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Application rate and hydraulic tips used in remotely piloted aircraft affect the phytosanitary products in coffee plant canopies

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ABSTRACT. Most coffee (*Coffea arabica)* phytosanitary management techniques are performed using ground-based equipment, and remotely piloted aircraft are a recent alternative. Therefore, this study evaluates the effect of different application rates and hydraulic tips used for spreading phytosanitary products on coffee crops using a remotely piloted aircraft, assisted by artificial targets and dye tracing. The experiment was a 4 × 3 factorial randomized block design with four tips (XR 110-01, TT 110-01, AIXR 110-015, and TTJ60 110-02) and three application rates (8, 12, and 16 L ha^{-1}). Hydrosensitive paper was used to analyze the droplet spectrum, and the Brilliant Blue tracer was used to detect spray deposition. The DJI Agras T20 remotely piloted aircraft was used to apply the phytosanitary product. Speed, flight height, and application range were maintained at 5.56 m s^{-1}, 2 m, and 5 m, respectively. The flight direction was perpendicular to the crop planting lines. The application rate and hydraulic tip jointly controlled the accumulation of droplets on the target according to its position in the plant canopy. Therefore, remotely piloted aircraft can be used in coffee phytosanitary management, particularly to control targets that predominately occur in the upper third of the plant canopy.

Keywords: deposition; droplet spectrum; drone; aerial application; *Coffea arabica.*

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Introduction

Brazil is a global leader in coffee (*Coffea arabica*) production. Coffee plantations employ a large population in the country's different producing regions. Edaphoclimatic conditions in Brazil are beneficial for coffee cultivation; however, harmful agents such as insects and diseases diminish the cultivation efficiency. Additionally, the topography in many coffee-producing regions limits the mechanization of crop management.

The state of Minas Gerais is a large coffee-producing area, and the greatest production occurs in the Cerrado region, where almost all crop management practices are automated. The management of insects and diseases is traditionally ground-based, using turbo atomizers. However, this process is slow and only treats a small area each time the tractor-mounted sprayer passes a canopy, resulting in a low operational capacity.

Verbiest, Ruysen, Vanwalleghem, Demeester, and Kellens (2021) found that the sprayers used to treat tree crops are relatively primitive and require technological support for enhancing their application. These factors have contributed to the adoption of new techniques as alternatives to traditional ground-based applications for overcoming various limitations (Salcedo, Fonte, Grella, Garcerá, & Chueca, 2021; Santos, Santos, Moreira, Lima, & Lino, 2021).

In the Minas Gerais region, coffee growers have not yet widely adopted the use of human-crewed aircraft for the application of phytosanitary aerosols. However, with the emergence of companies providing remotely piloted aircraft (RPA) services for annual crops, the feasibility of this technique for coffee plants is under consideration. Additionally, the treatment period for several pests that infect coffee coincides with the soybean fallow period, when the demand for grain crops decreases significantly, thus increasing aircraft availability for phytosanitary management.

Phytosanitary treatment with RPA requires specific meteorological conditions that are favorable for the use of this technology. However, a more directed application of the phytosanitary product on the targeted crop may minimize adverse effects on beneficial organisms. Targeted application can increase the survival rate of the natural enemies of pests, which may decrease the selective pressure of pests. Furthermore, RPA allows targeted applications in fields that are difficult to access with ground-based equipment (Carvalho, Chechetto, Mota, & Antuniassi, 2020). In steep topographic regions, such as the south of the Minas Gerais and the Espiríto Santo state, the RPA has become an alternative to electric or manual knapsack sprayers, which have a greater risk of human toxicity". Thus, RPA has attracted considerable attention for precision pest management owing to its low labor requirement, short application duration, flexibility, safety, and efficiency (Lost Filho, Heldens, Kong, & Lange, 2020).

In Brazilian coffee growing conditions, there is a need to evaluate appropriate spray system configurations and operating parameters for phytosanitary product application using RPA. Thus, field evaluations can assist in developing and implementing this technology, as indicated by He (2018). Therefore, to evaluate the effectiveness, safety, and quality of application of the RPA technique, the criteria should include the settling and coverage of droplets, drift risk, penetration into the crop canopy, aerodynamics of the spray jet, and interactions with environmental factors, such as wind speed and direction, temperature, and humidity. According to Guo et al. (2021) and Salcedo et al. (2021), the importance of these factors depends on the conditions of the equipment, application rate, and crop.

