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RESEARCH ARTICLE

Spray deposition efficiency of two multirotor UAV sprayers versus conventional methods in *Coffea arabica* under mechanizable and non-mechanizable field

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Abstract

Comparative evidence on UAV sprayer applications and conventional techniques in coffee plantations under contrasting terrain conditions remains limited. This study evaluated the spray deposition efficiency of two multirotor unmanned aircraft, DJI Agras T10 and DJI Agras T30, compared with conventional spraying methods in *Coffea arabica* fields under mechanizable and non-mechanizable terrain. Two experimental sites were evaluated: a 9 % slope area sprayed using UAV sprayers and a tractor-mounted air-blast sprayer, and a 20 % slope area sprayed using UAV sprayers and a backpack mist-blower. At each site, three application methods were arranged in strips, with four sampled trees per treatment and six water-sensitive papers per tree distributed across the lower, middle, and upper canopy strata. Covered area, droplet density, and volumetric median diameter were quantified and analyzed using generalized linear models. On mechanizable terrain, the air-blast sprayer achieved up to sevenfold higher coverage and four- to sixfold greater droplet density than UAV sprayers across canopy strata. On non-mechanizable terrain, UAV sprayers reached more than 50 droplets cm^{-2} in the upper canopy, whereas the backpack mist-blower did not exceed 5 droplets cm^{-2} and showed similar performance to UAV sprayers only in the middle and lower strata. Droplets produced by UAV sprayers had a consistent VMD of around 220 µm, while the backpack method produced very fine droplets with higher drift-risk potential inferred from droplet size. These results indicate that UAV sprayers are a technically viable alternative for mountainous coffee areas, whereas tractor-mounted air-blast sprayers remain superior where mechanization is possible.

Keywords: coffea arabica; UAV sprayers; air-blast sprayer; spray deposition; mountainous terrain.

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1. Introduction

Brazil is the world's largest producer and exporter of coffee, with Minas Gerais as its primary producing state (Ministério da Agricultura e Pecuária, 2025). Coffee occupies approximately 2.23 million hectares in the country. Although Brazil has the largest mechanized coffee-growing area worldwide, nearly 40 % of plantations, both *Coffea arabica* and *C. canephora*, are still located in mountainous regions (United States Department of Agriculture, 2022). In southern Minas Gerais, for instance, steep slopes dominate the landscape, fostering high-quality bean production but severely limiting mechanization in several management stages, particularly crop protection (Alves & Lindner, 2020).

Despite the challenges posed by steep terrain, plant-protection practices remain essential. Manual backpack sprayers are predominantly used on slopes, whereas mechanized sprayers are employed where terrain allows mechanization. These methods, however, face major obstacles such as labor shortages, limited field capacity, low application efficiency, and excessive spray volumes, which lead to product losses on the soil and contamination of the environment and workers (Ribeiro et al., 2025). Recent technological advances have offered potential alternatives. Unmanned aerial vehicle (UAV) sprayers enable access to difficult areas, reduce operator exposure, and allow more frequent applications (Radoglou-Grammatikis et al., 2020; Reddy Maddikunta et al., 2021). UAV sprayers, for example,

give producers easier and more frequent access to difficult areas, enhancing crop protection and ultimately increasing productivity (Dhananjayan et al., 2020).

In shrub and tree crops, UAV sprayers have shown high operational efficiency. Studies report effective droplet penetration in apple (Wang et al., 2022) and peach (Meng et al., 2020), as well as more uniform coverage than mechanized sprayers in olive and citrus (Martinez-Guanter et al., 2020) and chestnut orchards (Arakawa & Kamio, 2023). They also help reduce drift, increase application precision and minimize environmental pollution, as observed in mango (Irfan et al., 2021) and papaya (Ribeiro et al., 2023); lower applicator exposure risk, as noted in eucalyptus (Ribeiro et al., 2025); achieve more effective pest control in guava (Verma et al., 2022); and improve the management of fungal diseases in mountainous coffee plantations (Vitória et al., 2023).

Recent coffee-specific studies have further shown that spray deposition from UAV sprayers is strongly affected by canopy position, spray system, application rate, and environmental conditions. Marques Filho et al. (2025), comparing two remotely piloted aircraft systems in *Coffea arabica*, found that the position of water-sensitive papers in the canopy was the main factor affecting deposition, with internal canopy positions receiving few droplets. In dense *Coffea canephora*, Vitória & Oliveira Ribeiro (2026) reported that increasing the application rate from 5 to 15 L/ha increased droplet coverage and deposition, indicating the importance of adjusting spray volume to canopy architecture. In commercial coffee farms, Nishimoto et al. (2026) observed that unmanned aerial spray systems produced lower coverage and droplet density than ground-based systems, whereas canopy position and wind strongly modified deposition patterns. These recent findings indicate that the key question is no longer whether UAV sprayers can spray coffee, but under which terrain, canopy, and equipment conditions they can complement or replace conventional sprayers.

Such effectiveness can be achieved only when spraying is performed under favorable meteorological conditions, higher relative humidity, mild temperatures, and low wind speeds, combined with appropriate operational settings for flight height and speed, spray volume, nozzle type, flight direction, and swath width (Carneiro et al., 2024; Gugan & Haque, 2023; Guo et al., 2020; Richardson et al., 2020). A major challenge in defining these parameters for UAV sprayer applications lies in the crop's architecture: coffee exhibits a dense canopy, which demands deep droplet penetration into the interior of the plant (Silva et al., 2024; Vitória et al., 2023).

Despite growing evidence, the literature still lacks direct comparisons between different UAV sprayer models and conventional spraying in flat and mountainous coffee-growing areas, making it impossible to confirm whether UAV sprayers are a viable spraying alternative across varied terrain. Therefore, this work assesses whether UAV sprayer applications can serve producers operating in non-mechanizable areas and, additionally, function as an alternative application method in mechanized fields, offering a technical solution for both production scenarios.

Therefore, this study aimed to compare the spraying efficiency of two multirotor UAV sprayer models with conventional methods in *Coffea arabica* under mechanizable (gentle slopes) and non-mechanizable (steep slopes) terrain.

2. Methodology

2.1 Characterization of the study areas and crop

The experiment was carried out in two experimental areas in the state of Minas Gerais, Brazil, both owned by the Empresa de Pesquisa Agropecuária de Minas Gerais (EPAMIG). The sites are located at 21° 20′ 33″ S, 45° 28′ 54″ W in the municipality of Três Pontas and at 21° 40′ 51″ S, 45° 56′ 35″ W in the municipality of Machado.

