https://doi.org/10.71252/2177-34912026730010
ISSN: 2177-3491

revista Ceres

Drift and deposition on coffee trees using a hydropneumatic sprayer at different application rates[1]

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[1] This article was extracted from the first author's Master Dissertation which is available at http://doi.org/10.14393/ufu.di.2024.455

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Editors:
Marihus Altoé Baldotto

Submitted: July 7th, 2025.
Accepted: June 21st, 2026.

ABSTRACT

Spraying is essential for applying nutrient solution and phytosanitary treatments, necessitating efficient deposition on the target areas. However, during application, some of the spray solution drifts into the environment. Therefore, understanding the effectiveness of spraying equipment is crucial to reduce losses. This study aimed to evaluate spray deposition on leaves and drift above the canopy, on the soil, and on leaves in rows adjacent to the target area using a hydropneumatic sprayer at different application rates. The JA1 and MAG2 nozzles were used to spray 200 and 400 L ha^{-1}, respectively. Deposition was evaluated by incorporating a marker into the solution and subsequently analyzing it via spectrophotometry. The assessment covered included four adjacent rows on each side of the sprayer. The application rate, side, and row were used to fit a linear mixed model, with the means being compared using the Tukey test with Šidák correction. All parameters exhibited greater deposition on the left side compared to the right, with increased deposition on the right side only occurring due to a wind direction. Drift was detected on the soil, above the canopy, and up to the fourth assessed row, influenced by application rate, wind direction and droplet classification.

Keywords: spray losses, spray tank, air jet sprayer, *Coffea arabica* L.

INTRODUCTION

Coffee production (*Coffea arabica* L.) is a crucial agricultural activity, with Brazil being the world's largest producer and exporter.[1] Coffee crops are susceptible to attacks by pests and diseases, often requiring chemical control measures.

In coffee production, spraying could be used to apply nutrient solutions and phytosanitary treatments. The central objective of this method is to homogeneously deposit the solution on the plant, ensuring the application of the correct dose to effectively control the desired target with minimum losses to the environment. Nevertheless, part of the spray may not reach the target during application, be deposited directly on the soil, drip off the plants, or be drifted by air currents.[2] Thus, the spraying equipment needs to be optimized to guarantee correct application and effective phytosanitary control, enhancing environmental safety.

Hydropneumatic sprayers are mostly used in vertical crops, such as citrus, vineyards, and trees, for lateral spraying and upward the canopy with an airflow.[3] Speed, air volume, application rate, nozzle type, and the best nozzle orientation for the vegetation sprayed should be considered to correctly adjust the sprayer.[2]

Palma et al[4] evaluated two droplet classifications (fine and coarse), two application rates (250 and 400 L ha^{-1}), and two adjuvants, reporting that droplet classification was the most essential factor for solution deposition in coffee crops, followed by the use of adjuvants and the interaction between adjuvants and application rates, and that the application rate strongly influenced coverage and droplet density.

Alves et al[5] analyzed solution deposition on coffee leaves and Petri dishes placed on the soil. They considered different application rates, canopy volumes, and phenological stages, reporting that plate deposition increased as the application rate increased, regardless of phenological stage or canopy volume. Studies have been conducted evaluating deposition at different application rates and losses to the soil near the sprayed area. However, little is known about the behavior of these characteristics in areas adjacent to the target zone within the coffee field on both sides of the hydropneumatic sprayer.

Crause et al[6] analyzed conilon coffee (*Coffea canephora* Pierre ex Froehner) and reported that drift decreased as the distance from the target increased, with greater drift up to 15 m from the area where the solution was applied using a hydropneumatic sprayer at a rate of 600 L ha^{-1}. Kasner et al[7] observed drift in an orchard up to 52 m in the direction of the wind using a hydropneumatic sprayer. Drift tests have been conducted using hydropneumatic sprayers in other tree crops. However, few studies have evaluated drift in rows adjacent to the sprayed area in coffee crops.

Therefore, this study aimed to evaluate deposition in a target area planted with *Coffea arabica* L and drift above the canopy, on the soil, and on leaves in rows adjacent to the target area using a hydropneumatic sprayer at different application rates.