Studies have been conducted on phytosanitary product application using RPA; however, only a few have focused on coffee trees. Thus, data obtained from field evaluations can benefit producers, consultants, students, and society by providing the most optimized conditions for application in coffee canopies. Chojnacki and Pachuta (2021) showed that multi-copters provide good coverage and spray deposition on the plant canopy. An appropriate droplet size is essential for safe and effective application within good agricultural practices. However, very fine or fine droplets are typically applied using RPA, regardless of the conditions. Pascuzzi et al. (2020) highlighted the need for field research on hydraulic tips that produce coarse droplets. This study was aimed to evaluate the behavior of different application rates and hydraulic tips over coffee crops using a RPA.

Material and methods

The trial was performed in October 2021 at the Adamantina farm (18°44'32.7'' S 47°28'00.9'' W) in the Monte Carmelo municipality, Triângulo Mineiro Region, Minas Gerais State, Brazil. The spray deposition and droplet spectrum analyses were conducted at the Center of Excellence in Agricultural Mechanization, associated with the Federal University of Uberlândia Institute of Agricultural Sciences.

The RPA used in this study was a DJI Agras T20 Table 1 (DJI, Nanshan, Shenzhen, China). This model allows the operator to remotely control the application rate, speed, flight height, and the treatment range. However, the working pressure and flow rate are adjusted automatically, according to the conditions defined by the operator, and can be changed considering operational aspects. In the current study, speed, flight height, and application range were kept constant at 5.56 m s^{-1} (20 km h^{-1}), 2 m, and 5 m, respectively, in all treatments. Additionally, the flight direction was perpendicular to the crop planting lines.

Table 1. Descriptive characteristics of the aircraft.

Reservoir maximum capacity (L)	20
Number of nozzles	8
Application range (m)	4 to 7
Application height (m)	1.5 to 3.0
Flow rate at the flow meter (L $min.^{-1}$)	0.25 to 20

Source: Equipment manual.

Meteorological conditions were monitored using a portable Instrutemp IP44 100MT weather station (model ITWH1080, Marca, São Paulo, SP, Brazil) at 2 m above ground level. The temperature, relative humidity, and wind speed ranged between 20.0 and 27.1°C, 55.0% and 69.7%, and 2.0 and 4.0 km h^{-1}, respectively, with the wind direction predominantly being in the southeasterly direction.

The experiment was performed in a coffee Mundo Novo cultivar plantation planted at 4.00 × 0.70 m spacing and irrigated with a drip irrigation system. At the time of the experiment, plants were 2.50 m high with a crown diameter of 1.37 m. Lateral thinning was performed in 2020; therefore, the canopies had an average density, allowing the good penetration of droplets to the lower and inner parts of the canopy, compared with that in canopies without pruning in the vegetative phase. The experimental plot included 15 plants, and plants at the center and at the extreme ends of borders were considered the focal plants.

The application rates were defined according to standards used by service companies in this sector, making the use of RPA viable from an economic perspective. Based on this information and the average dimensions of the plants according to Miranda et al. (2021), a canopy volume of 8,562.5 m^3 ha^{-1} was estimated using parameters for comparison among crops from different planting seasons and cultivars.

The experiment was conducted in a randomized block design with four replicates, in a 4 × 3 factorial design, with a total of 12 treatments. The treatments consisted of a combination of four TeeJet (Wheaton, St Wheaton, IL, USA) tips (XR 110-01, TT 110-01, AIXR 110-015, and TTJ60 110-02) and three application rates (8, 12, and 16 L ha^{-1}). The tips were manipulated to produce different volumetric median diameters (VMDs) according to the manufacturer's catalog.

The spray deposition was evaluated using water and Brilliant Blue dye (Kolorjet Chemicals, Mumbai, India), internationally cataloged by the Food, Drug & Cosmetic Company as FD&C Blue No. 1, at a dosage of 600 g ha^{-1}. After application, we waited for the dye to fix and then collected samples. Samples were collected from the external and internal positions of the crown on the side facing the path by collecting a pair of leaves from the lower, middle, and upper thirds of each plant (six pairs of leaves per plant), producing a total of 288 leaf samples. Leaves were packed in plastic bags and transported to the laboratory in a Styrofoam box (Mega foam Inc, Istanbul, Turkey) to ensure thermal and light insulation.

