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Research Article

Laboratory Evaluation of Flat-Fan Nozzles for Improving Spray Uniformity in Drone-Assisted Fertilizer Application

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ABSTRACT

Unmanned aerial vehicles (UAVs) are increasingly being adopted for foliar nutrient application due to their operational efficiency, precision and labour-saving potential. However, achieving uniform spray distribution remains a major challenge, particularly due to nozzle configuration and operating parameters. This study evaluated the performance of flat-fan nozzles with orifice angles of 80°, 90°, 110° and 120° under laboratory conditions using a custom-built spray patternator. Discharge rate, swath width and spray uniformity were assessed at four operating pressures (1, 2, 3 and 3.5 bar). Individual nozzle performance revealed that wider orifice angles produced greater swath widths, while increasing pressure gradually expanded coverage. To address uneven spray deposition observed in drone-mounted asymmetrical nozzle arrangements, four dual-nozzle combinations (110° & 80°, 110° & 90°, 110° & 110° and 110° & 120°) were tested at a fixed height of 80 cm. Spray uniformity was quantified using the coefficient of variation (CV). Among all combinations, the 110° & 80° nozzle configuration exhibited superior performance, achieving the lowest CV (55.32%) at 3 bar pressure with an effective swath width of 185 cm and a manageable discharge rate of 692.1 ml/min. Although slightly better uniformity was recorded at 3.5 bar, the excessive discharge rate exceeded the drone's operational capacity, making it unsuitable for field application. The results highlight the importance of optimising nozzle selection and operating pressure to balance spray uniformity and system compatibility. This study provides a practical framework for improving nitrogen use efficiency in wheat through precision UAV-based foliar spraying.

Key words: UAV spraying, Flat-fan nozzle, Spray uniformity, Coefficient of variation, Nitrogen application

Introduction

Unmanned aerial vehicles (UAVs) also known as drones, have emerged as a high-tech method for applying foliar nutrients to the crops (Zhang & Kovacs, 2012). The multi-nozzle spraying system allows the drone to apply fertilizers quickly and accurately, which can save labour hours and reduce input waste. The wheat field has a relatively uniform canopy structure, which is especially well-suited to effective control by the drone-spraying system. Foliar nutrients applied via drones at the right time of day can greatly enhance plant performance, deposition and uptake efficiency. The droplet coverage across the canopy needs to be uniform; otherwise, efficacy will be compromised. Uneven deposition causes

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areas of over- and under-fertilisation, which diminishes the effectiveness of treatments.

Uniformity of spray delivery, which is heavily reliant on the features within the nozzle system used on a UAV Solution. These nozzles are mostly mounted on booms or directly on drones' arms by various automotive sprayer machine manufacturers (Jin *et al*., 2021). The spray pattern (which depends on nozzle type, angle, orifice size, and spacing) determines where droplets are applied to the crop surface. Asymmetrical nozzle spacing, such as larger distances between front nozzles and smaller spacings at the rear, will make the overlap zones nonuniform. As a result, some areas receive more spray due to spraying overlap, while other areas get less where the overlap is poor. So, in one flight of the drone, the spray is not uniform across the entire field. The full benefits of foliar spraying can only be realised when the placement of nozzles is adjusted to achieve an optimal droplet size, resulting in consistent nutrient application.

Apart from the system configuration, plant and environmental variables also affect the effectiveness of foliar application. When the leaves have just sprouted, they are close together, which reduces mutual shading and helps water droplets remain on the leaf surface longer, increasing nutrient absorption. Other factors like leaf hairs, waxy cuticle, and the nature and distribution of stomata are also important in determining how well foliar-applied nutrients can be taken up by the plant (Matthews, 2000). The structure of the spray solution, including its tension and adjuvant content, controls droplet adherence and distribution on leaves. Physical characteristics of droplets are affected by conditions at the time of spraying, with wind speed, temperature and humidity playing key roles. Strong winds can worsen drifting, and high temperatures with low humidity can help the material evaporate more quickly (Qiu *et al*., 2020). To overcome these challenges, foliar applications have to be performed in the early morning or late afternoon for better nutrient uptake and to minimize losses (Hong *et al.*, 2020).

Due to the complexity of UAV-based foliar spraying, a need exists for evaluating and optimizing nitrogen delivery efficiency in wheat cultivation with respect to operational parameters. Drone-assisted application has attracted attention for its capability in the new generation of agricultural systems, however, low research output is available for parameters regarding fine-tuning sprays (e.g., nozzle type, orientation and flight settings) targeting nitrogen use efficiency in wheat.