MATERIAL AND METHODS

The study was conducted at the Jataí farm, in Monte Carmelo, Minas Gerais, Brazil, in May 2023 (18°49'21,4" S, 47°22'45,4" W, average altitude of 1,000 m) in April 2023. We used an Arbus 2000 TF 2P hydropneumatic sprayer (Jacto, Pompeia, SP, Brazil) with twelve nozzles on each bar (totaling 24 nozzles), a manual section control, an 850 mm nine-blade fan with a fixed angle, an air speed of 26 m s^{-1}, and an air volume of 11.2 m^3 s^{-1}. The sprayer was operated using a 275 Massey Ferguson tractor of 55 kW (Massey Ferguson, Itu, SP, Brazil), at a working speed of 6.85 km h^{-1}.

Drift was measured above the canopy, on the soil, and on leaves in rows adjacent to the target area using a 2 × 2 × 4 hierarchical factorial design with five repetitions, at two application rates (200 and 400 L ha^{-1}), on both sides of the sprayer (left and right), and on four rows adjacent to the target area (Left side, L1, L2, L3 and L4; Right side, R1, R2, R3 and R4) (Figure 1).

Deposition was measured in the target area using a 2 × 2 × 3 hierarchical factorial design with five repetitions, at two application rates (200 and 400 L ha^{-1}), on both sides of the sprayer (left and right), and on three-thirds of the plant (top, middle, and bottom).

We used the ceramic JA1 (Jacto, Pompeia, SP, Brazil) and MAG2 (Magnojet, Ibaiti, PR, Brazil) hollow conical nozzles at an angle of 80°, with a nozzle filter 50 mesh, at application rates of 200 and 400 L ha^{-1} and working pressures of 482 and 585 kPa, respectively. The droplet spectrum was evaluated at working pressure using a portable VisiSize P15 particle analyzer (Oxford Lasers, Didcot, Oxfordshire, United Kingdom).

The sprayer was calibrated after determining the flow rate at all nozzles, with a coefficient of variation (CV) of 4.06% for the JA1 nozzles and 2.52% for the MAG2 nozzles. The drifts above the canopy and directly on the soil were reduced by aligning the angle of the nozzles toward the canopy at a mean height of 2.75 m.

The deposition was determined by incorporating 1.0 kg ha^{-1} brilliant blue dye (Food, Drug & Cosmetic) into the solution for subsequent spectrophotometry. A total of 200 L of the spray solution was prepared for each application rate (200 and 400 L ha^{-1}), added with 1.0 kg and 0.5 kg of dye, respectively. The sprayer was washed with water between sprays to rinse off the dye.

An ITWH1080 meteorological station (Instrutemp, Belenzinho, SP, Brazil) was positioned near the coffee plot at a height of 2.75 m from the soil to monitor meteorological conditions at the time of application (Table 1).

The experiment was conducted in an area with five-year-old coffee plants of Mundo Novo cultivar spaced 3.8 × 0.60 m. The plot was 2.75 m high and 1.54 m wide, totaling a tree row volume of 11,144.73 m³ ha^{-1}.[(8)] The analyzed areas were 38 m wide and 27 m long, with 50 m spacing.

The treatments were randomized, and the sample was hierarchically collected from each assessed area (side and row). The drift above the canopy was assessed using a 1-m long and 0.016-m wide polyethylene tape placed on a PVC (polyvinyl chloride) support fixed to the orthotropic branch to ensure that the tape was 0.01 m above the canopy, perpendicular to the spray direction on the rows adjacent to the target area (Figure 1). The drift to the soil was assessed using a 0.14-m Petri dish positioned between rows and in the same direction as adjacent rows. Drift was evaluated on adjacent rows using the third or fourth pair of leaves from the end of branches in the middle and upper thirds of the same plants where the PVC support was installed, which were 1.4 m and 2.3 m above the soil, respectively.

The deposition was evaluated in the target area using a pair of external (third or fourth pair from the end of the branch) and internal (second or third pair from the orthotropic branch) leaves collected from each side of the sprayer at different thirds. The treatments were randomized, and the sample was hierarchically collected from each assessed area (side and third).

