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RESEARCH ARTICLE
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Deposition of Insecticide Applied with Remotely Piloted Aircraft in Dense *Coffea canephora* Crops[1]

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ABSTRACT - The use of remotely piloted aircrafts (RPAs) for spraying operations and the application of agricultural pesticides in conilon coffee crops has increased significantly. Dense planting is an alternative for increasing crop yield, but phytosanitary control under this planting system has received little investigation. This study evaluated insecticide deposition and residue resulting from spraying in a dense conilon coffee crop using RPA at different application rates across canopy layers. Sprays were performed in a conilon coffee crop planted at a spacing of 1.5 m × 0.5 m. A randomized block design with a split-plot arrangement was used. Water-sensitive cards and artificial targets were used to estimate coverage, droplet density, deposition, and volume median diameter, whereas residual deposition was estimated by chromatography. Droplet coverage increased by more than 2.2 times between application rates of 5 and 15 L ha^{-1}, and droplet density increased from 10.50 droplets cm^{-2} at 5 L ha^{-1} to 18.23 droplets cm^{-2} at 15 L ha^{-1} in the upper canopy layer. Average residual deposition at the application rates of 10 and 15 L ha^{-1} was 0.670 mg kg^{-1}, approximately three times higher than that observed at 5 L ha^{-1}. Application rates between 10 and 15 L ha^{-1} are recommended for spraying in dense conilon coffee crops.

Keywords: Application technology. Unmanned aerial vehicle. Spraying drone. Conilon coffee. Abamectin.

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INTRODUCTION

Coffee is one of the most traded agricultural commodities globally because of its importance to global economy, culture, and society. In Brazil, the 2023 harvest is estimated to yield a total production of 54.74 million processed bags, including 37.93 million bags of *Coffea arabica* and 16.81 million bags of *Coffea canephora* (CONAB, 2023).

Dense planting in conilon coffee crops is widely used because it increases productivity, improves space use, and suppresses weeds. However, dense planting increases competition for natural resources such as water, nutrients, and light and alters the microclimate around plants, thereby facilitating the development and spread of diseases and pests. These factors limit productivity and require specific phytosanitary control measures adapted to dense planting conditions (Paula *et al*., 2022).

Conventional methods for applying agricultural pesticides in coffee crops rely on ground-based equipment, including backpack sprayers, hydraulic sprayers, and tractor-mounted hydropneumatic and pneumatic sprayers. These methods are sometimes inefficient because equipment cannot access inter-rows in dense or mountainous crops, and when poorly adjusted or calibrated, they result in uneven application, droplet runoff, and drift (Dantas *et al*., 2021). In addition, coffee plants present challenges for spray solution penetration throughout the canopy because canopy architecture varies with species and genotype and is characterized by high leaf area index and canopy volume, which hinder droplet penetration (Souza *et al*., 2022; Vitória *et al*., 2022).

The use of remotely piloted aircraft (RPA) has increased for phytosanitary control in agricultural crops (Felipetto *et al*., 2023; Moraes *et al*., 2023). Compared with conventional equipment, RPAs offer the advantages of low application rates, reduced water use, and suitability for mountainous terrain, muddy fields, and low-growing crops with a high leaf area index. RPAs are not constrained by terrain topography, maneuvering space, cropping pattern, planting density, or the canopy architecture of the cultivated plant (Hu *et al*., 2022; Xu *et al*., 2022).

In recent years, studies on the application of agricultural pesticides using RPAs have increased in perennial crops such as citrus (Meng *et al*., 2022), almond (Li *et al*., 2022), pear (Qi *et al*., 2023), mango (Li *et al*., 2023), and coffee (Souza *et al*., 2022; Vitória *et al*., 2023). Operational parameters, including flight height and speed, application rate, spray nozzle type, application swath, and flight path, interact significantly in droplet deposition. These parameters are fundamental considerations in flight planning and vary with the canopy characteristics of the cultivated plant (Ribeiro *et al*., 2023). However, no studies have specifically examined droplet distribution, uniformity, and residual deposition in densely planted perennial crops.

Given the importance of coffee production and the lack of studies on RPA application technology in dense coffee plantations, this study evaluated droplet deposition and insecticide residues from spraying in a dense conilon coffee crop using an RPA at different application rates across canopy layers.

