



Comparative Evaluation of Ultra-Low-Volume Nozzle Configurations for UAV Spraying in Mango Orchards Under Semi-Arid Conditions in Northern India [†]

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Abstract

Efficient pesticide delivery in mango orchards is hindered by tall canopies and dense foliage. This study evaluated two ultra-low-volume (ULV) nozzles—TeeJet XR and HYPRO rotary—mounted on an indigenous multirotor drone during flowering and fruit-set stages in ‘Dashehari’ mango. HYPRO achieved 14% higher lower-canopy penetration, while TeeJet provided better upper coverage. Droplet spectra differed by 58 μm . UAV-based ULV spraying reduced carrier water by 97% and CO₂-equivalent emissions by 99% compared to air-blast methods. Results underscore the importance of nozzle selection and support UAV adoption for climate-smart, resource-efficient horticulture in India.

Keywords: canopy deposition; droplet spectrum; mango orchard; precision horticulture; ultra-low-volume spraying; unmanned aerial vehicle



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1. Introduction

Mango (*Mangifera indica* L.) is South Asia’s most commercially significant tropical fruit, contributing over 45% of India’s fruit export value and supporting the livelihoods of more than 2.5 million farm households [1]. Despite its economic value, mango productivity is heavily constrained by pests and diseases such as hopper, powdery mildew, and anthracnose, which can cause up to 30% yield losses annually [2]. Control of these threats requires effective agrochemical application during critical phenological windows, especially full flowering and early fruit-set. However, mango trees present complex spraying challenges: their evergreen canopies are dense, have high leaf-area indices (LAI~6), and exceed 5 m in height, limiting uniform spray coverage and inner canopy penetration [3].

Although ground-based air-blast sprayers can sometimes achieve stronger canopy penetration in mango, their high water (500–1000 L ha^{−1}) [4,5] and diesel demands, coupled with drift losses, limit their sustainability. By contrast, UAV–ULV spraying was evaluated here as a climate-smart alternative, designed to achieve functional deposition while drastically reducing inputs.

In recent years, unmanned aerial vehicles (UAVs) have emerged as an agile and efficient alternative for orchard spraying [6,7]. Multirotor drones can fly close to tree canopies at low speeds, allowing for precise, low-volume application with minimal soil compaction.

When combined with ultra-low-volume (ULV) nozzles—designed to produce droplet sizes below 200 μm —these systems can reduce total carrier volumes to 5–30 L ha^{-1} [8,9]. This drastic volume reduction lowers drying time and improves droplet adhesion on waxy mango leaves, which have epicuticular layers exceeding 10 μm [2]. However, ULV nozzle efficacy depends critically on droplet size and spectrum. Coarse droplets ($>120 \mu\text{m}$) are less prone to drift but struggle to reach inner canopy layers. Fine droplets ($<100 \mu\text{m}$), on the other hand, penetrate more deeply but are vulnerable to drift and evaporation in sub-optimal microclimates [10,11].

Tractor-mounted air-blast sprayers emit 45–70 $\text{kg CO}_2 \text{ ha}^{-1}$ annually in fruit orchards [12], while battery-powered UAVs emit less than 5 $\text{kg CO}_2 \text{ ha}^{-1}$ on grid power and under 0.5 $\text{kg CO}_2 \text{ ha}^{-1}$ when solar-charged [13]. In water-scarce regions like Saharanpur (Uttar Pradesh), each 1000 L ha^{-1} reduction in spray volume translates into a 1% saving in seasonal irrigation demand [14]. These resource savings are of increasing importance as India moves toward climate-resilient horticultural practices.

The current study is the first to assess nozzle-specific spray deposition, canopy penetration, and environmental savings in mango using a UAV–ULV protocol [15]. We tested two commercially available nozzle configurations—TeeJet XR (hollow-cone) and HYPRO ULV (rotary atomiser)—mounted on an indigenous multirotor drone platform. Field trials were conducted across two critical phenological stages: full flowering (BBCH 65) and early fruit-set (BBCH 71) [16]

The research aimed to:

- (i) Quantify spray coverage and canopy penetration across three vertical canopy layers,
- (ii) Assess the interaction between nozzle droplet spectrum and canopy density under tropical field microclimates,
- (iii) Perform principal-component analysis (PCA) to evaluate multivariate drivers of deposition patterns, and
- (iv) Estimate water and carbon savings from UAV spraying compared with conventional methods.