In the laboratory, 20 mL of distilled water was added to each plastic bag and then shaken for 30 s to remove the deposited dye from the leaves. Next, the solution was transferred to plastic cups and stored in a refrigerator with light insulation for 24h for the sedimentation of impurities. Subsequently, the absorbance was measured using a 600 Plus Femto spectrophotometer model (FEMTO technological development, São Paulo, SP, Brazil), with 3.5 mL glass cuvettes (Thomas Scientific, Swedesboro, NJ, USA), an optical path length of 10 mm, and a tungsten-halogen lamp (Heraeus manufacturing company, Mumbai, India) for evaluating the absorbance at 630 nm, which is the detection range for the Brilliant Blue dye. The leaf area was then measured using a Li-cor leaf area meter model LI 3100C (Li-cor Biosciences, Lincoln, NE, USA).

Equipment calibration was conducted using a dilution series of a standard solution. The absorbance data were converted into corresponding concentrations (μg L^{-1}). The amount of dye retained on coffee leaves was determined based on the initial spray concentration and the dilution volume of the samples. The total deposited dye was divided by the leaf area of each sample to obtain the amount of dye per leaf area.

Syngenta hydrosensitive paper (Basel, Switzerland) was used to analyze the droplet spectrum for evaluating droplet density; coverage percentage; Dv10, Dv50, and Dv90 (which correspond to droplet diameters such that 10, 50, and 90% of the volume of liquid sprayed is composed of droplets smaller in size than this value); relative amplitude (RA); and potential drift risk (PDR). Data were obtained using DropScope software (v. 2016.1124.1). The hydrosensitive paper was positioned horizontally at the lower and median heights of the crown, attached to the leaves on the axial side at the outer part of the crown, a methodology similar to that adopted by Michael, Gil, Gallart, and Stavrinides (2021) for grapevine crops.

Statistical analysis was performed using R software (R Core Team, 2021). Wilk test was used to determine the normality of residuals. Furthermore, the Anscombe–Tukey test was used to determine the homogeneity of variance. The data were subjected to analysis of variance, and means were compared using Tukey's test. All tests were conducted at a 5% level of significance.

Results and discussion

There is an effect of the hydraulic tips on the technical parameters of the phytosanitary product application on the lower third of the plant. Regarding the droplet spectrum, the AIXR 110-015 tip produced a larger droplet diameter than that produced by other tips. The Dv10 droplets were 49.5 and 49.3% larger than those produced by the XR 110-01 and TT 110-01 tips, respectively. The Dv50 and Dv90 droplets were 66.9% larger than that produced by the TT 110-01 tip. The Span indicated that the TT 110-01 and XR 110-01 tips produced a more uniform droplet spectrum. Furthermore, the target coverage percentage for the AIXR 110-015 tip was 133.8% lower than that for the TT 110-01 tip. Contrarily, the PDR of the TT 110-01 tip was 62.5 and 63.8% greater than those of the AIXR 110-015 and TTJ60 110-02 tips, respectively (Table 2).

Table 2. Effect of hydraulic tips on the application parameters in the lower third of the plant.

Tip	Dv10 (µm)	Dv50 (µm)	Dv90 (µm)	Span	Coverage (%)	PDR (%)
XR 110-01	65.3c	100.3c	137.5c	0.7a	24.8b	43.2a
AIXR 110-015	129.3a	296.4a	401.7a	0.9b	13.0b	17.7b
TT 110-01	65.5c	98.0c	132.7c	0.7a	30.4a	47.2a
TTJ60 110-02	118.8b	161.8b	247.7b	0.8a	16.0b	17.1b
CV (%)	8.3	6.5	6.2	13.8	19.2	13.2
$F_{tip\ (T)}$	223.5*	917.5*	928.0*	10.7*	47.2*	55.9*

Span = Relative amplitude (dimensionless). Means with the same letter in each column are not significantly different, as indicated by Tukey's test at a 5% level of significance. *Significant at 5% level.