The experimental site in Três Pontas has gently rolling topography, with an average slope of 9 % and an elevation of 920 m. The stand consists of 26-year-old *Coffea arabica* L. cv. Catuaí Vermelho IAC 99, spaced 3.50 m between rows and 0.70 m between plants, resulting in a density of 4,082 plants/ha. Mean plant dimensions were 2.50 m in height and 1.55 m in canopy width, the latter measured between the outermost plagiotropic branches on opposite sides of each tree.

The second experimental area, located in Machado, Minas Gerais, lies at an altitude of 955 m and is classified as non-mechanizable because the terrain has an average slope of 20 %. The cultivar grown there is Topázio MG 1190, planted at a spacing of 2.80 m between rows and 0.60 m between plants, resulting in a density of 5,952 plants/ha. The trees are 15 years old and have canopy dimensions of 2.10 m in height and 1.45 m in width.

2.2 Characterization of the equipment used

Regardless of the experimental site, both DJI AGRAS T10 and DJI AGRAS T30 multirotor UAV sprayers (DJI, SZ DJI Technology Co., Ltd., Shenzhen, China) were used for spraying operations (Table 1). Each UAV sprayer was fitted with hydraulic spray nozzles standardized to the FlexDROP CVE-9001 hollow-cone tip (Projeta Agrícola, Marília, São Paulo, Brazil). This nozzle maintains a 90° spray angle at pressures

above 1 bar, delivers a flow rate of 0.38 L/min (0.10 gal/min), exhibits minimal variation in volumetric median diameter (VMD), and helps reduce drift while improving droplet deposition and uniformity during application.

Table 1
Technical specifications of the UAV sprayer models used in the experiment

Specification[a]	T10	T30
Tank capacity, full load (L)	8	30
Number of spray nozzles	4	12
Effective spray width at 1.5 – 3.0 m flight height (m)	3.0 – 5.5	4.0 – 9.0

[a] Source: DJI (2021a, 2021b).

In addition to the UAV sprayers, commonly used application methods for coffee production areas with steep slopes and areas suitable for mechanized cultural practices were evaluated (Table 2). In the steeper site (EPAMIG–Machado), spraying was carried out with a combustion-powered backpack mist-blower (STIHL SR 420, STIHL Ferramentas Motorizadas Ltda., São Leopoldo, RS, Brazil) fitted with a conical deflector. In the mechanizable site (EPAMIG–Três Pontas), a tractor-mounted pneumatic air-blast sprayer (Jacto Arbus 400, Máquinas Agrícolas Jacto S.A., Pompeia, SP, Brazil) was used.

Table 2
Technical specifications of the mechanized and backpack sprayers used in the experiment

Specification	Mechanized sprayer	Backpack sprayer
Model	Jacto Arbus 400	Stihl SR 420
Tank capacity (L)	400	13
Fan air velocity (km/h)	146	364
Fan air volume (m^3/s)	10.20	0.21

2.3 Experimental design

The experimental plots were arranged in strips, a sampling layout widely adopted in spray-application studies because it minimizes environmental variability among plots and facilitates treatment comparisons (Biglia et al., 2022; Gil & Escolà, 2009; Miranda-Fuentes et al., 2016). At both sites the same three treatments were evaluated: one strip receiving the conventional farm sprayer and two additional strips treated with the DJI T10 and DJI T30 UAV sprayers, respectively.

At the Três Pontas experimental site, where the flat terrain allows mechanized spraying, the strip treated with the farm's conventional equipment was designated "Mechanized". Applications were carried out with an air-blast sprayer mounted on a TT.75F tractor (New Holland Agriculture, CNH N.V. ©, Curitiba, PR, Brazil) operating in gear L4 at an engine speed of approximately 1950 rpm, which generates a nominal 540 rpm at the power-take-off and a forward speed of about 6.5 km/h. Each strip covered roughly 1320 m^2 and comprised nine coffee rows approximately 41 m long (Figure S1A, Appendix).

At the Machado experimental site, the mountainous terrain prevented mechanized spraying, so the conventional strip, designated "Manual", was treated with a backpack sprayer. Each strip covered about 1440 m^2 and consisted of 12 or 13 coffee rows, depending on the treatment, with rows approximately 41 m long (Figure S1B, Appendix).

The spatial layout of the original treatment strips in Três Pontas and Machado is provided in Figure S1 (Appendix), whereas the overall experimental workflow, including study sites, treatments, canopy sampling structure, response variables, and statistical analysis, is summarized in Figure 1.

2.4 Description of treatments

2.4.1 Conventional method

For the strips treated at the Três Pontas site, the conventional method applied 400 L/ha of spray mixture. The tractor-mounted sprayer traveled between the coffee rows, so both sides of each canopy received spray coverage. Because each strip covered about 1320 m^2, roughly 52.8 L of spray mixture were applied in the "Mechanized" treatment.

For the strips treated at the Machado experimental site, the conventional method also applied 400 L/ha of spray mixture. The backpack sprayer was carried between the coffee rows, ensuring that both sides of each canopy were covered. Given that each strip encompassed roughly 1440 m^2, approximately 57.6 L of spray mixture were applied in the "Manual" treatment.

In summary, the spraying parameters for the DJI Agras T10 and T30 UAV sprayers, along with those for the mechanized and backpack sprayers, are presented in Table 3.

2.4.2 UAV sprayers

In both experimental sites, the plots treated using UAV sprayers received an application rate of 20 L/ha, supplemented with the multifunctional adjuvant CP Essencial Neutro (AgroCP Indústria e Comércio de Fertilizantes LTDA, Santana da Vargem, MG, Brazil), which functions as a spreader–sticker, drift reducer, antifoaming agent, and spray-solution conditioner.

For the Três Pontas site, the spray mixture used for each UAV sprayer contained 5.28 mL of adjuvant (as per the manufacturer's recommendation) and 2.63 L of water, totaling 2.64 L per T10 or T30 UAV sprayer treatment plot. At the Machado site, each mixture consisted of 5.76 mL of adjuvant and 2.87 L of water, totaling 2.88 L per T10 or T30 UAV sprayer treatment plot.