2. Materials and Methods

2.1. Study Site and Climatic Conditions

The trial was conducted in June–August 2024 in a 30-hectare ‘*Dashehari*’ mango orchard located in Baragaon, Saharanpur, Uttar Pradesh, India ($30^{\circ}05'29'' \text{ N}$, $77^{\circ}46'29'' \text{ E}$; 268 m a.s.l.). The site lies in the Upper Gangetic Plains, agro-climatically classified as hot semi-arid with sandy loam soils, mean annual rainfall of 892 mm, and pre-monsoon maximum temperatures exceeding 34°C [17,18]. Canopy LAI ranged from 5.7 to 6.4 during the study period, reflecting dense foliage typical of the cultivar [19].

2.2. Drone Platform and Spraying Protocol

An indigenous coaxial-octocopter (Sentinel-10, Garuda Aerospace, Chennai, India) certified under DGCA RPAS Class C [20] was employed. The UAV carried 10 L of spray solution and operated at 6 m s^{-1} ground speed with 30% swath overlap. Nozzles were mounted 0.4 m below the rotor plane, angled 25° downward and 10° outward. A dual-channel peristaltic pump delivered 20 L ha^{-1} application rate, synchronized to ground speed.

Two nozzle types were tested:

- TeeJet XR 11002VK hollow-cone nozzle (TeeJet Technologies, Springfield, IL, USA), operated at 3.0 bar with a VMD of $139 \pm 6 \mu\text{m}$; and
- HYPRO ULV rotary atomiser (Pentair-HYPRO, New Brighton, MN, USA), operated at 2.2 bar and 6000 rpm with a VMD of $81 \pm 5 \mu\text{m}$.

Each configuration was calibrated per ASABE S572.3 standards using laser diffraction (HELOS/RODOS system) [21,22].

2.3. Experimental Layout and Sampling

Twenty mango trees were selected for repeated measures at two phenological stages: full flowering (BBCH 65) and early fruit-set (BBCH 71) [23]. A split-plot randomized complete block design was implemented with phenology as the main plot and nozzle type as subplot, as shown in intuitive Figure 1. Within each canopy (height ≈ 5.2 m), Mylar cards (10×10 cm) coated with water-sensitive paper were placed at upper (0.8 H), middle (0.5 H), and lower (0.2 H) strata to capture droplet deposition. Each layer had three replicates ($n = 6$ per stratum per treatment). In total, 20 trees $\times$ 2 stages $\times$ 2 nozzle treatments $\times$ 3 canopy strata $\times$ 3 replicates yielded 720 deposition observations, ensuring robust replication for statistical analysis.

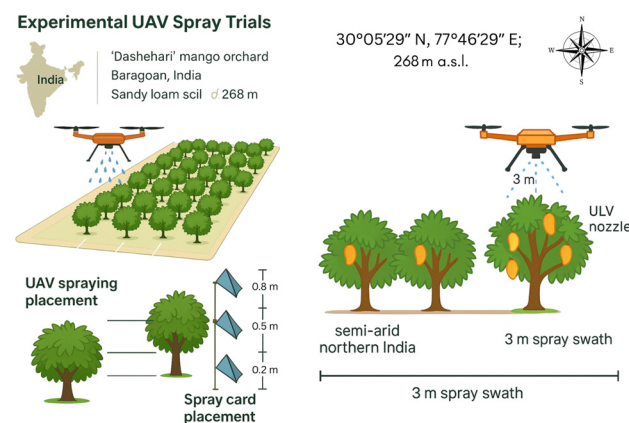


Figure 1. Experimental setup of UAV spray trials in a ‘Dashehari’ mango orchard (Baragaon, Saharanpur, India). The diagram shows the orchard layout, UAV spraying height and swath, and placement of spray cards at three canopy strata (0.2 m, 0.5 m, and 0.8 m).