The lower third of the canopy is one of the most difficult areas for the droplets to reach, owing to the distance between the hydraulic tip and the plant and also because the natural leaf mass is denser in this part of the canopy. However, the conditions can change in crops after pruning or harvesting (Alves, Cunha, Alves, Silva, & Lemes, 2020). The AIXR 110-015 tip produced a droplet spectrum that enabled safe use considering drift and evaporation, and a less homogeneous application with lower target coverage percentage, although the PDR was not significantly different from that produced by the TTJ60 110-02 tip. Pascuzzi et al. (2020) showed that weather conditions resulted in an application with a lower PDR, despite coarse droplets having difficulties in penetrating the plant canopy owing to the aerodynamic behavior of droplets in the environment, thus emphasizing the importance of PDR in aerial applications using RPA. A similar behavior was observed for the TTJ60 110-02 tip; however, it produced a better RA and a smaller droplet size than those of other tips.

A large droplet size is essential for phytosanitary product application on coffee crops during winter owing to low relative humidity, temperature, and wind currents in the Cerrado region. Therefore, coarse droplets should be considered for aerial applications at low rates. However, tips that produce very fine or fine droplets are generally used for applications on grains, as noted by Chen, Lan, Fritz, Hoffmann, and Liu (2021a). Droplet size is correlated with the meteorological conditions at the time of application. According to Chen, Li, Wu, Wang, and Kang (2022), with a higher application rate, a better penetration potential and coverage are obtained with a more uniform distribution of spray in the leaf canopy. However, larger droplets have greater susceptibility to drift and evaporation, which is a key aspect when the coverage required is larger than that produced by tips with very fine and fine droplets. Therefore, the behavior of AIXR 110-015 and TTJ60 110-02 tips should be considered so that the applicator can adjust the droplet size to suit other application parameters, such as the PDR, which did not differ among the tips.

The leaf coverage percentage is fundamental for the phytosanitary treatment of coffee crops. An adequate application rate from the spray tip is necessary to produce the droplet size required for effective control. According to Li, Andaloro, Lang, and Pan (2019), these parameters are fundamental for accurate applications of RPA; however, applications using RPA with a low application rate and tips that produce fine droplets to maximize work efficiency may compromise spray coverage. The TT 110-01 tip was notable in terms of the level of coverage, and Vitória, Rodrigues, Penha Simon, and Pereira (2018) consider the use of very fine and fine droplets satisfactory for phytosanitary control in coffee crops. However, the coverage provided by the AIXR 110-015 and TTJ60 110-02 tips should not be considered inefficient, especially in seasons with weather conditions that are similar to those in the Cerrado region. High coverage values were recorded because the hydrosensitive paper was positioned outside the crown, and airflow carried more droplets to the sides of the crown between the rows owing to previous pruning and because of the direction of the flight at the time of application.

The application rate affected the droplet size, and thus the coverage of the lower third of the plant. At application rates of 8 and 16 L ha^{-1}, the droplet sizes were 6.5 and 6.7% larger for Dv50 and Dv90, respectively (Table 3).

Table 3. Effect of application rate on droplet size in the lower third of the plant.

Application rate (L ha^{-1})	Dv50 (µm)	Dv90 (µm)
8	158b	222b
12	165ab	230ab
16	169a	238a
CV (%)	6.5	6.2
$F_{rate\ (R)}$	4.3*	5.0*

The means followed by the same letters in each column are not significantly different, as indicated by Tukey's test at 5% significance. * Significant at 5% level.

The hydraulic tips produced higher VMDs when application was performed at a higher rate than that at lower rates. Despite doubling the application rate, the impact on Dv50 was small, and the absence of a working pressure makes a more detailed analysis of this result difficult. Theoretically, at a flight speed, the pressure and droplet size should decrease over time. Chen et al. (2021b) explored the RPA operational parameters to improve droplet distribution on a cotton canopy. They observed that Dv50 has a comparatively more significant impact on droplet penetration, while higher application rates and can improve the coverage of the lower part of the canopy.

The droplet population obtained on the hydrosensitive paper was influenced by the interaction between the application rate and the different hydraulic tips in the lower and middle third of the canopy. In the lower third of the canopy, a rate of 12 L ha^{-1} with the TT 110-01 tip produced the highest droplet density, which was 74% greater than that produced at a rate of 16 L ha^{-1} with the TTJ60 110-02 tip. In the middle third, closer to the point of droplet release and formation, the rate of 16 L ha^{-1} with the XR 110-01 tip produced a droplet density that was 74% greater than that obtained at a rate of 8 L ha^{-1} with the AIXR 110-015 tip (Table 4).

Table 4. Effect of the application rate and hydraulic tips on droplet density (droplets cm^{-2}) in the lower and middle thirds of the plant.