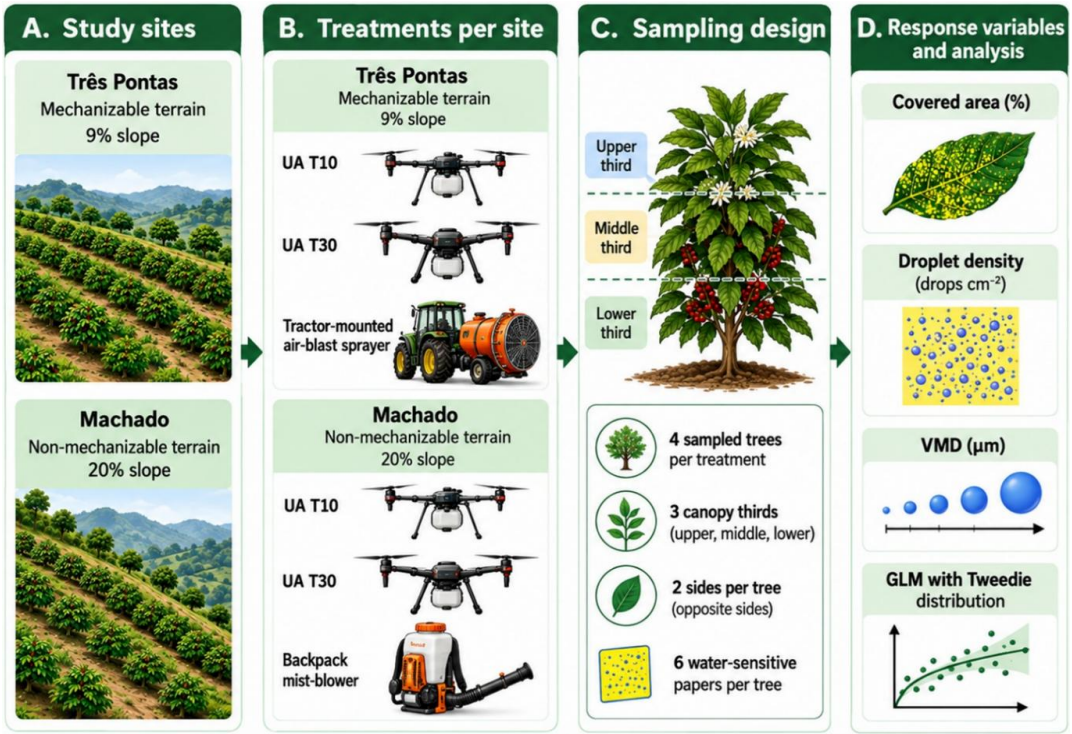


Figure 1. Experimental design used to compare UAV sprayer and conventional spraying methods in mechanizable and non-mechanizable coffee areas.

Table 3
Spraying parameters used in the experiment

Parameter	UAV sprayer	Mechanized sprayer	Backpack sprayer
Flight height	3.0 m above the crop canopy	–	–
Application rate (L/ha)	20	400	400
Travel speed (km/h)	12.00	6.50	3.15
Nozzle type	Hollow-cone	–	–
Application path	Over the coffee row	Between coffee rows	Between coffee rows
Swath width	Based on row spacing	–	–

Prior to spraying, the areas assigned to both UAV sprayer models were surveyed using a DJI Mavic 3M unmanned aircraft (DJI, SZ DJI Technology Co., Ltd., Shenzhen, China) to collect RGB imagery. These images were processed in DJI TERRA software (DJI, SZ DJI Technology Co., Ltd., Shenzhen, China) to generate treatment-specific flight routes, which were then uploaded to the UAV sprayers' flight controllers. Spectral data collection and spraying with the T10 and T30 UAV sprayers were performed using differential correction provided by a D-RTK 2 Mobile Station (DJI, SZ DJI Technology Co., Ltd., Shenzhen, China).

When the spray flight plan was created in DJI TERRA, a calibration point was set to correct any ortho-mosaic displacement. The flight altitude was fixed at 3 m, and the application path was programmed so that the UAV sprayer sprayed directly over each coffee row, making the spray width equal to the row spacing specific to each experimental field.

Once the flight plans generated in DJI TERRA had been uploaded to the UAV sprayer controllers, several pre-spray procedures were performed directly on the controller's spray-system menu. Air was purged from the pump hoses, and the flowmeter was calibrated to ensure that pump output matched the preset application rate. To avoid waste, the mixture expelled during calibration was collected in buckets placed beneath each nozzle and subsequently returned to the UAV sprayer's tank.

Weather conditions were monitored throughout every spraying operation. Air temperature (°C) and relative humidity (%) were recorded with a digital thermo-hygrometer (AKSO, São Leopoldo, RS, Brazil), and wind speed (km/h) was measured with a digital anemometer from the same manufacturer. All applications were performed only within favorable meteorological windows, namely relative humidity above 55 %, wind speed between 2 and 10 km/h, and ambient temperature from 20 °C to 30 °C (Vargas & Gleber, 2005).

2.5 Analyzed variables

In each experimental area, 26 × 76 mm water-sensitive papers (WSpaper Comércio de Papeis Ltda., Presidente Prudente, SP, Brazil) were attached with clips to the adaxial surface of the third pair of leaves on a plagiotropic branch at three canopy heights, lower, middle, and upper thirds, placing one card on each side of the plant, for a total of six cards per tree. Sampling was performed on four randomly selected trees per treatment, with preference given to those located near the center of each treatment strip.

After each treatment had been applied and the water-sensitive papers had dried, droplet quantification and characterization were performed with the DropScope® system (SprayX, São Carlos, SP, Brazil). This system combines an offline application with a wireless digital microscope that captures droplet images directly in the field. Its image sensor accurately detects and counts droplets from the stain patterns, separates partially overlapping spots, and resolves diameters as small as 25 µm.

The report generated by the DropScope® app provided key spray-quality parameters, namely: covered area (the percentage of the analyzed surface occupied by droplets), droplet density (number of droplets per unit area, expressed as droplets cm^{-2}), and volumetric median diameter (VMD, the droplet diameter in µm that splits the total spray volume into two equal halves).