All the samples were separately packed in plastic bags and placed in polystyrene boxes to maintain the

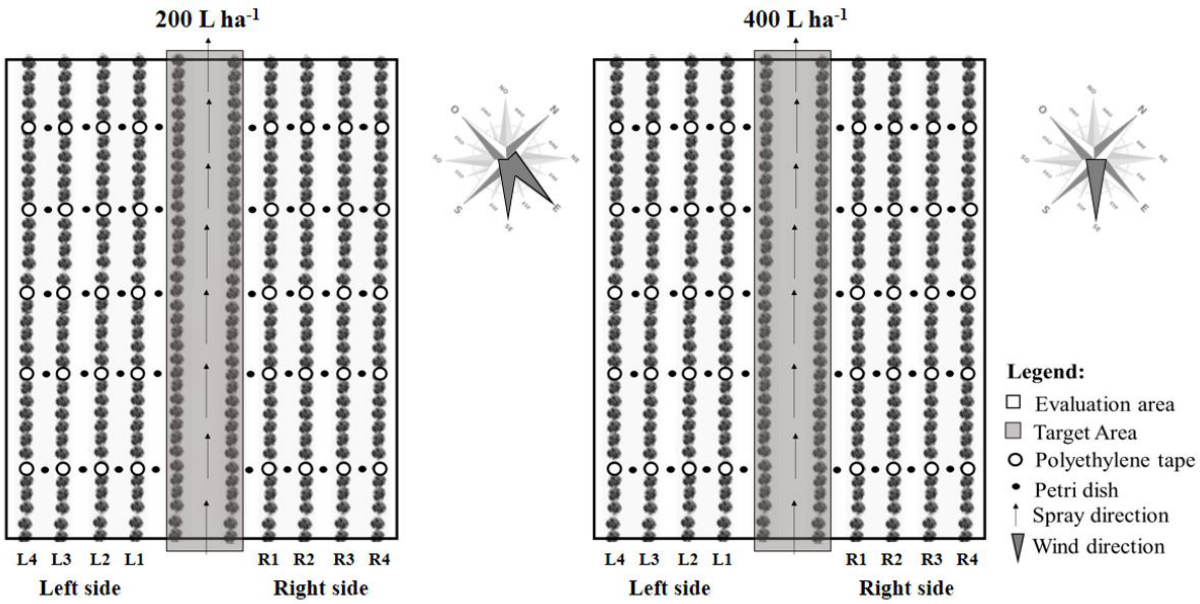

Figure 1. Layout of spray drift collectors above the canopy and on the soil in the assessed area and wind direction at the time of application.

Table 1. Mean weather conditions during the study

Application rate (L ha^{-1})	Temperature (°C)	Wind speed (m s^{-1})	Wind direction	Relative humidity (%)
200	21.7	1.73	E/SE	77.25
400	21.1	2.88	SE	78.75

temperature and protect them from light for subsequent laboratory analysis. Each sample was administered with 20 mL of distilled water and shaken for thirty seconds to recover the dye. The liquid was then transferred to plastic cups and left for 24 h in a refrigerator.

Subsequently, an aliquot of 3 mL was gathered from the cups and placed into glass cuvettes for spectrophotometric reading on an ESPEC-V-5000 digital spectrophotometer (Tecnal, Piracicaba, SP, Brazil) at a wavelength of 630 nm. The tracer deposit was determined per unit area (µg cm^{-2}) using the calibration curve, sample dilution volume, and collectors' area.(4) Leaf area was determined by a Leaf Area Meter LI-3100C benchtop meter (Li-Cor, Lincoln, Nebraska, USA).

The parameter analysis was performed using the R software version 4.3.(9) The incidence of extreme data and outliers was verified through a boxplot test and removed from the analysis. A linear mixed model was fitted using the lme4 package,(10) where the model parameters were estimated using restricted maximum likelihood.(7) Assumptions of homoscedasticity, data normality, linearity, and independence were checked through the QQ-plots analysis.(11)

The application rates, rows, sides, their interactions, and their isolated effects were considered fixed factors for the model. The hierarchical structure of the collection was considered random, consisting of a row, a side, and a block for drift above the canopy and on the soil. Thirds, inside the row, sides, and blocks were considered for drift on the leaf. The rates, sides, and thirds were fixed factors for deposition in the target area; for the random factor, within thirds, sides, and blocks were the positions used.