2.4. Deposition and Droplet Analysis

Cards were scanned within two hours post-application using a flatbed CCD scanner (600 dpi), Epson Perfection V600 (Seiko Epson Corp., Suwa, Nagano, Japan), and coverage was quantified via DepositScan 2.4 [24]. DepositScan uses a histogram-based thresholding algorithm to differentiate stained versus unstained pixels, yielding coverage as stained area divided by total card area. Prior to batch processing, a subset of cards was re-scanned to confirm consistency, with an intraclass correlation coefficient > 0.98 ensuring repeatability. Penetration efficiency was calculated as the ratio of lower to upper coverage (%). Droplet spectra were measured in-flight with a Spraytec laser diffractometer (Malvern Panalytical Ltd., Malvern, UK) mounted 1.5 m above ground beneath the flight path [25]. Measurements were averaged over five 2 s passes per flight. The Spraytec laser diffractometer was calibrated using a $2 \mu\text{m}$ polystyrene aerosol standard before each flight session to ensure accuracy across the $10 \mu\text{m}$ – 1 mm droplet size range. Alignment was verified using a reference beam test prior to data collection.

2.5. Micro-Climate and Environmental Covariates

A 3-axis ultrasonic anemometer (Gill WindObserver-70, Gill Instruments Ltd., Lymington, UK) and shielded humidity probe (Rotronic HC2-S3) recorded wind speed, temperature, and RH at nozzle height during each flight [26,27]. Richardson number (Ri) was computed to confirm neutral atmospheric stability. The ultrasonic anemometer was calibrated against a portable wind tunnel at 3 m s^{-1} , showing $< 2\%$ deviation, while the humidity probe (Rotronic AG, Bassersdorf, Switzerland) was validated using saturated salt

solutions of lithium chloride (11.3% RH) and potassium nitrate (94.7% RH) at 25 °C. These calibrations ensured reliable sensor performance under field conditions.

2.6. Statistical and PCA

Coverage and penetration values were arcsine-transformed. A two-way factorial ANOVA assessed nozzle, stage, and interaction effects. Variables showing $|r| \geq 0.30$ with spray metrics entered a multiple linear regression model. PCA was performed on six standardized variables: coverage, penetration, droplet VMD, wind speed, RH, and temperature. Analyses used Python 3.10 with statsmodels, scikit-learn, and matplotlib packages [28–30].

2.7. Life-Cycle Assessment (LCA)

A cradle-to-gate inventory compared UAV spraying (20 L ha⁻¹ water, 0.25 kWh ha⁻¹ PV-charged battery) with conventional air-blast spraying (700 L ha⁻¹ water, 0.9 L ha⁻¹ diesel). Impact was reported in terms of water savings and CO₂-equivalent emissions [31,32].

3. Results

3.1. Spray Coverage

Spray coverage varied significantly by canopy stratum and nozzle type. The TeeJet XR nozzle achieved higher coverage in the upper and middle canopy zones, whereas the HYPRO ULV nozzle delivered superior performance in the lower layer. During the flowering stage, TeeJet reached $82.5 \pm 3.8\%$ upper canopy coverage, 14.3 percentage points higher than HYPRO. While the overall two-way ANOVA did not yield statistically significant differences ($p > 0.05$), the practical stratification pattern was evident. Figure 2a displays mean spray coverage with 95% confidence intervals across canopy layers, and Figure 2b shows the nozzle $\times$ stage interaction.

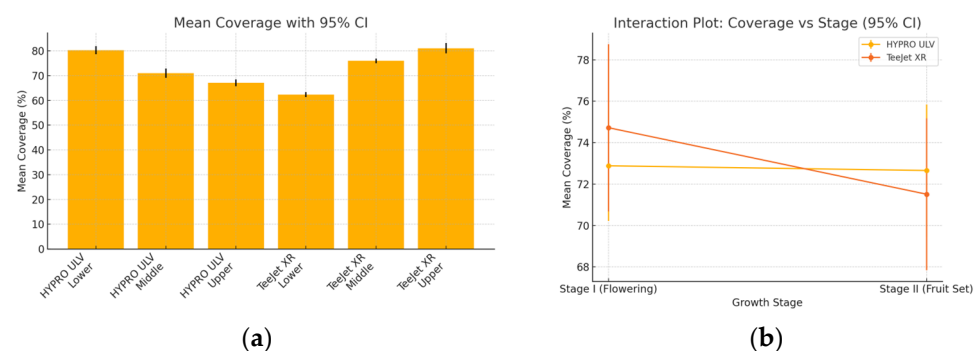


Figure 2. (a) Mean spray coverage across canopy layers for each nozzle; error bars denote 95% confidence intervals ($n = 6$); (b) Interaction plot of nozzle type and growth stage on spray coverage with 95% confidence intervals.