2.6 Data analysis

Each response variable was analyzed separately in R version 4.4.1 in RStudio. Outliers were identified and removed within each treatment group using Tukey's rule. At each site, each application method was evaluated in a single treatment strip, and each strip received one spray application. Four trees were sampled within each strip, and the water-sensitive papers placed on each tree were treated as subsamples. Therefore, the strip was the application unit, whereas trees and papers represented sampling units and subsamples, respectively. Because there was no independent replication of application strips within each site, comparisons among application methods should be interpreted as comparisons among the sampled strips under the evaluated field conditions, rather than as replicated treatment effects.

Given that the response variables were non-negative, right-skewed, and contained several zero or near-zero values, we selected a generalized linear model (GLM) with a Tweedie distribution and logarithmic link function. The Tweedie distribution was chosen based on the empirical characteristics of the data, such as the presence of zeros, asymmetric distribution, and increasing variance with the mean, features that violate assumptions of standard linear models with Gaussian or Gamma distributions.

The model was fitted using the glmmTMB package, with "application method", "canopy third", and their interaction specified as fixed effects. The GLM was used to describe response patterns associated with application method, canopy third, and their interaction within the sampled strips. Plant and paper identifiers were used to describe the sampling structure but were not treated as independent treatment replications.

Model fit was assessed using simulation-based residual diagnostics with the DHARMa package. This included visual inspection of standardized residuals versus predicted values, Q-Q plots, and uniformity tests, confirming the adequacy of model assumptions.

Estimated marginal means were obtained using the emmeans package, and multiple comparisons among factor levels were performed using Tukey's test (adjusted for multiple comparisons), with statistical significance declared at $p < 0.05$.

3. Results and discussion

Throughout the evaluation period, weather conditions remained within safe limits for spraying. Air temperature ranged from 23.9 °C to 26.0 °C, relative humidity from 57 % to 61 %, and wind speed stayed below 1.4 m/s. Applications were carried out during two-time windows: 7:00 – 10:00 a.m. and 5:00 – 8:00 p.m.

3.1 Covered area (%)

The covered area differed markedly among application methods: in all three canopy thirds, the tractor-mounted mechanized sprayer outperformed both the DJI Agras T10 and T30 UAV sprayers (Figure 2A). Thus, in the mechanizable plot, the mechanized system provided greater coverage than the UAV sprayer treatments in every canopy stratum.

When the UAV sprayer applications were compared with the manual backpack method in the steeper plot (Figure 2B), both UAV sprayers achieved significantly higher mean coverage in the upper canopy third. However, no significant differences were detected among application methods in the middle and lower thirds.

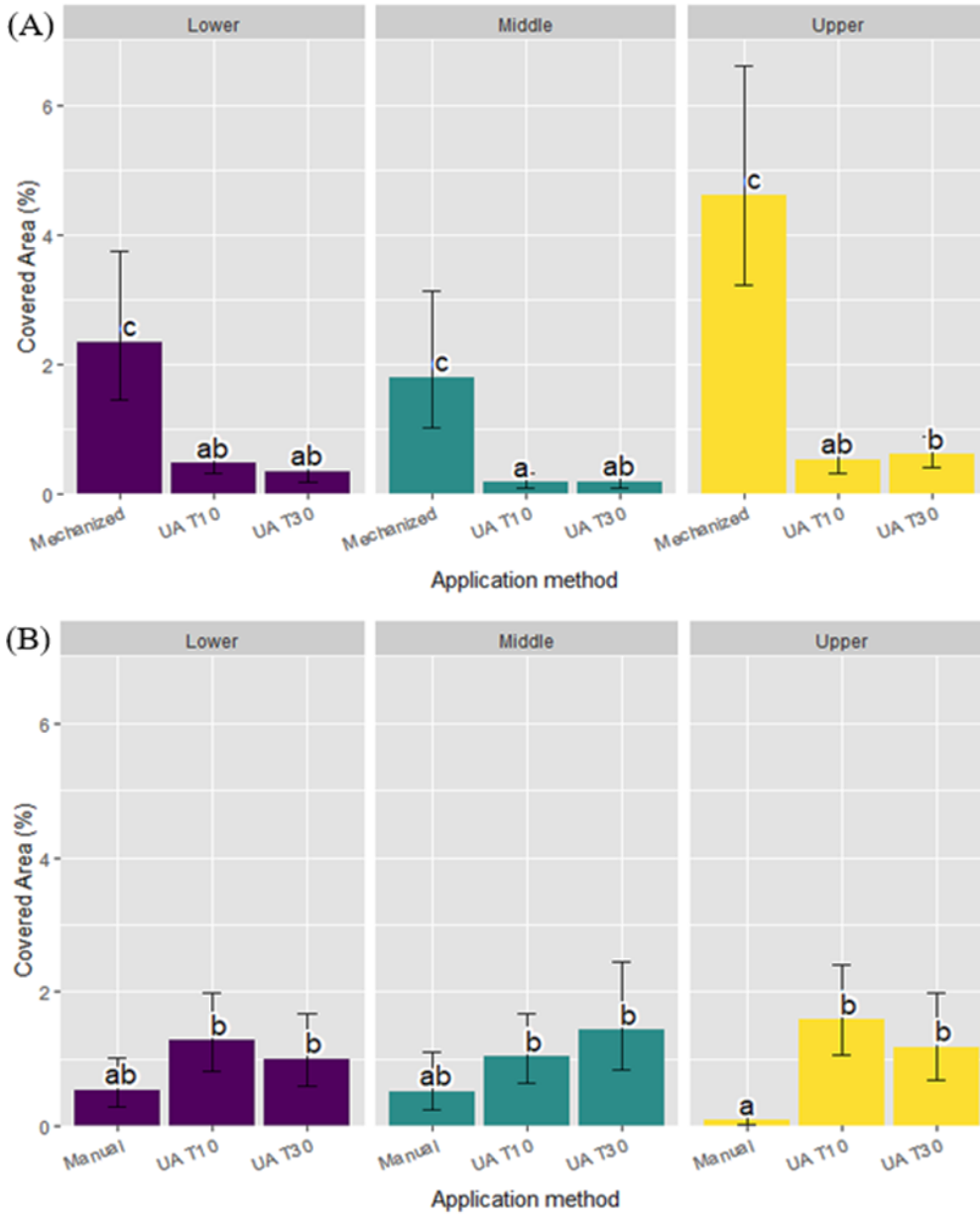


Figure 2. Covered area for the different application methods in the three canopy thirds on flat terrain (A) and on mountainous terrain (B).