A mixed model incorporating all fixed and random factors of the plot was initially constructed to find the best fit for the data. In cases where the convergence of the model was not observed, mainly because of its high complexity for the analyzed database, a new model was tested by reducing the complexity between the interaction of fixed factors and the structure of the random model. When significant differences were observed, the estimated means of the factors were compared using the Tukey test, with Sidak adjustment, using the emmeans package.(12)

RESULTS AND DISCUSSION

The mean volumetric diameter at working pressure were 97.64 and 100.06 µm Dv10, 117.26 and 132.46 µm Dv50, 169.88 and 237.18 µm Dv90, and 12.82 and 9.04 V100% for the JA1 and MAG2 nozzles, respectively. JA1 exhibited a lower Dv50 despite both tips having very fine droplets (Dv50 100–150 µm) according to the American Society of Agricultural and Biological Engineers S572.3 spray nozzle classification by droplet spectra.(13) The lower Dv50 and higher V100% for the JA1 nozzle indicate greater drift potential at an application rate of 200 L ha^{-1}, confirming the observations of other studies.(14)

Deposition on plants in the target area showed an interaction between application rates and spraying sides (Table 2). The deposition was 40.4% higher on the left side at an application rate of 400 L ha^{-1} than at a rate of 200 L ha^{-1}, which can be justified by the effect of wind direction increasing drifting to the right side at a rate of 200 L ha^{-1}. An additional factor that may explain greater deposition at the rate of 400 L ha^{-1} on the left side is the greater spray volume, with greater droplet coverage on the leaves consequently leading to greater product deposition.(4) There was no significant difference between application rates on the right side.

There was no difference between spraying sides at a rate of 200 L ha^{-1}. At a rate of 400 L ha^{-1}, deposition was 32.2% greater on the left side. This result can be explained

Table 2. Deposition on coffee trees in the target area by application rates, spray sides, and effect of plant thirds

Application rate (L ha^{-1})	Deposition (µg cm^{-2})	
	Left	Right
200	1.09 bA*	1.36 aA
400	1.83 aA	1.25 aB
Third	**Deposition (µg cm^{-2})**	
Lower	1.38 a	
Medium	1.57 a	
Upper	1.20 a	

* Means followed by the same lowercase letter in the column and uppercase letter in the row are not statistically different from one another based on the Tukey test at 5% probability.

by fan rotation(2,15,16) and wind directions. The Arbus 2000 clockwise turbine direction creates greater deposition on the left side at an application rate of 400 L ha^{-1}. This effect was not observed at a rate of 200 L ha^{-1} likely due to the east/southeast wind direction at the time of application, which favored spray drifting to the right side, in contrast with the 400 L ha^{-1} rate, at which the southeast wind direction increased drifting in the opposite direction at an angle of 180° relative to the spray line.

There was no significant deposition difference between plant thirds, which indicates uniform application at both application rates. Alves et al(5) observed greater deposition in the middle third. The uniform application can be explained by correct nozzle angle adjustment toward the canopy, which affects solution distribution on the canopy.(15)

Drifting one meter above the canopy and on leaves in the middle and upper thirds was influenced by the interaction between the row adjacent to the target area and the application rate and side (Table 3). Evaluating drift above the canopy and between the rows, for the rate of 200 L ha^{-1}, there was a difference only on the right side with greater drift on rows 1, 2, 4, and 3, successively. This result can be explained by the finer droplets produced at this rate and by wind direction, which favored spray drift to the right side. A study has shown the interference of wind direction on spray drift.(17) Wind direction and the parabolic trajectory of droplets resulted in lower deposition on R3, an effect that increased deposition above the canopy 15.2 m away from the target area (R4) compared to deposition at 11.4 m (R3).

For drift on the leaf, this effect of significant difference between rows to the right side at a rate of 200 L ha^{-1} was also observed with greater drift of the dye in R1 followed by R2 and lower drift in rows 3 and 4, which did not significantly differ from each other. Garcerá et al(17) reported that wind direction influenced drift between sprayer sides, but did not reverse the variation caused by airflow from the fan.

For the rate of 400 L ha^{-1}, the difference between subsequent rows was observed only on the left side with greater drift above the canopy observed on R2, followed by rows 1 and 3, and lower drift on R41. Drift on the leaf at this rate also showed a difference only on the left side with greater drift on R1 followed by R3 and R2 and lower deposition on R4. There was no significant difference between rows on the right side.

This effect of the difference between rows on this side occurs due to the upward movement of air from the turbine

Table 3. Drifting above the canopy and on a leaf in rows adjacent to the target area by application rate and side