Material and Methods

While working with drones for foliar spraying, a noticeable asymmetry often arises in the spatial arrangement of the nozzles. A clear example of this is shown in the configuration in Fig. 1, where the front two nozzles are set 142 cm apart, whereas the rear pair is separated by only 72 cm. When all four nozzles are activated together in a horizontal alignment, this imbalance results in an uneven spray distribution, as illustrated in Fig. 2. The most

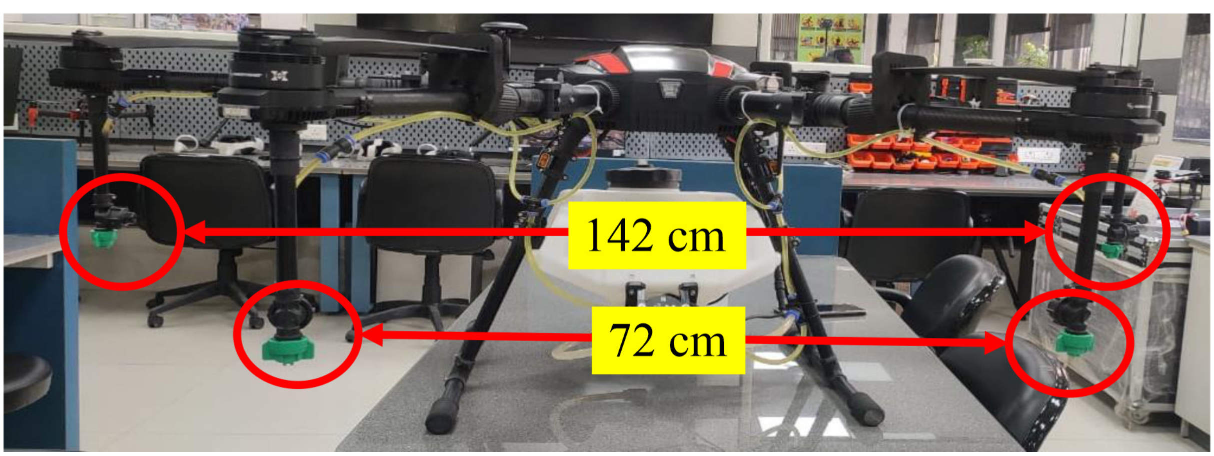

Fig. 1. Placement of nozzles in the spraying drone

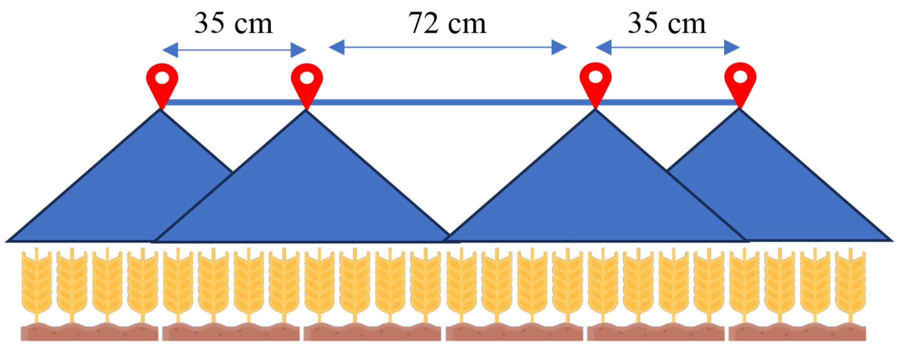

Fig. 2. Spray distribution pattern with 4 nozzles placed below the propeller

significant irregularities occur in the central section of the spray path, where inadequate overlap between neighbouring spray cones causes poor coverage. These variations in deposition highlight how critical nozzle positioning and selection are for achieving uniform application. Understanding these dynamics not only underscores the complexity of drone-based spraying but also forms a foundational step toward optimising foliar nutrient delivery systems for use in precision agriculture.

Nozzle selection

A nozzle is a device designed to control the direction, flow and spray pattern of a liquid. It breaks the liquid into fine droplets for effective coverage during spraying applications. The spray area covered per unit time of the flat fan nozzle is large, and its cost is also low. The most common nozzle used in drone spraying is a flat fan nozzle with a 110 ° spray angle. The flat-fan nozzles with four orifice angles, i.e., 80°, 90°, 110° and 120° were selected in the present study.