When only the upper canopy layer is considered, our findings echo those of Vitória et al. (2023), who also reported similar performance between mechanized spraying and UAV sprayer applications. In the present study, however, the mechanized sprayer produced a markedly larger difference in covered area relative to the UAV sprayers in the middle and lower canopy thirds. This consistent advantage of the mechanized method is likely attributable to the directed airflow generated by the turbo-atomizer.

In comparison between the manual backpack sprayer and the UAV sprayers, the greatest difference in covered area was observed in the upper canopy third, again favoring the UAV sprayer treatments over the manual method. This disparity is likely linked to crop architecture: trees in the non-mechanizable plot average 2.10 m in height, with just 1.35 m between canopy edges along the row, leaving a narrow aisle for the operator. Under such constraints, the discharge tube of the backpack sprayer is held close to the target and preferentially directed toward the lower strata, making it difficult to reach the upper third. Moreover, lifting the discharge tube above head height increases the risk of the spray plume blowing back toward the operator's face, prompting applicators to avoid spraying the upper canopy altogether.

In the lower canopy thirds, the UAV sprayers (T10 and T30) showed no significant advantage over the manual method; covered area values for these treatments on the non-mechanizable slope were statistically identical, reflecting the ease with which an operator using a backpack sprayer can reach the lower strata. In the mechanizable site, however, the tractor-mounted sprayer delivered far greater coverage than the UAV sprayers even in the lower canopy thirds. This result corroborates earlier findings that UAV sprayers struggle to reach the innermost lower foliage, particularly in dense-canopied crops such as coffee (Vitória et al., 2023). Hence, in the lower layers of the canopy, UAV sprayer efficiency was comparable to that of manual backpack spraying but remains inferior to mechanized application whenever terrain allows the use of tractor-driven equipment.

It is important to note that canopy coverage in the different strata of coffee plants is closely linked to the nozzle type used on UAV sprayers. Certain nozzle designs can maximize coverage, as reported for hollow-cone tips (Ribeiro et al., 2023). The specific nozzle model also affects the coefficient of variation (CV): conical nozzles generate lower CVs and more uniform droplet distributions when UAV sprayers spray directly over the crop row, because the spray is concentrated along the center of the swath (Alves et al., 2025). Consequently, the use of hollow-cone tips combined with over-row flight in the present study may explain the lack of significant differences in canopy coverage among UAV sprayer treatments across the upper, middle, and lower thirds, both in mechanizable and non-mechanizable areas.

Reaching the lower canopy third of perennial crops such as coffee is undeniably challenging when spraying with UAV sprayers, particularly when the plants are tall and densely foliated (Silva et al., 2024).

3.2 Droplet density (drops cm^{-2})

As in the case of covered area in the mechanized plot, droplet density was higher when spraying was performed with the air-blast sprayer in every canopy third (Figure 3A), especially in the upper third. Nevertheless, when only the UAV sprayer treatments were compared on the same terrain, the upper third still showed a greater droplet density than the middle third, a pattern not observed for covered area.

Similar results have been reported in other tree crops, such as in eucalyptus sprouts, whose canopy architecture resembles that of coffee because foliage is denser in the middle and lower layers. Even so, higher droplet densities were recorded in the upper canopy layer, since the downward rotor airflow first impinges on the most exposed leaves at the top and only later disperses into the inner canopy, favoring the upper third (Ribeiro et al., 2025).

Conversely, in the non-mechanizable area UAV sprayer applications again outperformed the manual method in the upper canopy third, producing a significantly higher droplet density (Figure 3B). The T10 UAV sprayer delivered more than 50 droplets cm^{-2}, meeting the 30 – 60 droplets cm^{-2} range recommended on many commercial insecticide and fungicide labels, whereas the backpack sprayer did not exceed 5 droplets cm^{-2}.

This difference is probably linked to the position of the water-sensitive paper, fixed to the adaxial surface of the third leaf pair on an upper plagiotropic branch, and to the applicator's spraying motion. With a backpack sprayer on plants roughly 2.10 m tall, the operator moves the lance in a wave-like pattern; at the crest of that wave the spray plume strikes mainly the abaxial side of the top leaves, so the adaxial surface where the paper was attached receives little or no spray. This limitation is critical when evaluating the upper canopy layers of coffee trees on mountainous terrain.

The vertical airflow generated by the UAV sprayers' rotors moves downward through the canopy, covering both leaf surfaces at once and depositing a higher number of droplets on the foliage. This downward stream also helps fine droplets penetrate the plant structure, increasing the likelihood of uniform coverage across the entire canopy, including the lower layers.

Although the differences between the T10 and T30 were not statistically significant, the slightly higher droplet density observed for the T10 may be associated with differences in spray plume concentration and nozzle distribution. Both UAV sprayers operated at the same flight height, speed, spray volume, nozzle model, and over-row flight path; however, the T10 has fewer nozzles and a narrower spraying structure, whereas the T30 is designed with more nozzles and a wider effective spraying width. Under the narrow coffee-row conditions evaluated in this study, a more concentrated spray plume may have favored droplet interception by the target canopy, while the larger spraying system of the T30 may have dispersed part of the droplets laterally or intensified airflow–droplet interactions. Therefore, the small numerical advantage of the T10 should be interpreted as a possible interaction between aircraft geometry, nozzle distribution, rotor downwash, and coffee canopy architecture, rather than as evidence of intrinsic superiority of one model.