MATERIAL AND METHODS

The experiment was conducted on a farm at the municipality of Nova Venécia, in the northwest region of Espírito Santo, Brazil (18°37′53″S, 40°22′37″W; 90 m altitude). The predominant climate in the region is Aw (tropical savanna), according to the Köppen classification, characterized by a defined dry season.

The experimental crop consisted of 24-month-old conilon coffee plants with an average height of 1.75 m; leaf biomass was concentrated in the upper half of the plant because of the training pruning system. The coffee genotypes were K61, LB1, A1, and 143, planted under a dense spacing system (1.5 × 0.5 m). Leaf and soil nutrient management was uniform throughout the experimental area, and a drip irrigation system was used.

The remotely piloted aircraft (RPA) used was the T10 model from DJI (Dà-Jiāng Innovations Science and Technology, Shenzhen, China) with a 10 L tank capacity and configured for spraying in coffee crops. In addition to the product tank, the RPA was equipped with a water pump, piping circuit for liquid circulation, four single flat-fan spray nozzles, XR110-015VS (TeeJet Technologies, Springfield, USA), electronic valve control, and other components. The four spray nozzles were positioned equidistantly and perpendicular to the longitudinal axis of the aircraft at 1.0 m spacing.

Data on application quality variables (coverage, droplet density, droplet deposition, volume median diameter, and residual insecticide deposition on coffee leaves) were collected and subjected to statistical analysis in a randomized block design with a split-plot arrangement. Main plots consisted of three RPA application rates (5, 10, and 15 L ha^{-1}), and subplots consisted of two canopy layers (upper and lower). Each treatment was replicated six times. Flight speed was maintained at 5.0 m s^{-1}, mean flight height at 3.0 m above the coffee canopy, and theoretical swath width at 5.0 m for all treatments. Each experimental unit measured 1,200 m^2 (60 × 20 m), and only the central plants were sampled for data collection. Treatment details are shown in Table 1.

Table 1 - Description of the experimental treatments

Treatment	Application rate (L ha^{-1})	Canopy layer	Flow rate (L min^{-1})	Abamectin concentration (mL L^{-1})
T1	5.0	Upper	0.75	17.00
T2	5.0	Lower	0.75	17.00
T3	10.0	Upper	1.50	8.50
T4	10.0	Lower	1.50	8.50
T5	15.0	Upper	2.25	5.67
T6	15.0	Lower	2.25	5.67

The spray solution used in all treatments consisted of the insecticide abamectin (Volian Targo® SC, Syngenta, São Paulo, Brazil) at 85 mL ha^{-1}, a penetrating adjuvant (alkyl esters of the phosphoric acid group) at 400 mL ha^{-1} (Ochima® EC, Syngenta, São Paulo, Brazil), an adjuvant to minimize drift in aerial applications at 0.2% v v^{-1} (Helper Air®, ICL, São Paulo, Brazil), and Brilliant Blue food dye at 500 g ha^{-1} (Selecta®, Duas Rodas, Jaguará do Sul, Brazil).

Applications were performed in the morning, and weather conditions were monitored throughout the experiment using a Thal-300 digital anemometer and an AKROM thermo-hygro-anemometer (model KR82). Temperature ranged from 24.7 to 28.1 °C, mean relative humidity was above 55%, and wind speed ranged from 1.8 to 4.2 km h^{-1} during the applications.

Water-sensitive paper cards (76 × 26 mm; WSPAPER®, Francisco Beltrão, Brazil) were used to determine coverage, droplet density, and volume median diameter of the sprayed droplets for each treatment. Artificial targets made of polyvinyl chloride (PVC) with the same dimensions as the cards were used to quantify deposition. PVC templates were used to position the cards at two heights within the coffee canopy. The cards and artificial targets were placed immediately before spraying. Approximately 20 min after application of each treatment, the cards and artificial targets were collected, placed in plastic bags, labeled, and stored in a closed box to protect them from solar radiation and oxidative degradation of the dye marker.

Coverage, droplet density, and volume median diameter were quantified on each water-sensitive paper card using a DropScope® wireless system (SprayX®, São Carlos, Brazil), consisting of application software and a wireless digital microscope with a digital image sensor resolution greater than 2500 dpi. This system estimates the overlapping of droplets larger than 35 µm. Water-sensitive paper cards have limitations in detecting very fine droplets; however, this method was used because of its practicality for obtaining droplet spectrum data.

