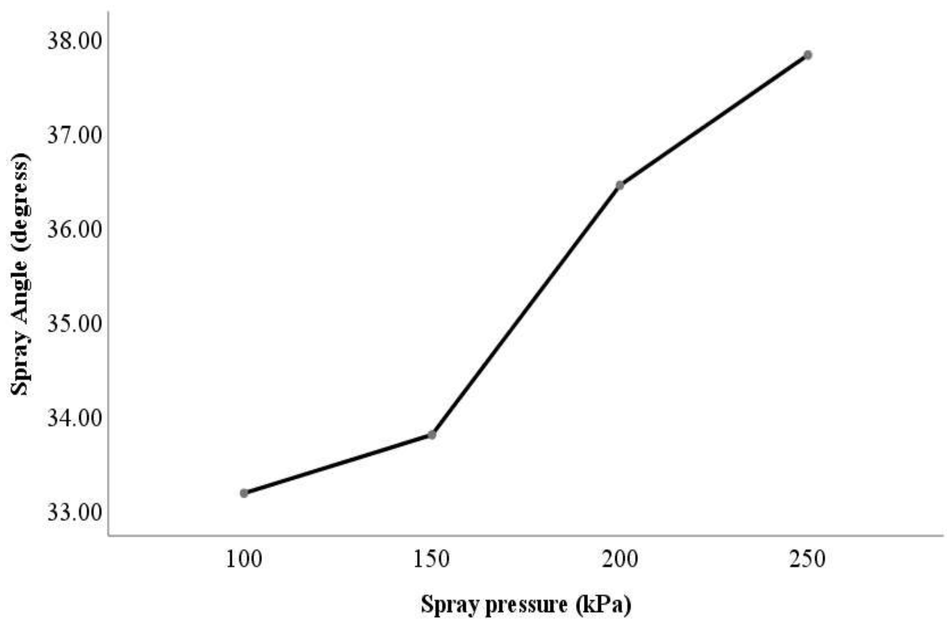

Figure 7: Effect of orifice diameter on spray angle

C. Spray uniformity

The graph in Figure 8 demonstrates the effect of spray pressure on spray uniformity. As pressure increased from 100 kPa to 250 kPa, spray uniformity consistently improved, indicating a steady reduction in the coefficient of variation (CV). This implies that higher pressures promote more uniform droplet distribution, likely due to enhanced atomization and better spray cone formation. Contrary to earlier assumptions of an optimal pressure, the graph does not show a decline beyond 200 kPa; instead, 250 kPa yields the highest spray uniformity, corresponding to the lowest CV observed in this study. This suggests that under the tested conditions, higher pressure enhances droplet breakup and uniformity of distribution, without reaching the point of over-atomization or turbulence-induced variability. These results align with those of Kole and Singh (2021), who noted that increasing spray pressure generally reduces CV, thereby enhancing spray consistency up to an operationally safe upper limit. Furthermore, the consistent improvement observed supports the findings of Lavernia et al. (2024), who highlighted that optimized pressure levels minimize drift potential and maximize chemical deposition efficiency. The results however, further emphasize the importance of selecting appropriate spray pressures to achieve high spray uniformity with minimal CV, thereby enhancing application precision, minimizing chemical waste, and supporting adequate crop coverage.

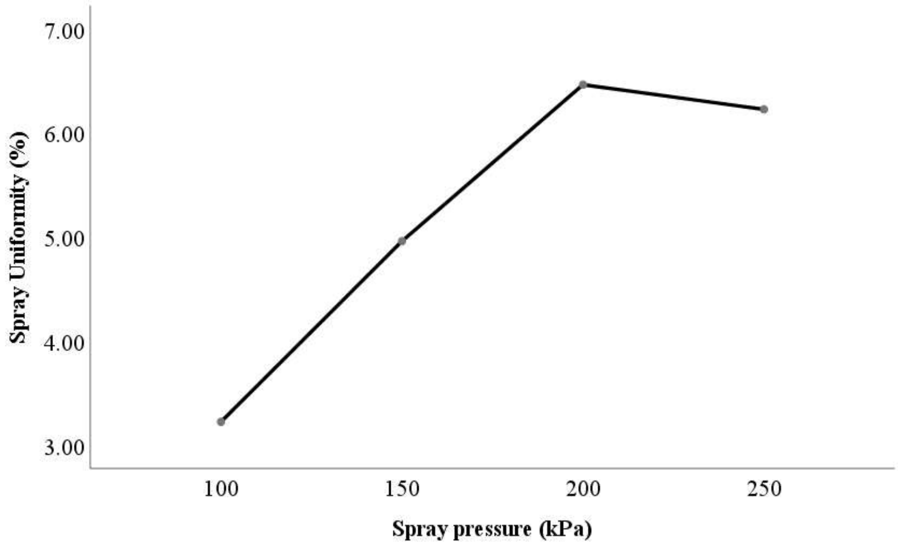

Figure 8: Effect of orifice diameter on spray angle

3.4 Effect of Spray Height on Spray Characteristics

A. Average size distribution

The average drop size as a function of spray height is presented in Figure 9. At lower heights, 40 cm, droplets had a shorter distance to travel and therefore experienced minimal breakup from air resistance or turbulence, resulting in larger droplet sizes. As the spray height increased, droplets travelled a longer path through the air, encountering greater resistance and fragmentation, which promoted droplet breakup and yields finer droplets. The smallest droplets were observed at a height of 80 cm, indicating that higher spray heights enhance atomization. This observation aligns with the findings of Tesfaye et al. (2016), who reported that increasing nozzle height significantly reduces droplet size, especially for hollow-cone and flat-fan nozzles.