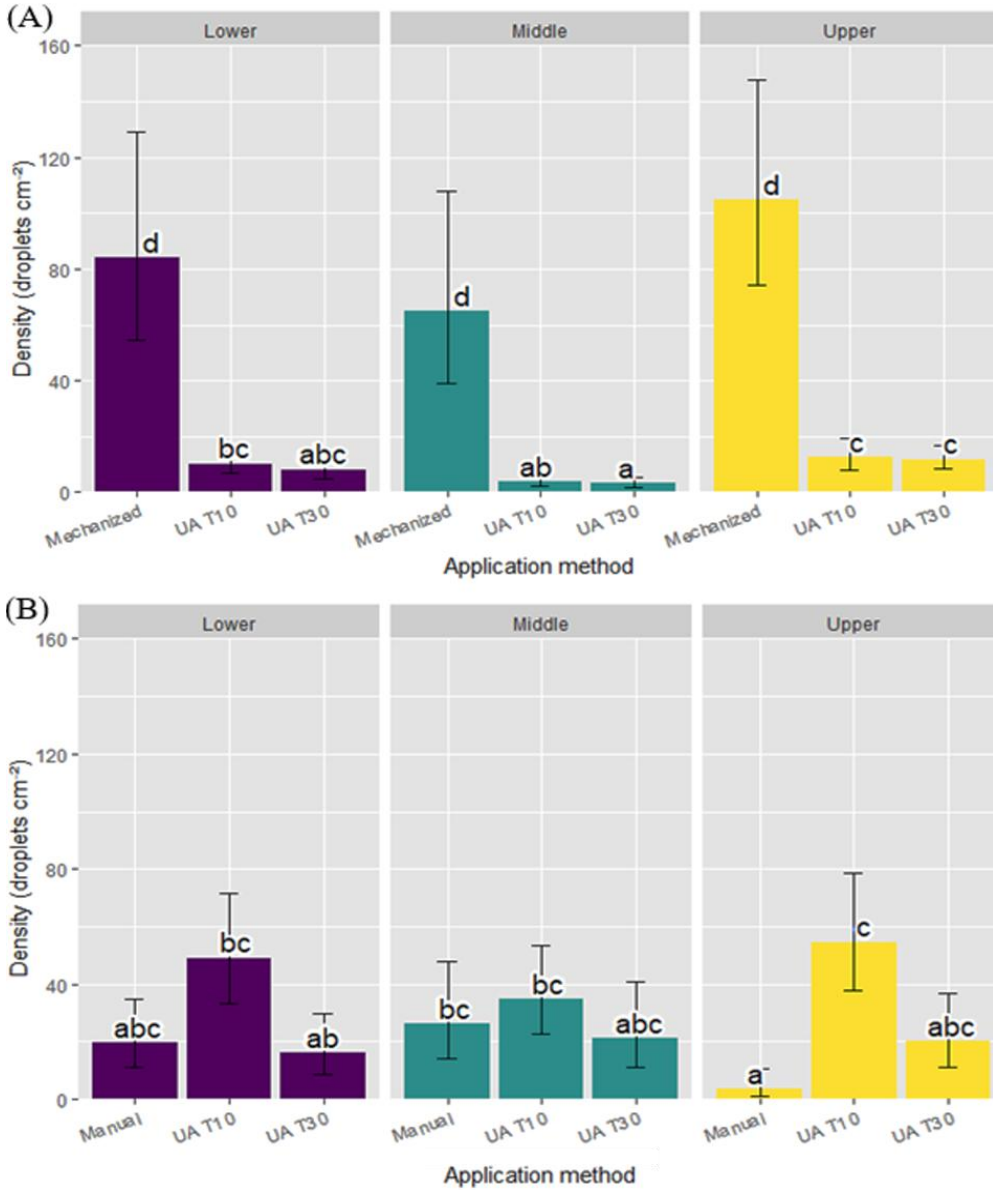


Figure 3. Droplet density (drops cm^{-2}) for the different application methods across the three canopy thirds on flat terrain (A) and mountainous terrain (B).

The critical point concerns the relationship between application rate, droplet density, and active-ingredient (a.i.) concentration. In mechanized spraying, the higher spray volume increases the number of droplets per square centimeter; however, each droplet contains a lower concentration of a.i. because the product is diluted in a larger spray volume. By contrast, UAV sprayers operate at volumes roughly twenty times lower, generating fewer droplets but with a higher a.i. concentration, which may enhance control efficacy, especially for systemic products that translocate within the plant and provide broader protection (Silva et al., 2024; Vitória et al., 2023; G. Wang et al., 2019). Additional research is therefore needed to determine whether this higher per-droplet concentration can improve the control of insect pests and diseases in coffee.

However, droplet density is not determined solely by the application rate; the droplet size produced by each application method must also be considered. Extremely coarse droplets reduce the number of droplets per square centimeter and markedly increase the risk of internal drift, as reported by Ribeiro et al. (2023).

Thus, as illustrated by the representative water-sensitive papers shown in Figure S2 (Appendix), the mechanized sprayer produced finer droplets than the other treatments because the droplets were broken up by the air stream generated by the

turbo-atomizer fan. Consequently, although its spray volume was twenty times greater than that of the UAV sprayers, the droplet density did not rise in the same proportion, precisely due to the smaller droplet size.

To place these findings in context with recent evidence from coffee and other perennial crops, Table S1 (Appendix) summarizes studies involving UAV sprayer applications, conventional spray systems, and canopy deposition responses. Overall, the comparison shows that spray depositions are strongly affected by canopy position, application platform, spray volume, wind conditions, and crop architecture, supporting the interpretation that UAV sprayers should be evaluated as complementary technologies rather than universal replacements for conventional sprayers.

3.3 Volumetric Median Diameter (VMD, µm)

The VMD values obtained for each application method showed very little variation across canopy thirds (Figures 4A and 4B), indicating a narrow droplet-size range and highly uniform spray spectra for all devices. The sole exception was the DJI T30, which produced slightly larger droplets in the middle third than in the upper and lower thirds at the mechanizable site.