The artificial targets were transported to the laboratory, where the dye was extracted by washing each sample with 50 mL of distilled water. The absorbance of the resulting solutions was measured using a spectrophotometer (Genesys 10 UV®, Thermo Scientific, Waltham, USA) at a wavelength of 630 nm. Residual insecticide deposition on leaves was quantified by liquid chromatography–tandem mass spectrometry (LC-MS/MS), using abamectin as the target analyte. After each treatment application, a 20-minute waiting period was observed to allow the leaves to dry. Thereafter, 200 leaves were collected from each canopy layer of the sampled plants. The collected leaves were placed in labeled kraft paper bags and stored in an expanded polystyrene box to protect them from solar radiation. The samples were subsequently transported to the laboratory and kept refrigerated at 4 °C until extraction. The leaves were dried in a forced-air oven at 60 °C to constant weight.

Abamectin was extracted from leaves using the QuEChERS method and quantified by liquid chromatography–tandem mass spectrometry using a Shimadzu liquid chromatograph (Kyoto, Japan) coupled to an AB SCIEX QTrap 5500 hybrid triple quadrupole–linear ion trap mass spectrometer (Applied Biosystems/MDS Analytical Technologies, Foster City, USA). The QuEChERS method is widely used for abamectin extraction in many crops, and the analytical procedure was validated by Wu *et al*. (2020). After extraction, mean abamectin concentrations were expressed as mg kg^{-1} for each treatment.

Prior to statistical analysis, data on coverage, droplet density, droplet deposition, volume median diameter, and residual abamectin deposition were tested for normality (Shapiro-Wilk test) and homogeneity (Levene's test) of variances. Data were transformed when necessary and subjected to analysis of variance. Means of variables related to spraying and application quality were compared using Tukey's test. Data on estimated deposition and abamectin residue as a function of application rate and canopy layer were analyzed using the Welch's t-test.

RESULTS AND DISCUSSION

Mean values of coverage and droplet density obtained at different application rates and in two canopy layers of the coffee plants are presented in Table 2. Overall, increasing the application rate increased both variables in the upper and lower canopy layers.

Droplet coverage on the targets was not affected by the interaction between application rate and canopy layer. When analyzed separately, droplet coverage increased by more than 2.2 times as the application rate increased from 5 to 15 L ha^{-1} (3.32% and 7.62%, respectively). Droplet coverage in the lower canopy layer was approximately 17% lower than that in the upper layer, corresponding to an absolute reduction of 1.08 percentage points. No reference values for the percentage of covered area on targets considered ideal for pest and disease control have been reported in the scientific literature for most crops. However, low coverage values may reduce the efficacy of contact products. Arakawa and Kamio (2023) reported that low droplet coverage (less than 2.0%) was insufficient for the efficacy of contact insecticides in chestnut trees, particularly in the lower third of the plants.

Droplet density increased significantly as the application rate increased from 5 to 15 L ha^{-1} in both canopy layers. No significant difference in droplet density was observed between the application rates of 10 and 15 L ha^{-1} in either canopy layer. Droplet density increased from 10.50 droplets cm^{-2} at 5 L ha^{-1} to 18.23 droplets cm^{-2} at 15 L ha^{-1} in the upper canopy layer. A similar significant trend occurred in the lower canopy layer, with mean values of 6.88 droplets cm^{-2} at 5 L ha^{-1} and 16.98 droplets cm^{-2} at 15 L ha^{-1}. Overall, the mean droplet density values obtained were lower than the range of 20 to 30 droplets cm^{-2} suggested for insecticide application (Mewes *et al*., 2013). However, this range should not be used as a reference for defining application quality or control efficacy in RPA spraying operations because droplets applied with this equipment have a higher concentration of active ingredient than those applied with tractor-mounted sprayers used by Mewes *et al*. (2013). Verma *et al*. (2022) reported successful control of bioinsecticides applied with RPA in guava crops even with droplet densities below 20 droplets cm^{-2}.