Drift above the canopy			
Row	**Application rate (L ha^{-1})**	**Deposition (µg cm^{-2})**	
		Left	**Right**
1	200	0.529 bB α*	0.258 bA γ
	400	0.355 aB αβ	0.092 aA α
2	200	0.425 aB α	0.227 bA βγ
	400	0.399 aB β	0.046 aA α
3	200	0.488 bB α	0.069 aA α
	400	0.371 aB αβ	0.123 aA α
4	200	0.412 bB α	0.100 aA αβ
	400	0.248 aB α	0.016 aA α
Drift on the leaf			
Row	**Application rates (L ha^{-1})**	**Deposition (µg cm^{-2})**	
		Left	**Right**
1	200	0.244 aA α*	0.224 bA β
	400	0.290 bB γ	0.104 aA α
2	200	0.292 bB α	0.187 bA αβ
	400	0.228 aB αβ	0.057 aA α
3	200	0.261 aB α	0.166 bA α
	400	0.255 aB βγ	0.052 aA α
4	200	0.266 bB α	0.146 bA α
	400	0.199 aB α	0.093 aA α

* Means followed by the same lowercase letter in the column, uppercase letter in the row, and Greek letter between rows are not statistically different from one another based on the Tukey test at 5% probability.

to this side of the spray, which directed the drops above the canopy, tracing a trajectory that favored drift on R2 for drift above the canopy and an increase observed in the R3 for drift on the leaf. Other studies have reported the effect of the parabolic trajectory of the droplets.[18] Different from the rate of 200 L ha^{-1}, there was no drag effect of the cloud due to the wind direction, with the prevalence of the effect of asymmetry on the sides of the spray.[17,19] For the right side, this effect was not observed due to the direction of the turbine, which favors a downward direction toward that side of the spray, producing fewer drops above the canopy.

Evaluating the effect of the application rate on the left side, rows 1, 3, and 4 showed greater drift above the canopy for the rate of 200 L ha^{-1}. For drift on the leaf, on this side, the rate of 200 L ha^{-1} showed less deposition on R1 and greater deposition on R2 and R4; for R3, there was no difference between the rates. The greater drift is explained due to the lower Dv50 and higher V100% produced by the tip at a rate of 200 L ha^{-1}, with drops more susceptible to the air intensity of the fan, which also allowed greater drift over long distances. Less deposition was observed in the target area for the rate on that side.[14]

Drift above the canopy was statistically equal between application rates on row two. According to the speed of the air produced and the direction of the tip relative to the canopy, the inertia caused by thicker drops at a rate of 400 L ha^{-1} resulted in a route that favored greater deposition to the left side on this row, where gravity exerted greater influence for the thicker droplet class, as observed on row 3 for the drift on the leaf. The largest drift on the leaf on row 1, for the rate of 400 L ha^{-1}, on the left side, can be explained by the horizontal and then upward movement at the sprayer exit, which likely crossed the canopy of the coffee tree in the target area and increased deposition on the leaves of R1, added to the effect of drift above the canopy.[20]

For the right side, drift above the canopy, at the rate of 200 L ha^{-1}, was higher on rows 1 and 2; on rows 3 and 4, there was no difference between application rates. Drift on the leaf, at the rate of 200 L ha^{-1}, exhibited greater dye deposits in all rows assessed. The greatest drift effect for the rate of 200 L ha^{-1} can be explained due to the lower Dv50 observed for this set, with drops more prone to drift, and by the predominantly southeast/east direction of the wind[21] which favored greater drag and greater drift of above the canopy and on the leaf compared to the highest rate, where the predominant wind was east and did not favor the drag of the cloud of drops to this side. Studies show that wind direction changes the direction of the spray jet and influences droplet deposition on targets with or against the wind direction.[7,22]

Evaluating the drift above the canopy on spray sides, there was greater drift toward the left side when compared to the right side for the two application rates and the four subsequent rows studied. For drift on the leaf, only in the first row, at a rate of 200 L ha^{-1}, was there no difference between the sides. All the other rows for this rate and for the rate of 400 L ha^{-1} exhibited greater dye deposition on the left side of the spray compared to the right.

This effect of greater drift to the left side is related to the variation in the fan air distribution, which presents an upward distribution to the left side and a downward distribution to the right side, depending on the direction of the turbine rotation, which can cause greater drift of drops above the coffee tree canopy and favor greater drift to the left side of the spray. Depending on the direction of the fan, which configures an upward or downward movement of the spray, the air exit velocity varies between the sides of the hydropneumatic sprayer and in height, in a vertical profile;[2,23] a higher exit velocity increased deposition volume in height in a vertical profile.[18] Drift on the leaf equal between the left and right sides for the rate of 200 L ha^{-1} occurred due to the direction of the wind at the time of application, which favored the dragging of the dye to the leaves on R1 on the right side.