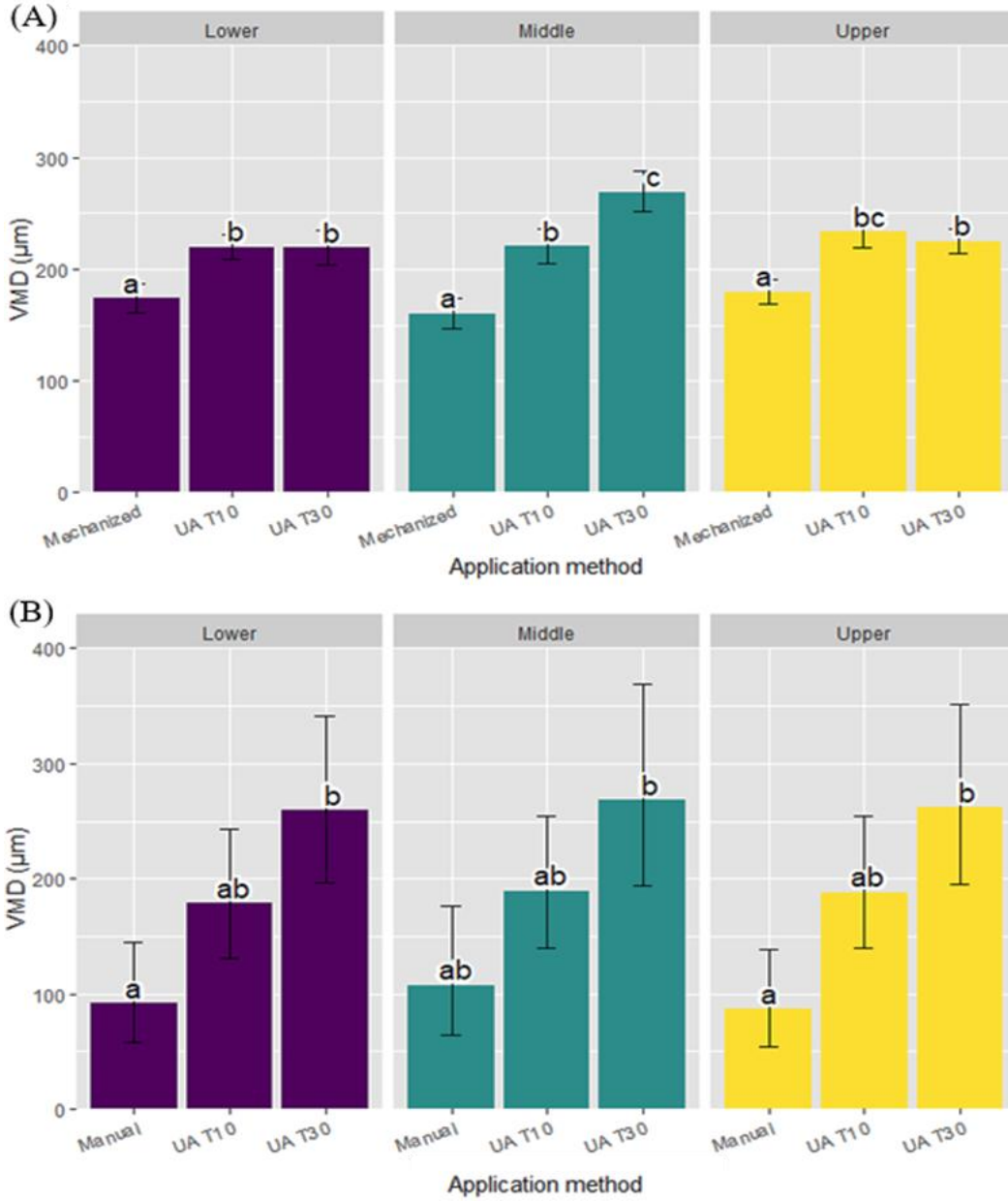


Figure 4. Volumetric median diameter (VMD, µm) for the different application methods in the three canopy thirds on flat terrain (A) and on mountainous terrain (B).

Across both sites, the UAV sprayers produced VMD values that consistently hovered around 220 µm, a predictable outcome given that both UAV sprayer models were equipped with identical hollow-cone nozzles. According to the manufacturer, this nozzle design minimizes variation in VMD, promotes a highly uniform droplet spectrum during application, and consequently helps reduce spray drift.

This uniformity in droplet size across treatments is important, because Silva et al. (2024) noted that greater size variability indicates difficulty in achieving an even spray distribution with UAV sprayers, a common issue in crops with complex canopies such as coffee, where the upper layers typically intercept most of the spray.

However, droplet size uniformity alone does not guarantee high coverage or droplet density, as illustrated in Figures 3 and 4. Smaller droplets generally improve coverage and density by enhancing penetration in shrub-type crops, whereas larger droplets, which carry greater kinetic energy due to their higher mass and velocity, tend to reduce drift inside the canopy but limit coverage in the lower layers (Li et al., 2021; Shan et al., 2022; Vitória et al., 2022).

To reach the lower canopy layers, UAV sprayers exploit the downwash effect, a downward airflow generated by rotor rotation that is regarded as a key factor in droplet distribution and deposition (Lan et al., 2021; Wen et al., 2019). This airflow particularly favors fine droplets (Wang et al., 2023) because of the turbulence it creates beneath the plant canopy.

However, while finer droplets can maximize coverage and penetration, they also increase the overall drift potential within the canopy (Ribeiro et al., 2025). This risk is further amplified by manual and mechanized sprayers that rely on high-velocity air streams from turbo-atomizer fans, which produce substantially finer droplets than the UAV sprayers. The large spray volumes typically applied with these ground sprayers exacerbate drift even more.

The backpack pneumatic sprayer used on the non-mechanizable slope produced a VMD of roughly 100 µm. According to the ANSI/ASAE S572.3 droplet-size classification standard (American Society of Agricultural and Biological Engineers, 2025), this corresponds to a "very fine" spray with a high drift potential, especially because the diameter below which 10 percent of the spray volume is contained (D0.1) was about 55 µm. This smaller VMD compared with the other treatments, and particularly with the tractor-mounted air-blast sprayer, is likely due to the high air velocity generated by the backpack unit's fan, which fragments the spray into finer droplets even though its total air volume is much lower.

According to the ANSI/ASAE S572.3 droplet-size classification standard (American Society of Agricultural and Biological Engineers, 2025), the mechanized sprayer produced fine droplets, and the UAV sprayers, with a VMD around 220 µm, also fell within the fine category, consistent with the manufacturer's specifications for the FlexDROP CVE-9001 hollow-cone nozzle. This droplet size is a desirable feature of cone nozzles because fine droplets penetrate dense canopies more easily, especially when delivered by an air-blast sprayer, thereby increasing coverage, droplet density, deposition, and overall spray uniformity (Ribeiro et al., 2023).

Although the droplets produced by UAV sprayers were in the fine range, this smaller size is beneficial for improving penetration into the lower canopy, a critical factor for effective pest and disease control. Finer droplets are also more prone to drift and evaporation (Silva et al., 2024). However, although fine droplets are more susceptible to drift and evaporation, adding the multifunctional adjuvant that acts as a spreader-sticker, drift reducer, antifoaming agent, and water conditioner may have helped keep drift to a minimum. Tank-mix adjuvants that include drift-reducing agents have been shown to shorten drift distances compared with water alone and to enhance crop coverage, thereby increasing resource efficiency and lowering environmental impacts (Semenišin et al., 2025).