Mean droplet deposition was affected by the interaction between application rate and canopy layer, whereas the volume median diameter (VMD) was not affected by this interaction (Table 3). Droplet deposition increased with application rate and was lower in the lower canopy layer.

Deposition increased by 60.3% in the upper canopy layer and by 56.0% in the lower canopy layer as the application rate increased from 5 to 15 L ha^{-1}. Thus, deposition more than doubled between the application rates of 5 and 15 L ha^{-1}. Mean deposition values did not differ

Table 2 - Mean values of coverage (%) and droplet density (droplet cm^{-2}) in two canopy layers (Upper and Lower) of coffee plants as a function of application rate

Application rate (L ha^{-1})	Coverage (%)		
	Canopy layer		Mean
	Upper	Lower	
5	4.02	2.62	3.32 B
10	7.02	5.92	6.47 A
15	7.98	7.25	7.62 A
Mean	6.34 a	5.26 b	
CV = 28.5%; WL = 1.68; WS = 0.985; F_{rate} = 375.5*; F_{layer} = 65.0*; $F_{interaction}$ = 2.11^{ns}			
Application rate (L ha^{-1})	Droplet density (droplet cm^{-2})		
	Canopy layer		Mean
	Upper	Lower	
5	10.50 aB	6.88 bB	8.69
10	18.10 aA	16.90 aA	17.50
15	18.23 aA	16.98 aA	17.61
Mean	15.61	13.59	
CV = 31.2%; WL = 0.68; WS = 0.977; F_{rate} = 1.171*; F_{layer} = 37.4*; $F_{interaction}$ = 5.72*			

Means followed by the same lowercase letter within a row or the same uppercase letter within a column do not differ significantly according to Tukey's test at the 5% probability level ($p < 0.05$). CV: coefficient of variation of the ANOVA (%); WL: Levene's test for homogeneity of variances; WS: Shapiro–Wilk test for normality; F values from the ANOVA for the factors application rate (F_{rate}), canopy layer (F_{layer}), and their interaction ($F_{interaction}$ – rate × layer). * Significant at the 5% probability level ($p \leq 0.05$); ns: not significant significantly between the 10 and 15 L ha^{-1} rates when each canopy layer was analyzed separately. However, significant differences were observed between canopy layers when rates were analyzed separately. At the 10 L ha^{-1} rate, mean deposition was 1.472 µg cm^{-2} in the upper canopy layer and 1.091 µg cm^{-2} in the lower canopy layer. At the 15 L ha^{-1} rate, mean deposition was 1.572 µg cm^{-2} in the upper canopy layer and 1.140 µg cm^{-2} in the lower canopy layer.

No significant difference in VMD was observed between the 10 and 15 L ha^{-1} rates, but VMD at both rates differed significantly from the value at 5 L ha^{-1}. The differences in VMD relative to the 5 L ha^{-1} rate were 20.4 µm for the 10 L ha^{-1} rate and 24.2 µm for the 15 L ha^{-1} rate, regardless of canopy layer. Mean VMD was significantly higher in the upper canopy layer (200.3 µm) than in the lower canopy layer (173.8 µm), corresponding to an average reduction of 13.2% regardless of application rate. Overall, droplet size across treatments ranged from 164 to 213 µm.

In addition to application rate and target characteristics that influence spreading and retention, droplet size also affects coverage of the sprayed surface. Very fine droplets are prone to drift, whereas coarse droplets reduce penetration into the canopy of shrubby plants; therefore, droplet size in RPA spraying operations should ideally range between 60 and 280 µm under suitable weather conditions (Meng *et al*., 2022; Wang *et al*., 2023).

Uniformity of distribution and droplet size are among the main parameters that must be quantified during spraying to evaluate application quality with RPA (Ahmad *et al*., 2022; Cunha; Silva, 2023). The results for coverage, droplet density, droplet deposition, and volume median diameter showed that application rate significantly affected droplet distribution throughout the canopy layers of the dense conilon coffee crop. These variables increased with increasing application rate regardless of target position within the canopy. Lower mean values of coverage, droplet density, deposition, and volume median diameter were generally observed in the lower canopy layer than in the upper canopy layer. This difference is explained by the fact that the upper canopy layer is the first target contacted by the sprayed droplets. Adequate coverage in both the upper and lower parts of the coffee plant is necessary to ensure pesticide application efficacy. However, the dense leaf biomass in the upper part of the plants, combined with the narrow spacing, hindered droplet penetration to the lower part. Higher deposition in the upper canopy layer has been commonly reported in other studies on droplet penetration in perennial crops (Ribeiro *et al*., 2023; Ru *et al*., 2023; Vitória *et al*., 2023).