Evaluation of nozzle performance parameters in laboratory conditions

The independent and dependent parameters studied for the nozzles under laboratory conditions using a spray patternator are presented in Table 1.

Spray distribution pattern using spray patternator

Spray distribution refers to the dispersion of liquid droplets from a nozzle, measured from the centre outward. The shape and intensity of this distribution characterize the nozzle type and define its swath width - the lateral coverage of the spray. To evaluate these characteristics, a spray patternator was used. The study employed a spray patternator (2 m × 1 m) fabricated from galvanized iron (GI) sheet. This experiment was carried out at the Division of Agricultural Engineering, ICAR-Indian Agricultural Research Institute, New Delhi utilizing a custom-built patternator designed to assess spray behaviour under varying conditions of liquid pressure, nozzle height and inter-nozzle spacing. The patternator setup included 40 V-shaped channels, each with internal dimensions of 5 cm × 120 cm (width × length). A matching rack with 40 graduated glass tubes (30 mm diameter) and 40 corresponding holders was installed to collect sprayed liquid from each channel (Fig. 3). Nozzles were mounted centrally at the top of the frame. The liquid supply system utilized a brushless motor, commonly used in drones, to deliver the spray solution. The motor was connected to the drone's remote controller, allowing precise regulation of spray pressure.

Table 1. Experimental plan for evaluation of the nozzles in laboratory

Independent variables	Treatment	Level type	Dependent variables
Orifice angle of nozzle	4	80%, 90%, 110% & 120%	Discharge rate (ml/min) and swath width (mm)
Nozzle operating pressure (bar)	4	1.0, 2.0, 3.0 and 4.0	

Fig. 3. Spray patternator used in the study

Determination of discharge rate, swath width of individual and combined nozzle configuration

At first, 4 different orifice nozzles were tested individually in the patternator. One nozzle is placed in the centre of the patternator and operated according to the different treatment combinations given in Table 1. The sprayed water was collected in tubes kept along each channel of the patternator for a duration of 2 minutes, and the observed data were recorded. The mean liquid volume collected from each channel was used to evaluate the spray distribution pattern and discharge rate. This procedure was replicated three times for each combination of independent paramter ensuring data collection for all dependent parameters.

To determine the impact of operating pressure on the nozzle discharge rate, the liquid discharge rate was measured. Once the operating pressure stabilised and a consistent flow was observed over a 2-minute interval. The observations were repeated three times. The average liquid distribution width across the patternator channels was defined as the swath width corresponding to the particular operating pressure and nozzle height.

Among the four selected flat-fan nozzles with orifice angles of 80°, 90°, 110° and 120°, the 110° nozzle was individually paired with each of the other three, as well as with another 110° nozzle, to create the following four combinations: 110° & 80°, 110° & 90°, 110° & 110° and 110° & 120°. In all configurations, the nozzles were mounted 35 cm apart, and spray patterns were collected at a height of 80 cm above the target surface. Each experimental setup was replicated three times to ensure consistency and reliability of results.

Initially, the existing drone setup included all 110° nozzles. To evaluate the most effective configuration, this setup was compared with the other nozzle combinations (110° & 80°, 110° & 90°, and 110° & 120°) in terms of spray pattern uniformity and swath coverage.

Results and Discussion

Spray distribution of individual nozzles at 80 cm height

The spray distribution characteristics of individual flat-fan nozzles (80°, 90°, 110° and 120°) varied significantly with operating pressure,