Overall, most sampling points showed that both UAV sprayers (T10 and T30) favored the upper canopy third, regardless of terrain type and under the operational settings used in this study; the mechanized air-blast sprayer in the mechanizable field displayed the same pattern. In the steep, non-mechanizable area, however, the manual backpack sprayer favored the middle canopy third, since this zone imposes the least ergonomic restriction on operators during spraying, one of the main challenges associated with backpack equipment, especially on mountainous slopes (Ribeiro et al., 2025).

4. Conclusions

In terrain that allows mechanized plant protection, the air-blast sprayer provided higher spray quality than UAV sprayer applications for both covered area and droplet density in every canopy third, largely because the continuous axial airflow generated by the sprayer enhanced droplet penetration into the dense coffee canopy. In sloped

areas where backpack sprayers are traditionally used, UAV sprayers proved to be a viable alternative to manual application, especially in the upper canopy third, and yielded results comparable to the manual method in the middle and lower thirds for the variables evaluated. Although the two UAV sprayer models showed no significant differences for the variables evaluated when operating on the same type of terrain, their performance diverged between mechanizable and non-mechanizable areas, indicating that slope affects spraying efficiency. Overall, these results highlight UAV sprayer applications as a technically viable solution for mountainous coffee cultivation, while conventional mechanized sprayers remain superior under flat conditions; future research should integrate deposition data with pest-control efficacy, cost analysis, and operational logistics to guide adoption.

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Ethics approval
Not applicable. This study did not involve humans or animals.

Conflicts of interest
The authors declare no conflict of interest.

Data availability
Data is available from the corresponding author upon reasonable request.

Authors' contribution
R. F. Q. Alves: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft. **T. O. C. Barboza:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **V. C. Figueiredo:** Investigation. **A. D. Ferreira:** Funding acquisition, Resources, Writing – review & editing. **G. R. Carvalho:** Funding acquisition, Resources. **A. F. dos Santos:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Appendix



(A)



(B)

Figure S1. Plot layout for the experimental fields in Três Pontas (A) and Machado (B).

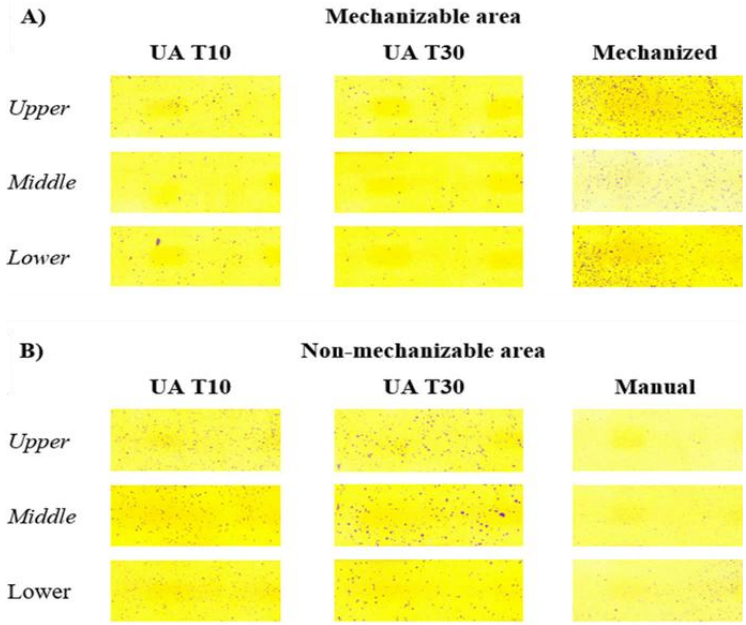


Figure S2. Droplet distribution on water-sensitive papers for the different application methods across the three canopy thirds on mechanizable and non-mechanizable terrain.

Table S1
Comparison of recent studies on spray deposition and UAV/RPA spraying in coffee and related perennial crops

Study	Crop/system	Platform	Assessment	Main finding	Use in present discussion
Vitória et al. (2023)	Mountain coffee (*Coffea arabica*)	UA and pneumatic sprayer	Disease control, deposition and coverage	UA spraying was technically feasible for disease management in mountain coffee, with performance comparable to the conventional method in part of the canopy.	Supports the viability of UAV in steep coffee areas and provides a direct comparison with a conventional ground sprayer.
Silva et al. (2024)	Coffee plants of different ages	Spray drone	Spray volume, flight speed and deposition efficiency	Operational settings and plant architecture affected spray efficiency in coffee.	Supports discussion of canopy architecture, flight settings and deposition differences among canopy thirds.
Marques Filho et al. (2025)	*Coffea arabica*	Remotely piloted aircraft; two spray systems	Water-sensitive papers and droplet deposition	Canopy position was the main factor affecting deposition; internal canopy positions received few droplets.	Reinforces the relevance of evaluating lower, middle and upper canopy thirds.
Nishimoto e al. (2026)	Commercial coffee farms	Aerial and ground-based spray systems	Coverage, density, droplet-size metrics, canopy position and wind	Canopy position and wind strongly influenced deposition, and deposition differed between aerial and ground systems.	Supports the interpretation that UA performance is context-dependent and complementary to ground-based systems.
Vitória & Oliveira Ribeiro (2026)	Dense *Coffea canephora*	Remotely piloted aircraft	Coverage, density, deposition, VMD and residue	Increasing application rate from 5 to 15 L ha^{-1} increased coverage and deposition; 10–15 L ha^{-1} was indicated for dense conilon coffee.	Shows that application rate and canopy structure strongly affect deposition in coffee.
Rodrigues et al. (2026)	Coffee with coffee berry borer	Low-volume remotely piloted aircraft with adjuvants	Deposition tracer and pest control efficacy	Low-volume RPA spraying with adjuvants affected deposition and coffee berry borer control.	Connects deposition results with biological efficacy, supporting the recommendation for future pest-control validation.
Present study	*Coffea arabica* under mechanizable and non-mechanizable terrain	UA T10, UA T30, tractor-mounted air-blast sprayer and backpack mist-blower	Covered area, droplet density and VMD across three canopy thirds	The tractor-mounted air-blast sprayer had greater coverage and droplet density where mechanization was possible; UAV improved upper-canopy deposition compared with the backpack mist-blower in the non-mechanizable area.	Highlights that spray-system choice should depend on terrain accessibility and canopy position.