Table 3 - Mean values of droplet deposition (µg cm^{-2}) and volume median diameter (VMD - µm) of sprayed droplets in two canopy layers (Upper and Lower) of coffee plants as a function of application rate

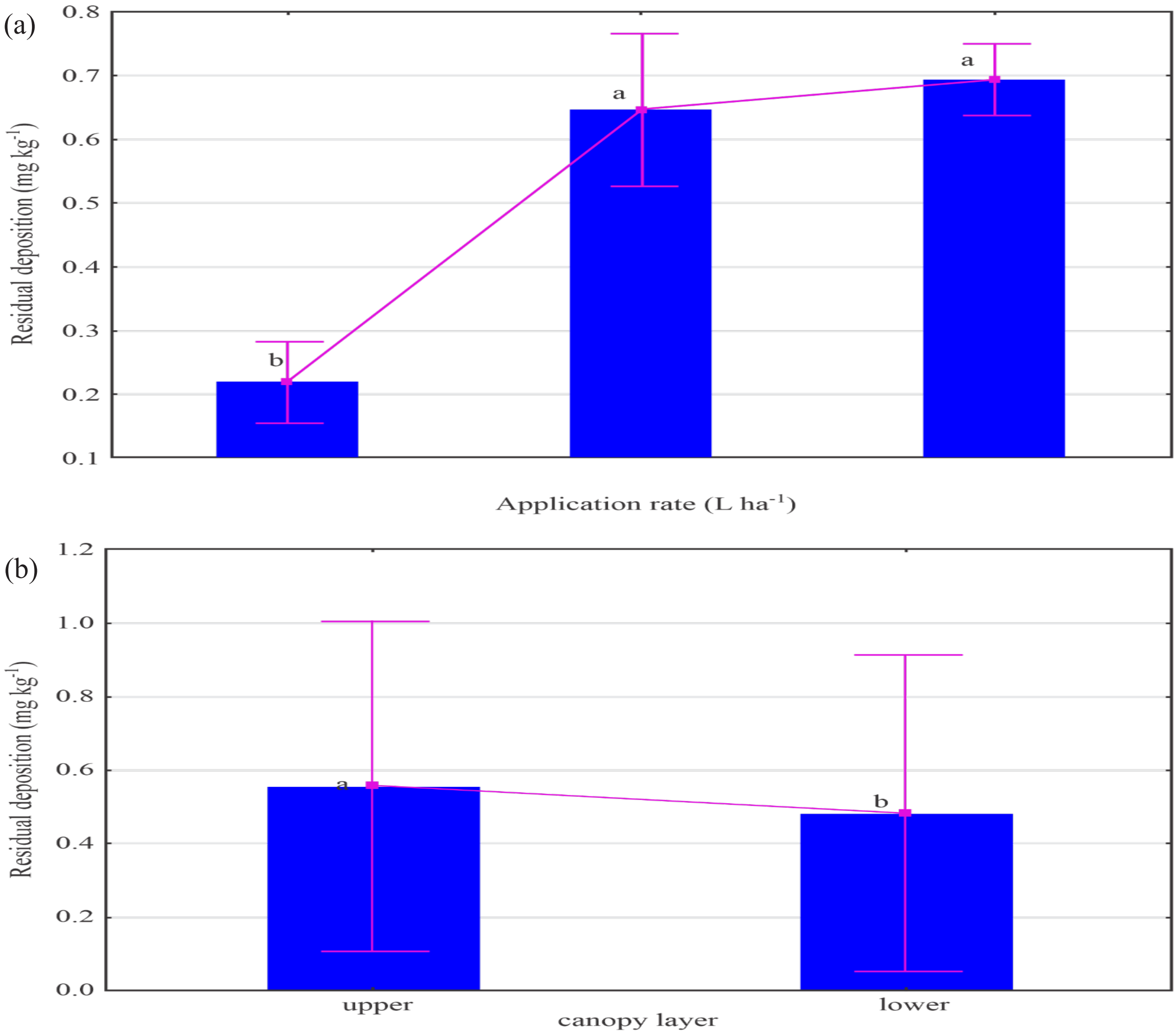
Application rate (L ha^{-1})	Estimated deposition (µg cm^{-2})		
	Canopy layer		Mean
	Upper	Lower	
5	0.624 aB	0.502 aB	0.563
10	1.472 aA	1.091 bA	1.282
15	1.572 aA	1.140 bA	1.356
Mean	1.223	0.911	
CV = 26.6%; WL = 0.41; WS = 0.971; F_{rate} = 5.924*; F_{layer} = 344.6*; $F_{interaction}$ = 2.25*			
Application rate (L ha^{-1})	**VMD (µm)**		
	Canopy layer		Mean
	Upper	Lower	
5	180.1	164.3	172.2 B
10	207.9	177.2	192.6 A
15	212.8	180.0	196.4 A
Mean	200.3 a	173.8 b	
CV = 30.3%; WL = 0.50; WS = 0.987; F_{rate} = 7.429*; F_{layer} = 1.111.6*; $F_{interaction}$ = 6.25^{ns}			