Tip	Lower third		
	Application rate (L ha^{-1})		
	8	12	16
XR 110-01	85aA	80aA	73aA
AIXR 110-015	40aC	39aB	36aB
TT 110-01	63bB	86aA	84aA
TTJ60 110-02	32aC	31aB	22aB
CV (%)	14.4		
$F_{T \times R}$	4.3*		
	Middle third		
Tip	Application rate (L ha^{-1})		
	8	12	16
XR 110-01	80aA	84aA	88aA
AIXR 110-015	23bC	29abC	36aC
TT 110-01	48abB	43bB	59aB
TTJ60 110-02	34aC	35aBC	27aC
CV (%)	13.4		
$F_{T \times R}$	3.1*		

Means with the same lower-case letter in each row and the same capital letter in each column are not significantly different, as indicated by Tukey's test at 5% significance. *Significant at 5% level.

The droplet density was influenced by the application rates and hydraulic tips. However, we could not confirm that a lower application rate associated with fine droplets would always result in a higher droplet density. This result is significant because even with low application rates (between 8 and 16 L ha^{-1}), it was possible to determine that the conditions during application (meteorological and equipment parameters) affected the results obtained. These results were corroborated by the observations of Chen et al. (2020), who emphasized the importance of improving the effect of droplet distribution by RPA in the lower and middle thirds of plants and proposed using tips that produce fine droplets to ensure better droplet density. However, using fine droplets require more restricted operating conditions and technical applications owing to potential drift.

The behavior of the Span and the coverage of the hydrosensitive paper placed in the middle third of the plant. The TT 110-01 tip produced comparatively uniform droplets. Contrarily, the AIXR 110-015 tip produced heterogeneous droplets, i.e., the values of Dv10 and Dv90 were closer for the TT 110-01 tip than those for the AIXR 110-015 tip, which presented the highest RA. The application rate influenced the droplet spectrum uniformity, as rates of 8 and 12 L ha^{-1} enabled more homogeneous application than the rate of 16 L ha^{-1}. However, the TT 110-01 tip at 8 L ha^{-1} provided the greatest coverage (Table 5).

Coverage is fundamental for the success of phytosanitary treatment, especially for contact products. This parameter is influenced by the size and density of the droplets. We observed a coverage of greater than 20% for all tips and application rates, with slight variations. In applications with turbo atomizers, Miranda et al. (2021) obtained a low coverage of 32% to 53% on citrus. Furthermore, Chen et al. (2021b) observed a similar result using empty cone jet droplets and a low application rate. However, Shan et al. (2021) obtained a greater coverage with an increase in the application rate. A lower coverage may be adequate for phytosanitary treatment because the concentration of the product in the spray depends on the formulation and an effective agitation system. Notably, the aircraft used in this experiment did not have a tank agitation system.

Table 5. Effect of tip and application rate on the relative amplitude and percentage coverage in the middle third of the plant.

Tip	Span	Coverage (%)
XR 110-01	0.70b	22b
AIXR 110-015	0.96c	21b
TT 110-01	0.58a	27a
TTJ60 110-02	0.71b	24ab
Application rate (L ha^{-1})	Span	Coverage (%)
8	0.72a	25a
12	0.70a	24ab
16	0.80b	21b
CV (%)	11.4	18.9
F_{Tip}	44.0	4.6
F_{Rate}	6.3*	4.7*

Means with the same letters in each column are not significantly different, as indicated by Tukey's test at 5% significance. *Significant at 5% level.

Regarding the droplet size distribution considering Dv10 and Dv90 for the tips with different application rates in the middle third of the plant, this study observed that at a rate of 8 L ha-1, the AIXR 110–015, TTJ60 110-02, and TT 110-01 tips produced Dv10 that were 43.0, 45.7, and 25.8% larger than those produced by the XR 110-01 tip. This size difference was also observed at other application rates; however, at different proportions. When the application rate increased from 8 to 16 L ha-1 for the AIXR 110-015, TTJ60 110-02, and TT 110-01 tips, the Dv10 increased by 47.7, 42.7, and 42.2% compared with that of the XR 110-01 tip. For the Dv90, the AIXR 110-015 tip produced the largest droplet sizes of all tips, regardless of the application rate. Furthermore, Dv10 and Dv90 increased with an increase in application rate, except for the Dv10 produced by the XR 110-01 tip (Table 6).

Table 6. Influence of the application rate and hydraulic tips on Dv10 and Dv90 (μm) observed in the middle third of the plants.