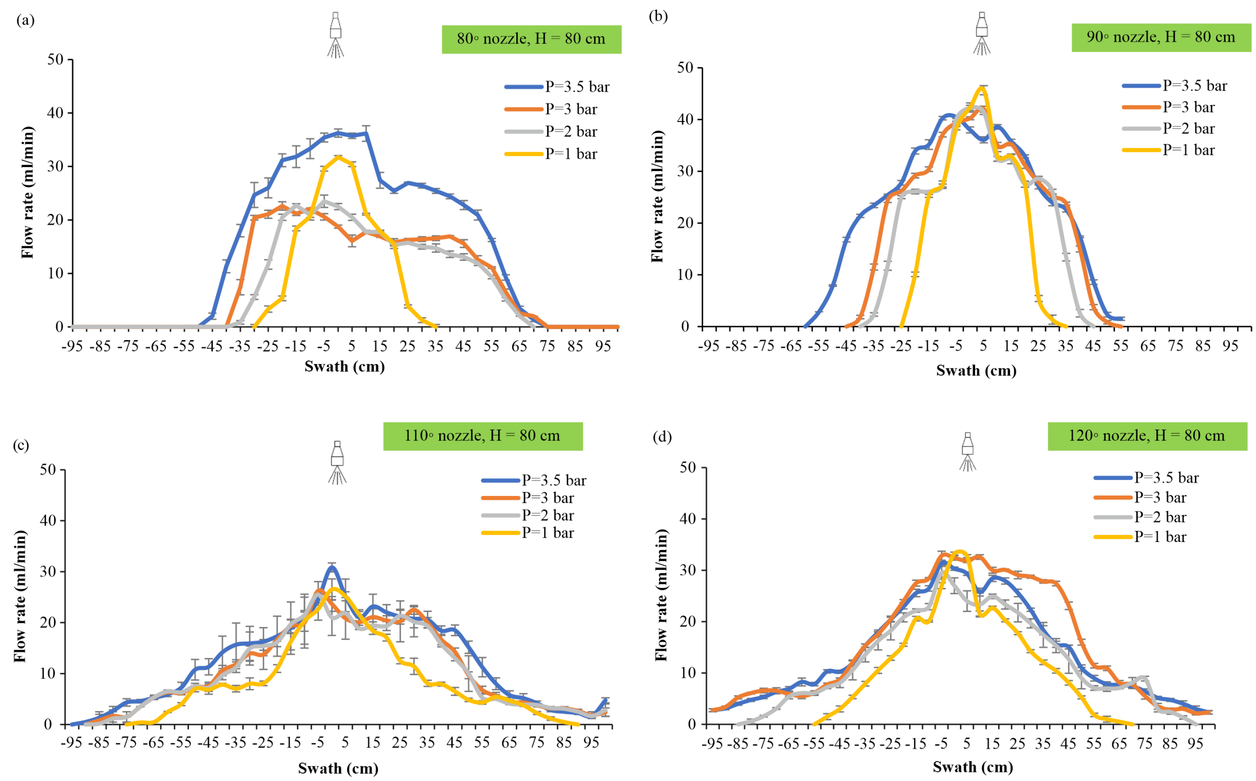

Fig. 4. Spray distribution pattern of individual nozzles (80°, 90°, 110° and 120°) at 80 cm height under different operating pressures

influencing swath width, peak discharge and overall deposition pattern (Fig. 4). These variations highlight the sensitivity of UAV-based spraying systems to nozzle geometry and hydraulic parameters. The 80° nozzle produced a highly concentrated spray pattern, particularly at lower pressures (1–2 bar), resulting in narrow swath widths (55–100 cm). This behaviour confirms earlier observations by Matthews (2000) and Fritz *et al*. (2021), who reported that narrow-angle nozzles generate coarse droplets with limited lateral spread, increasing penetration but reducing field coverage. Although higher pressures (3–3.5 bar) expanded the swath to 115 cm, the distribution remained sharply peaked, indicating a risk of localized nutrient accumulation. Such non-uniformity may lead to leaf scorching and inefficient nutrient utilization (Zhang *et al*., 2023).

The 90° nozzle exhibited a pronounced central peak across all pressures, indicating strong convergence of the spray cones. While this may benefit targeted spot applications, it is unsuitable for uniform broadcast spraying. Similar centralized patterns were reported by Qiu *et al*. (2020), who found that mid-angle nozzles produce excessive droplet density at the centre, increasing runoff losses. The 110° nozzle demonstrated a more balanced profile, generating broader swath widths (160–190 cm) and moderate peak flow rates. This nozzle maintained a relatively stable distribution across pressure levels, making it better suited for UAV operations where consistent coverage is essential (Hong *et al*., 2020). The 120° nozzle produced the widest swath (>195 cm), confirming that increasing orifice angle enhances lateral coverage. However, excessive widening may reduce droplet density per unit area, potentially lowering nutrient absorption efficiency (Zhang & Kovacs, 2012). These findings collectively demonstrate that nozzle angle and operating pressure interactively determine spray behaviour, supporting conclusions by Fritz *et al*. (2021) that optimal nozzle selection must consider both coverage and droplet concentration to achieve agronomically effective deposition.