Means followed by the same lowercase letter within a row or the same uppercase letter within a column do not differ significantly according to Tukey's test at the 5% probability level ($p < 0.05$). CV: coefficient of variation of the ANOVA (%); WL: Levene's test for homogeneity of variances; WS: Shapiro–Wilk test for normality; F values from the ANOVA for the factors application rate (F_{rate}), canopy layer (F_{layer}), and their interaction ($F_{interaction}$ – rate × layer). * Significant at the 5% probability level ($p \leq 0.05$); ns: not significant

The downwash generated by the airflow from the RPA rotors likely agitated the leaves throughout the canopy, thereby facilitating droplet penetration into the lower layer despite the dense spacing. Droplet penetration into the canopy of shrubby plants depends on application rate and flight height, as these parameters strongly influence the downwash effect. Although investigation of this effect was not an objective of the present study, the results are consistent with those reported by other authors who evaluated the influence of application rate, flight height, and related variables on droplet penetration in shrub crops, including citrus (Meng *et al*., 2022), pear (Qi *et al*., 2023), mango (Li *et al*., 2023), peach (Li *et al*., 2022), conilon coffee (Crause *et al*., 2023; Vitória *et al*., 2022), and Arabica coffee (Vitória *et al*., 2023). No specific studies were found on droplet deposition in shrubby crops planted in dense systems similar to that evaluated in this experiment.

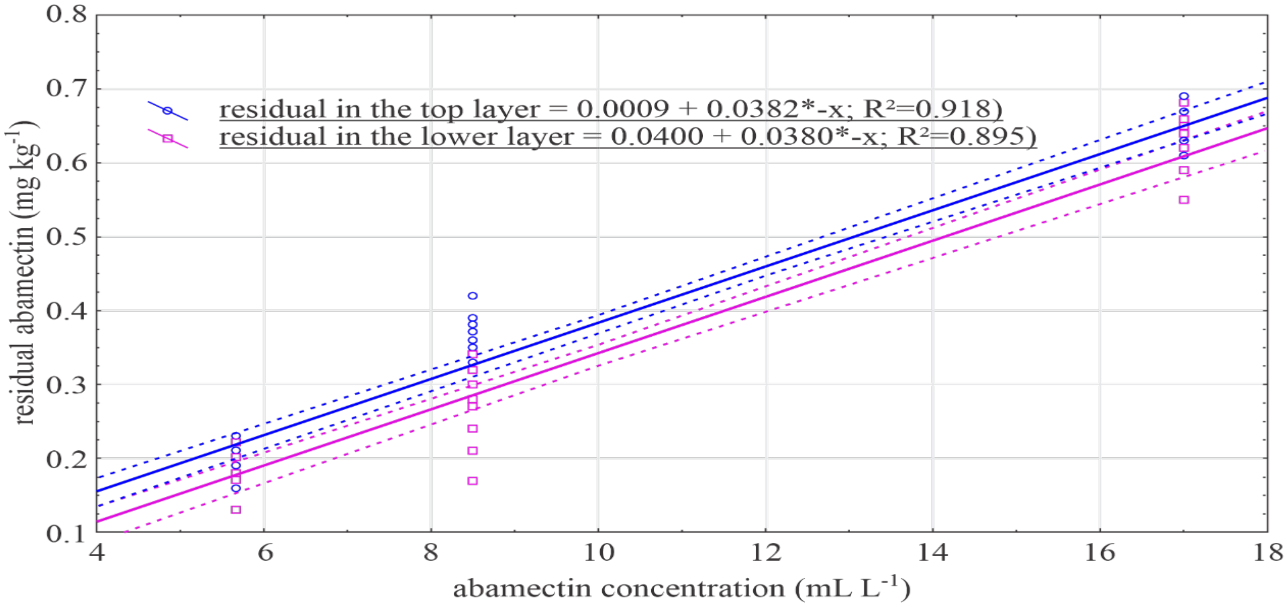
Mean residual abamectin deposition was affected independently by application rate and canopy layer, with no significant interaction between these factors (Figure 1).