On drift to the soil, there was an interaction between the factors rate and side. There was no significant difference between subsequent rows (Table 4). A greater drift of the dye to the soil was observed at a rate of 400 L ha^{-1} to the left side relative to the lowest application rate. The effect of greater drift to the soil at this application rate for this side can be explained by a larger droplet size produced by the tip for this rate. Due to the kinetics, thicker drops are more prone to drift to the soil.[17,24,25] For the right side of the spraying, a rate of 200 L ha^{-1} led to greater drift to the soil, as the wind direction favored the dragging of drops to that side. This caused an increase in drift to the soil under this rate compared to 400 L ha^{-1}.

When assessing drift to the soil, on spray sides for both rates, there was greater drift of the dye for the left side compared to the right side, as well as what was observed for drift above the canopy, where part of these drops drifted to the soil in the middle of the line due to the upward movement of the spray to that side, common in hydropneumatic sprayers.[17]

Table 4. Drift to the soil between the coffee tree rows under the interaction of application rates and spray sides, and the effect of subsequent rows

Application rate (L ha^{-1})	Deposition (µg cm^{-2})	
	Left	Right
200	0.222 aB*	0.165 bA
400	0.269 bB	0.098 aA
Row	**Deposition (µg cm^{-2})**	
1	0.214 a	
2	0.191 a	
3	0.186 a	
4	0.163 a	

* Means followed by the same lowercase letter in the column and uppercase letter in the row are not statistically different from one another based on the Tukey test at 5% probability.

For the rows, there was no significant effect observed. However, drift decreased along the assessed range with greater drift to the soil on R1 and reductions of 10.74, 13.08, and 23.83% of product drift on rows 2, 3, and 4, respectively, relative to the first assessment row.

Overall, a rate of 200 L ha^{-1}, in most observations, led to the deposition of more dye above the canopy and on the leaves in subsequent rows due to the pattern of finer droplets produced by the tip being more prone to drift. The greatest drift to the soil and deposition in the target area was observed for 200 L ha^{-1} on the right side, caused by the wind direction and application moment.

A rate of 400 L ha^{-1} led to greater product deposition in the target area and drift to the soil on the left side. Less deposition above the canopy and on the leaves of subsequent rows can be explained by the wind direction not having favored either side of the spraying and by the pattern of thicker drops being less subject to drift and more prone to drift to the soil. Previous studies have demonstrated that adjuvants may influence spray retention and deposition on coffee leaves by altering physicochemical properties of the spray solution, such as surface tension and spreading behavior.[4,26] Future studies should be conducted to evaluate deposition in the target area and spray drift using adjuvants and phytosanitary products in the spray mixture.

An asymmetry was observed between the spray sides, with greater dye deposition in the target area, above the canopy, on the leaves, and on the soil in subsequent rows in general for the left side compared to the right side for both application rates. When this effect was not observed, it was due to the influence of wind direction. Studies have been developed to increase deposition in the canopy and reduce drift on fruit trees by adjusting parameters such as fan speed and spray angle,[18] parameter spraying rate with directed air outlets,[27] change in the fan model,[28] and spraying with canopy volume sensors and airflow adjustment.[29]

CONCLUSIONS

Deposition was asymmetric between the left and right sides of the hydropneumatic sprayer, regardless of the application rate, with greater deposition and drift occurring on the left side of spraying.

Spray drift above the canopy, on leaves, and on the soil in adjacent rows was detected up to the fourth row on both sides of the sprayer.

The application rate of 400 L ha^{-1} increased deposition in the target area and reduced drift above the canopy and on leaves in adjacent rows but increased drift to the soil on the left side.

Under the conditions evaluated in this study, the higher application volume and larger droplets resulted in greater deposition in the target area.

Real-time monitoring of weather conditions, especially wind speed and direction, is important to reduce off-target losses during spray applications in coffee crops.

ACKNOWLEDGEMENTS, FINANCIAL SUPPORT AND FULL DISCLOSURE

To the Federal University of Uberlândia - UFU, Institute of Agricultural Sciences - ICIAG, Postgraduate Program in Agriculture and Geospatial Information - PPAIG and Agricultural Mechanization Excellence Center - CEMA for providing the necessary resources for the development of the experiment.

This research was partially funded by Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), APQ-00434-24 and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) processo nº 401650/2025-1.

The authors inform that there is no conflict of interest in carrying the research and publishing this manuscript.

DATA AVAILABILITY STATEMENT

All data supporting the results of this study are contained within this article.

AUTHOR CONTRIBUTIONS

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