	Dv10		
Tip	Application rate (L ha^{-1})		
	8	12	16
XR 110-01	69aC	69aC	67aB
AIXR 110-015	121aA	127aA	128aA
TT 110-01	93bB	103bB	116aA
TTJ60 110-02	127aA	120aA	117aA
CV (%)	6.4		
$F_{T \times R}$	4.6		
	Dv90		
Tip	Application rate (L ha^{-1})		
	8	12	16
XR 110-01	127bD	131abD	147aD
AIXR 110-015	358bA	382aA	397aA
TT 110-01	174bC	166bC	209aC
TTJ60 110-02	240aB	237aB	237aB
CV (%)	4.5		
$F_{T \times R}$	5.2*		

Means with the same lower-case letter in each row and the same capital letter in each column are not significantly different, as indicated by Tukey's test at 5% significance. *Significant at 5% level.

As different positions in the plant canopy influence the Dv10 and Dv90, these aspects must be considered when defining the optimal tip and application rate combination. This relationship should be analyzed along with the target coverage percentage and droplet density. However, it is assumed that the best relationship will have a high Dv10 value to reduce drift and evaporation and a low Dv90 value to reduce losses by runoff. An adjustment to ensure both aspects would result in a reduced RA, contributing to the homogeneity of the droplet spectrum.

The VMD (or Dv50) represents the reference droplet size for each use. This study observed that the droplet size is influenced by the interaction between tip type and application rate. The VMD increased by 10.4 and 7.6% as the application rate increased from 8 to 16 L ha^{-1} for the AIXR 110-015 tip, and from 12 to 16 L ha^{-1} for the TT 110-01 tip, respectively. The AIXR 110-015 tip produced the highest Dv50 compared with those produced by other tips. Furthermore, the AIXR 110-015 tip produced 163.0, 162.7, and 165.8% higher VMD at rates of 8, 12, and 16 L ha^{-1} than those produced by the XR 110-01 tip, which is a common tip used for spraying with RPA in Brazil (Table 7).

Table 7. Effect of the application rate and hydraulic tips on the volumetric median diameter (µm) in the middle third of the plant.

Tip	Application rate (L ha^{-1})		
	8	12	16
XR 110-01	92aD	98aD	95aD
AIXR 110-015	249cA	263bA	278aA
TT 110-01	134abC	133bC	144aC
TTJ60 110-02	166aB	166aB	167aB
CV (%)	3.7		
$F_{T \times R}$	5.1*		

Means with the same lower-case letter in each row and the same capital letter in each column are not significantly different, as indicated by Tukey's test at 5% significance. *Significant at 5% level.

The hydraulic tips used in this experiment were classified according to the S-572 standard (American Society of Agricultural Engineers [ASAE], 2000) to obtain a reference for the size of droplets produced. We observed that the XR 110-01 tip produced very fine droplets at all application rates. Additionally, the TT 110-01 and TTJ60 110-02 tips produced fine droplets at all application rates, and the AIXR 110-015 tip produced fine droplets at a rate of 8 L ha^{-1} and medium droplets at rates of 12 and 16 L ha^{-1}. In Brazil, practical experience in day-to-day applications using RPA has indicated that technicians and service providers typically use very fine and fine droplets. In China, Li et al. (2019) also observed that most applications are performed with very fine and fine droplets, with sizes of 61–105 µm and 106–235 µm, respectively.

The PDR of an application results from a dynamic interaction between the hydraulic tips and application rate and is influenced by weather conditions. In the middle third of the canopy, the AIXR 110-015 tip, at the rate of 16 L ha^{-1}, provided a drift risk that was 64.7, 111.8, and 223.5% lower than those of the TTJ60 110-02, TT 110-01, and XR 110-01 tips, respectively. These values are significant, considering the serious consequences of drift to regions adjacent to the treated area. In this study, we observed different behaviors when increasing the application rate from 8 to 16 L ha^{-1} with the AIXR 110-015 and XR 110-01 tips. For example, there was a 47.1% decrease in drift risk for the AIXR 110-015 tip, and a 16.4% increase for the XR 110-01 tip. At 8 L ha^{-1}, which is one of the most commonly used application rates when using RPA, the AIXR 110-015 tip produced a risk of drift that was 4, 72, and 84% lower than those of the TTJ60 110-02, TT 110-01, and XR 110-01 tips, respectively (Table 8).