Spray distribution of combined nozzles at 80 cm height

Dual-nozzle configurations were evaluated to replicate field conditions encountered in drone-mounted spraying systems. The 110° & 80° combination produced a relatively symmetrical and uniform distribution pattern. Adequate overlap between spray plumes minimized untreated gaps and reduced excessive accumulation zones. This finding is consistent with Jin *et al*. (2021), who reported that combining different nozzle angles improves overlap efficiency and reduces spatial variability. At lower pressures (1–2 bar), this configuration achieved stable peak flow rates and consistent swath widths (165–170 cm). At higher pressures (3–3.5 bar), swath width increased to 185 cm with enhanced uniformity. This improvement can be attributed to finer droplet formation and improved plume interaction, as described by Qiu *et al*. (2020).

The 110° & 90° configuration generated significantly higher central peaks, indicating excessive overlap. Although higher droplet density improves canopy wetting, it also increases runoff and nutrient wastage (Zhang *et al*., 2023). Such deposition patterns are undesirable for nitrogen spraying, where uniformity is critical to prevent patchy crop response. The 110° & 110° and 110° & 120° configurations produced the widest swath (>195 cm) but exhibited pronounced non-uniformity. Overlapping wide-angle plumes caused excessive central accumulation and marginal under-coverage. Fritz *et al*. (2021) similarly reported that pairing identical wide-angle nozzles on UAV booms often leads to erratic deposition patterns due to rotor-induced airflow disturbance. These results emphasize that nozzle symmetry alone does not guarantee uniform spraying. Instead, the strategic pairing of dissimilar nozzle angles improves spatial deposition consistency.

Effect of nozzle combination and pressure on the Coefficient of Variation

Spray uniformity quantified using the coefficient of variation (CV) revealed substantial differences among treatments (Table 2). The 110° & 80° combination consistently recorded the lowest CV values, decreasing from 58.96% at 1 bar to 53.02%

Table 2. Effect of nozzle combination and operating pressure on swath width, uniformity (CV%) and discharge rate

Nozzle combination	Operating pressure (bar)	Effective swath (cm)	CV (%) of spray distribution	Discharge rate (ml/min)	Peak flow rate/ effective swath (ml/min/cm)
110° & 80°	1	165	58.96	479.2	0.42
	2	170	56.14	608.0	0.41
	3	185	55.32	692.1	0.33
	3.5	185	53.02	726.0	0.38
110° & 90°	1	170	68.18	529.9	0.58
	2	175	65.54	634.9	0.48
	3	180	65.24	727.2	0.40
	3.5	185	62.82	826.9	0.44
110° & 110°	1	195	68.74	498.8	0.55
	2	195	67.39	671.6	0.51
	3	195	67.36	738.1	0.35
	3.5	195	68.06	786.9	0.46
110° & 120°	1	195	68.58	463.5	0.54
	2	195	64.04	654.9	0.42
	3	195	64.61	728.7	0.26
	3.5	195	65.15	779.1	0.36