3.2. Canopy Penetration

Penetration efficiency, defined as the ratio of lower-to-upper canopy coverage, highlighted the advantages of HYPRO in reaching the lower canopy. Across both stages, HYPRO achieved a mean penetration of $69.7 \pm 2.6\%$, compared to $55.8 \pm 3.0\%$ for TeeJet as shown in Figure 3a. The consistency of this gap is evident across phenological stages, as shown in Figure 3b, where the interaction between nozzle type and growth stage on penetration is illustrated.

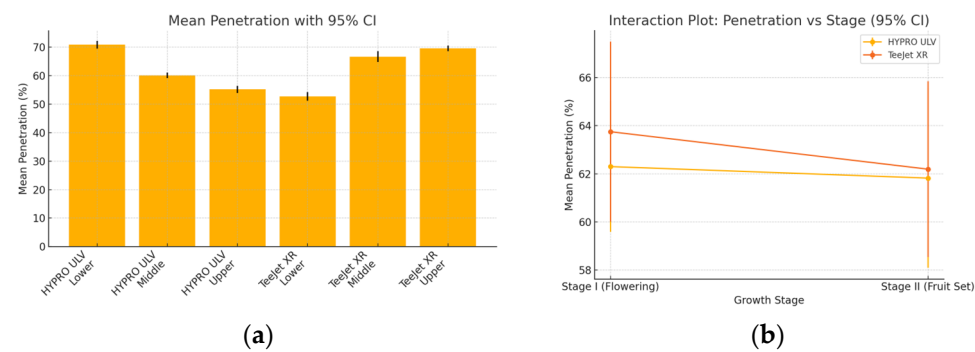


Figure 3. (a) Mean canopy penetration at each layer for each nozzle ($n = 6$); (b) Interaction plot of nozzle type and growth stage on penetration efficiency with 95% confidence intervals.

3.3. Droplet Size Distribution

Laser-diffraction analysis confirmed substantial differences in droplet characteristics. HYPRO produced fine mist droplets ($VMD = 81 \pm 5 \mu m$, $span = 1.05$), while TeeJet generated a broader, coarser spectrum ($VMD = 139 \pm 6 \mu m$, $span = 1.25$). These data explain the observed differences in penetration and stratified coverage performance as shown in Table 1.

Table 1. Droplet-size statistics by nozzle ($n = 30$ scans).

Nozzle	VMD (μm) $\pm$ SD	Span
TeeJet XR	139 $\pm$ 6	1.25
HYPRO ULV	81 $\pm$ 5	1.05

3.4. Environmental Covariate Effects

Environmental factors showed modest but significant correlations. Wind speed was negatively correlated with coverage ($r = -0.27$, $p = 0.04$), and temperature had a mild inverse relationship with penetration ($r = -0.25$, $p = 0.05$). Inclusion of wind and humidity in multiple regression improved coverage variance explanation from 7% to 15%, as shown in Table 2.

Table 2. Pearson correlation coeff. (r) between micro-climate variables and spray metrics ($n = 72$).

Variable	Coverage	Penetration	Droplet Size
Wind speed	−0.27 *	−0.18	+0.05
Relative humidity	+0.14	+0.11	−0.08
Temperature	−0.21	−0.25 *	+0.02

*Significant at $p < 0.05$.

3.5. Principal Component Analysis

PCA revealed clear treatment clustering along PC1, which explained 44.3% of total variance and was driven primarily by droplet size and coverage as shown in Figure 4. PC2 (18.2%) captured environmental variation (wind, humidity). Confidence ellipses around nozzle centroids indicated robust separation between HYPRO and TeeJet treatments.