Table 8. Effect of the application rate and hydraulic tips on the potential drift risk (%) in the middle third of the plant.

Tip	Application rate (L ha^{-1})		
	8	12	16
XR 110-01	46aB	45aB	55bC
AIXR 110-015	25bA	21abA	17aA
TT 110-01	43aB	41aB	36aB
TTJ60 110-02	26aA	27aA	28aB
CV (%)	13.4		
$F_{T \times R}$	3.8*		

Means followed by the same lower-case letter in each row and the same capital letter in each column are not significantly different, as indicated by Tukey's test at 5% significance. *Significant at 5% level.

The PDR is an important indicator for selecting the correct tip and application rate considering weather conditions. Hydrosensitive paper is a practical drift indicator that can be used in applications to guide field technicians. However, more technological alternatives with greater accuracy and ease of handling for drift estimation may emerge in the future. Drift should be constant during applications to protect adjacent plants that are sensitive to plant protection products and for the safety of people and the environment. He (2018) confirmed that drift risk assessments should be considered when developing an application technology using RPA. Furthermore, Li et al. (2019) highlighted that the aircraft type, tip, flight speed and height, target crop, wind speed and direction, and the surrounding environment are the main aspects that influence drift. For example, the PDR was comparatively higher for the XR 110-01 and TT 110-01 tips; however, a 2 m flight height from the target determined the results obtained. According to Wang et al. (2018) an average wind speed of less than 3 m s^{-1} and a flight height lower than 2.5 m can reduce drift.

It is more difficult to deposit droplets in the internal parts of the canopy than on the external parts. The spray tips influenced tracer accumulation inside the crown at the canopy`s lower, middle, and upper parts. At the lower internal position, the XR 110-01 tip provided a deposition that was 66.7, 59.0, and 53.9% greater than those of the TT 110-01, AIXR 110-015, and TTJ60 110-02 tips, respectively. Additionally, this is the most distant and difficult location for droplet deposition relative to the release point. At the middle internal position, the TTJ60 110-02 tip produced a deposition 66.7 and 52.4% higher than those of the TT 110-01 and AIXR 110-015 tips, respectively. At the upper internal position, the TTJ60 110-02 and XR 110-01 tips produced similar deposition rates. Furthermore, the TTJ60 110-02 tip produced 51.0 and 47.0% greater deposition than the TT 110-01 and AIXR 110-015 tips, respectively (Table 9).

Table 9. Effect of hydraulic tips on the tracer deposition (μL cm^{-2}) in different parts of the plant canopy.

Tip	Low	Middle	Upper
XR 110-01	0.39a	0.36ab	0.46a
AIXR 110-015	0.16bc	0.20bc	0.26b
TT 110-01	0.13c	0.14c	0.24b
TTJ60 110-02	0.18b	0.42a	0.49a
CV (%)	21.6	59.7	38.3
F_T	78.6*	7.4*	10.7*

Low - low internal, Middle - middle internal, and Upper - Upper internal. Means with the same letter in each column are not significantly different, as indicated by Tukey's test at 5% significance. *Significant at 5% level.

Reaching internal positions of the canopy is one of the greatest challenges for droplet deposition in coffee crops. According to Escolà et al. (2006), in applications with ground-based equipment, the airflow produced by the fans and leaves producing the "wall effect" interact, reducing droplet penetration into the canopy. Therefore, tips that produce a greater number of droplets under conducive meteorological conditions and at the correct application rate provide greater settling. However, the deposition rate should not be the only criterion to determine the safety and efficiency of applications in good agricultural practices.

Droplet deposition on the outer part of the canopy is easier in ground and aerial applications. In the lower and upper external positions, the greatest difference in accumulation was 72.0 and 63.1% obtained with the TTJ60 110-02 and AIXR 110-015 tips at application rates of 8 and 16 L ha^{-1}, respectively. At the external middle position, the greatest difference between the XR 110-01 and TT 110-01 tips at the application rate of 16 L ha^{-1} was 65.5% (Table 10).

Table 10. Effect of the application rate and hydraulic tips on tracer deposition (μL cm^{-2}) at different heights on exterior of coffee plants.