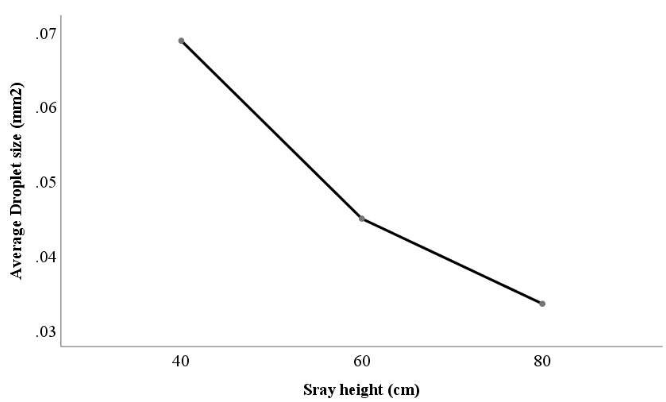

Figure 9: Effect of orifice diameter on spray angle

B. Spray angle

As shown in Figure 10, spray angle increased with height up to an optimal point at 60 cm, after which it began to decline. This suggests that 60 cm is the most efficient height for achieving the widest spray dispersion. Such behavior indicates the presence of an optimal spray height, around 60 cm, that maximizes lateral dispersion and coverage, which is crucial for achieving effective application uniformity. These findings align with those of Santosh et al. (2023), who found that spray height significantly influences spray angle and coverage, with medium heights providing the most effective dispersion.

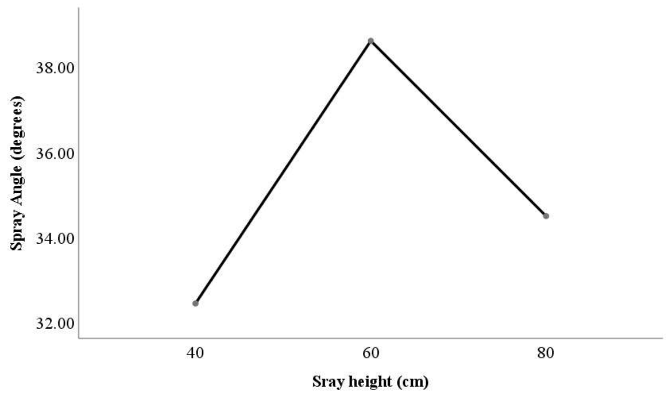

Figure 10: Effect of orifice diameter on spray angle

C. Spray uniformity

The graph in Figure 11 depicts that spray height has a significant effect on spray uniformity, with 60 cm emerging as the optimal height for achieving the most consistent spray distribution. This corresponds to the lowest coefficient of variation (CV) among the tested heights, indicating minimal variation in droplet deposition and a more uniform spray pattern. At lower heights (40 cm), the CV is relatively higher, implying reduced uniformity due to restricted spray dispersion and possible overlap or pooling. Conversely, at higher heights (80 cm), CV increases again, reflecting greater inconsistency in droplet distribution likely caused by increased drift, air resistance, or turbulence that disrupts uniform coverage. These findings align with Pan et al. (2016), who reported that excessive nozzle height introduces drift and coverage irregularities, and Singh et al. (2024), who found that drone sprayers achieved optimal uniformity at intermediate hover heights, with poorer performance at both lower and higher altitudes due to airflow and spray pattern disturbances. In summary, maintaining a spray height around 60 cm results in the lowest CV and thus the most uniform coverage, highlighting the importance of height control in precision spraying systems.

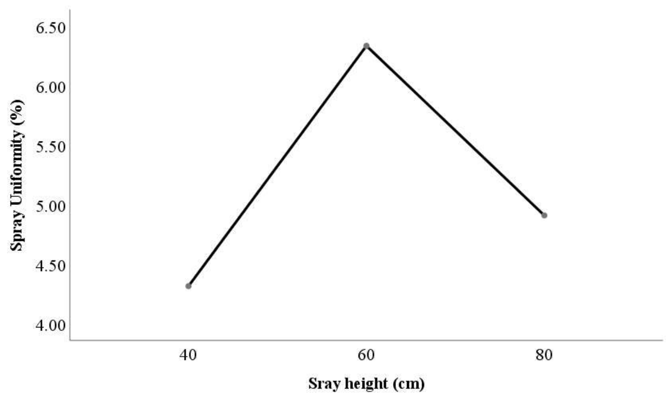

Figure 11: Effect of orifice diameter on spray angle

4.0 CONCLUSION

This study has been able to relate the effects of exit orifice diameter, spray pressure, and spraying height on agricultural spray characteristics (droplet size, spray angle, and uniformity). Among the parameters examined, orifice diameter mainly affects spray angle and uniformity, with larger diameters generally enhancing spray coverage. However, an optimal orifice size was identified, beyond which further increases yielded diminishing or negative effects on uniformity. Spray pressure demonstrated a moderate effect, primarily improving spray uniformity with minimal influence on droplet size and spray angle. Invariably, 200 kPa is the optimal pressure for achieving a balance between spray uniformity and spray droplet size.

Meanwhile, spray height had a nuanced impact, with 60 cm identified as the optimal height for maximizing spray angle and uniformity, while also promoting finer droplet formation at greater heights. The proper selection and combination of orifice size, operating pressure, and spraying height are essential for achieving efficient, uniform, and targeted application of pesticides or fertilizers. Careful calibration of these factors to suit specific crop requirements and environmental conditions can significantly enhance resource use efficiency, crop protection, and sustainability in modern agricultural practices.

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