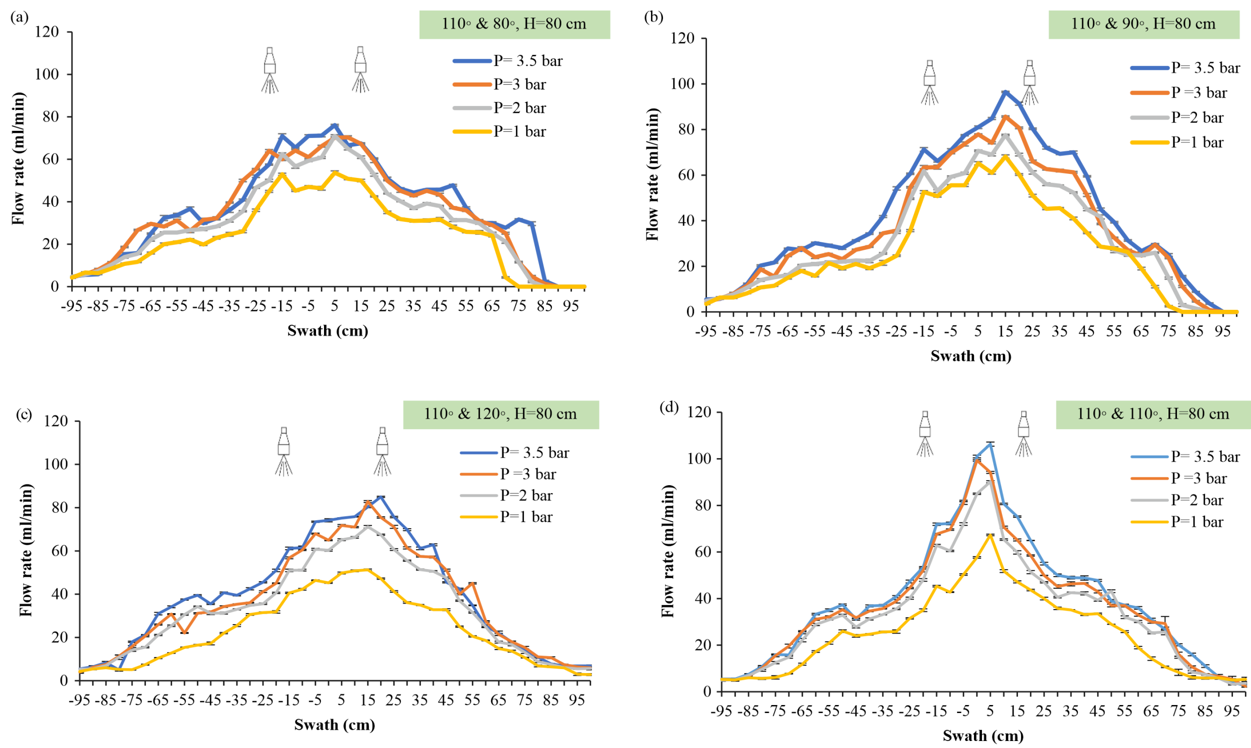

Fig. 5. Spray distribution pattern of combined nozzles at 80 cm height under different operating pressures

at 3.5 bar. This trend confirms that increasing pressure improves atomization and plume interaction, enhancing uniformity (Hong *et al*., 2020). The 110° & 90° combination showed relatively higher CV values despite achieving the highest discharge rates. This indicates that increased flow alone does not guarantee better spray quality. Similar conclusions were drawn by Zhang and Kovacs (2012), who demonstrated that excessive discharge often amplifies spatial variability due to turbulent airflow around UAV rotors.

For the 110° & 110° and 110° & 120° combinations, CV values remained consistently above 64%, reflecting poor uniformity. The identical nozzle pairing resulted in overlapping spray cones that intensified central accumulation while reducing edge coverage. Zhang *et al*. (2023) reported comparable patterns when identical nozzles were mounted symmetrically on multi-rotor drones. Although the lowest CV (53.02%) was observed at 3.5 bar for the 110° & 80° combination, this pressure generated an excessively high discharge rate (726 ml/min), exceeding the drone's optimal operational capacity. Excessive spray volume increases drift risk and reduces nitrogen use efficiency (Qiu *et al*., 2020).

Selection of optimal operational configuration

Considering both spray performance and operational feasibility, the 110° & 80° nozzle combination at 3 bar pressure was identified as optimal. This configuration achieved a favourable compromise between swath width (185 cm), discharge rate (692 ml/min) and spray uniformity (CV = 55.32%). This selection aligns with recommendations by Fritz *et al*. (2021), who emphasized moderate pressure to maintain optimal droplet size, reduce evaporation losses and ensure precise deposition. Similarly, Hong *et al*. (2020) reported that operating UAV sprayers at moderate pressure improves nutrient uptake by minimizing drift and enhancing canopy retention.

Conclusions

The present study demonstrates that nozzle configuration and operating pressure play a critical role in determining spray distribution uniformity in UAV-based foliar applications. Laboratory evaluation using a spray patternator revealed that individual nozzle performance varied significantly with orifice angle and pressure, influencing swath width and discharge rate. Wider-angle nozzles produced broader coverage, while increasing pressure enhanced swath width but also elevated discharge rates. Among the dual-nozzle combinations tested, the 110° & 80° configuration consistently exhibited superior spray uniformity compared to other treatments. At an operating pressure of 3 bar, this combination achieved an optimal balance between effective swath width (185 cm), acceptable discharge rate (692.1 ml/min) and low coefficient of variation (55.32%). Although marginally better uniformity was observed at 3.5 bar, the associated high discharge rate exceeded the drone's operational limits, making it impractical for field deployment. These findings emphasise the need to optimise both nozzle selection and operating pressure for drone-based foliar nutrient application. The selected configuration provides a reliable solution for achieving uniform nitrogen delivery in wheat, supporting precision agriculture objectives and enhancing nutrient use efficiency while minimizing spray losses and operational constraints.

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