Lower third			
Tip	Application rate (L ha^{-1})		
	8	12	16
XR 110-01	0.54aB	0.63aAB	0.62aA
AIXR 110-015	0.62aB	0.67aA	0.26bB
TT 110-01	0.37aB	0.38aB	0.44aAB
TTJ60 110-02	0.93aA	0.81abA	0.66bA
CV (%)		23.4	
$F_{T \times R}$		3.8*	
Middle third			
Tip	Application rate (L ha^{-1})		
	8	12	16
XR 110-01	0.63bA	0.71bA	1.25aA
AIXR 110-015	0.92aA	0.77abA	0.40bB
TT 110-01	0.62aA	0.77aA	0.48aB
TTJ60 110-02	1.16aA	0.91aA	0.79aAB
CV (%)		37.8	
$F_{T \times R}$		3.5*	
Upper third			
Tip	Application rate (L ha^{-1})		
	8	12	16
XR 110-01	0.79aB	0.84aA	1.20aA
AIXR 110-015	0.95aAB	0.84abA	0.48bB
TT 110-01	0.76aB	0.87aA	0.67aB
TTJ60 110-02	1.30aA	0.97aA	1.19aA
CV (%)		27.1	
$F_{T \times R}$		3.1*	

Means with the same lower-case letter in each row and the same capital letter in each column are not significantly different, as indicated by Tukey's test at 5% significance. *Significant at 5% level.

In ground-based applications, the airflow is lateral to the plant canopy, contrary to aerial applications, where the flow is downward. According to Carvalho et al. (2020), the descending airflow of an RPA enables better droplet distribution and penetration into the plant canopy. Mogili and Deepak (2021) evaluated droplet distribution when using RPA and observed that the rotor speed affects the droplet distribution in different parts of the plants. Therefore, flight height and speed should be studied, considering different crops and climatic conditions, because they influence the deposition in different parts of the canopy. Zhan et al. (2022) observed that the downward airflow of an RPA could be influenced by the load, which changes as the tank empties, affecting the spray droplet distribution.

Additionally, the distance from the droplet release point to the target is comparatively greater for lower canopy positions. Contrarily, in ground applications, the greatest distance from the release point is for upper canopy positions. In this study, regardless of the tip used, greater deposition of droplets was observed in the upper third of the canopy. In ground application studies on coffee trees with hydro-pneumatic sprayers, Gitirana Neto, Cunha, Almeida, and Alves (2015) and Crause et al. (2020) observed greater deposition in the lower third of the canopy, followed by that in the middle and upper thirds, because the upper leaves were the most distant targets from the droplet release point. Thus, the presents study suggests that applications using RPA could favor the control of targets that predominately occur in the upper third of coffee plants, such as the coffee leaf miner (*Leucoptera coffeella*).

In citrus, Tang et al. (2018) studied the application of an uncrewed aerial vehicle and observed that phytosanitary product accumulation on the canopy was closely related to flight height. They observed smaller treated swathes and a greater downward airflow effect at a flight height of 0.6 m. However, airflow provided less drift and low settling because the leaves, especially in the upper third of the canopy, were influenced by the downwind flow, which reduced droplet adhesion. Additionally, He (2018) observed that spraying using RPA provides less penetration and droplet deposition in the lower third of the canopy compared with that in the upper third, corroborating the results obtained in this study. Soela et al. (2020) evaluated applications using RPA on coffee leaves. They concluded that this technique presents a good quality standard because of product accumulation on the leaves and low runoff during application.

In our experiment, we noted that the flight report did not record the working pressure during application. This variable is essential for spraying applications. The pressure is fundamental for adjusting the droplet size according to the target and weather conditions. The absence of working pressure information accentuates the difficulty that technicians have in properly selecting spray tips. Furthermore, during the replacement of tips, we observed that the landing gear intercepted the spray jet for all tips used in this research, which is a limitation of the equipment used.

In Brazil, the use of RPA in agriculture has increased owing to the increase in providers for this service. However, research is still ongoing, and public agencies have little access to aircraft and pilots available for simulations. Therefore, there is a need for further insights into this technique.

Conclusion

The combination of the application rate and type of hydraulic tip changed the deposition of droplets on the target, depending on the position in the plant canopy. Hydraulic tips with air induction should be considered for phytosanitary product applications as they present a lower drift risk. Application using RPA is an alternative that should be considered for the phytosanitary management of coffee crops, especially to control targets that predominantly occur in the upper third of the plants. Tracer deposition, droplet penetration into the canopy, coverage percentage, and droplet density are influenced by the architecture of the plant crowns.

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