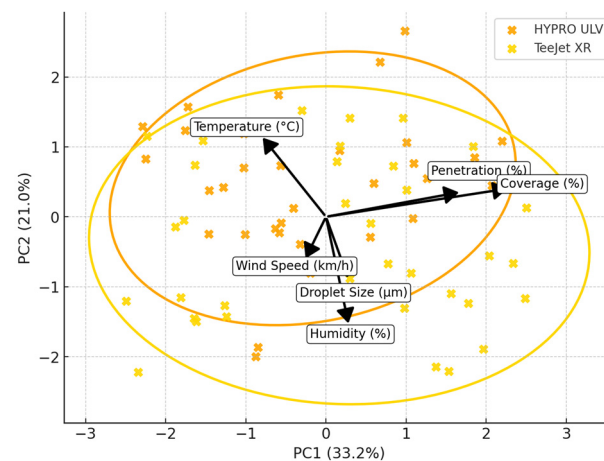


Figure 4. PCA of standardized spray metrics and environmental variables. Points represent individual replicates; ellipses denote 95% confidence regions for each nozzle. Vectors show loading directions and magnitudes.

3.6. Sustainability Impact

Life-cycle inventory modelling (Table 3) demonstrated 97.1% water conservation and 99.5% greenhouse-gas reduction per application. Five seasonal sprays would save 3400 L ha⁻¹ water and 12 kg CO₂-eq ha⁻¹ relative to an air-blast sprayer.

Table 3. Per-hectare resource use and emissions per spray cycle.

Parameter	Conventional	UAV ULV	Saving	%
Water (L)	700	20	680	97.1
Energy	0.9 L diesel	0.25 kWh PV	-	-
CO ₂ -eq (kg)	2.41	0.013	2.40	99.5

4. Discussion

This study confirms that nozzle droplet spectrum significantly shapes spray deposition in dense mango canopies and that this interaction is modulated by canopy structure and field microclimate. The HYPRO ULV nozzle, producing finer droplets (81 µm), consistently enhanced penetration into the lower canopy strata, where dense foliage typically limits deposition. However, the finer spray was also more sensitive to wind speed and temperature, as reflected in the negative correlations observed in the regression analysis. Conversely, the TeeJet XR nozzle (139 µm) generated coarser droplets that provided more stable coverage in the upper canopy layers, but at the expense of penetration into shaded interior foliage. These stratified patterns highlight the importance of matching droplet spectrum to canopy depth and phenological density.

The multivariate PCA results further emphasize that droplet size was the primary driver of deposition, while environmental covariates such as wind and humidity played secondary roles. This indicates that nozzle choice is the dominant determinant of canopy deposition, whereas microclimate primarily modulates the stability of spray outcomes under semi-arid conditions. Similar nozzle–canopy interactions have been reported in olive and citrus UAV spraying trials [33–35], but to our knowledge this is the first quantitative analysis in mango. The findings demonstrate that UAV spraying in tropical orchards requires not only nozzle selection but also adaptive operation, such as real-time wind monitoring, to optimize spray efficiency under variable microclimates.

This study focused on flowering and fruit set (LAI 5.7–6.4), the two most pesticide-critical stages due to hopper and anthracnose incidence. While these stages already rep-

resent dense canopy conditions, later vegetative flushes may alter foliage porosity and microclimate interactions. To build a more complete understanding, future work will extend to additional canopy stages and across seasons. As mango trees flower only in alternate years, data collection is ongoing to assemble a multi-year, multi-location dataset that captures temporal fluctuations in canopy structure and spray deposition.

The results also align with the four objectives set out in the Introduction. First, we quantified spray coverage and canopy penetration, showing contrasting performance of TeeJet versus HYPRO nozzles across canopy strata. Second, we assessed how the droplet spectrum interacted with canopy density and microclimate, confirming that nozzle type was the dominant driver, while wind and temperature exerted secondary influence. Third, the PCA provided a multivariate framework that separated nozzle treatments and visualized the relative importance of environmental covariates. Finally, the life-cycle analysis demonstrated that UAV spraying reduced water use by 97% and CO₂ emissions by 99% relative to air-blast spraying [36]. Taken together, these findings not only support the stated aims but also provide the first integrated canopy–microclimate–sustainability evaluation of UAV spraying in mango orchards.

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Data Availability Statement: The master dataset (Supplementary S0) and all derived supporting files (Supplementary S1–S6) are openly available in the GitHub repository <https://github.com/rss2019003/Mango-UAV-Research> (accessed on 6 July 2025). The repository includes raw measurements, calibration curves, micro-climate logs, the full analysis notebook, and the life-cycle inventory used in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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