Figure 1 - Residual abamectin deposition measured by liquid chromatography–tandem mass spectrometry after insecticide application with RPA at different application rates (a) and in different canopy layers of coffee plants (b). Additional information: Coefficient of variation of the ANOVA (26.6%); Levene's test for homogeneity of variances (0.41); Shapiro–Wilk test for normality (0.971); F value for the application rate factor (5.924); F value for the canopy layer factor (344.6); F value for the interaction between application rate and canopy layer (8.25ns). ns: not significant



Means followed by the same letter do not differ significantly according to Tukey's test ($p < 0.05$). CV = 26.6%; $W_L = 0.41$; $W_S = 0.971$; $F_{rate} = 5.924$; $F_{layer} = 344.6$; $F_{interaction} = 8.25^{ns}$

Figure 2 - Correlation between residual abamectin deposition and abamectin concentration in the spray solution in the upper and lower canopy layers of coffee plants



R^2 = coefficient of determination; * indicates significance of the slope at P = 0.05

Mean residual deposition at the 10 L ha^{-1} (0.647 mg kg^{-1}) and the 15 L ha^{-1} (0.693 mg kg^{-1}) application rates was 0.670 mg kg^{-1}, more than three times higher than that observed at the 5 L ha^{-1} rate (0.219 mg kg^{-1}). When canopy layers were analyzed separately, mean residual deposition was 0.556 mg kg^{-1} in the upper layer and 0.483 mg kg^{-1} in the lower layer. This difference of 0.073 mg kg^{-1} represents a 13.0% reduction from the upper to the lower layer. Standard deviations of the means were 0.224 mg kg^{-1} for the upper layer and 0.216 mg kg^{-1} for the lower layer, resulting in coefficients of variation of 40.3% and 44.7%, respectively. Application rate affected mean abamectin residue in the same manner that it influenced droplet coverage and density.

The correlations between mean residual abamectin deposition in the upper and lower canopy layers as a function of abamectin concentration in the spray solution are shown in Figure 2. Residual deposition increased with increasing abamectin concentration (5.67, 8.50, and 17.00 mL L^{-1}) in both layers, with significantly higher values in the upper layer than in the lower layer (Figure 2).

In the regression analyses, the coefficients of determination (R^2) for the relationship between residual deposition and abamectin concentration were significant ($p < 0.05$), with values of 0.918 for the upper and 0.895 for the lower canopy layer.

Residual abamectin deposition on coffee leaves was affected by both the concentration of the spray solution and the canopy layer from which the leaves were collected. Different abamectin concentrations in the spray solution produced significant differences in droplet density and coverage. Few studies have examined spray application technology using RPAs in coffee crops with respect to application rate, flight height, operating speed, spray swath, and spray solution atomization (Crause *et al*., 2023; Souza *et al*., 2022; Vitória *et al*., 2022, 2023). However, no information is available on the effects of spray solution concentration on pesticide deposition in this crop. The applications were performed at low application rates, which resulted in higher concentrations of the active ingredient in the spray solution. Consequently, residual abamectin deposition was directly proportional to the product concentration in the spray solution. Lower application rates are associated with smaller droplet sizes, and this reduction can decrease deposition on the target unless weather conditions, spray adjuvants, and spray solution preparation are managed appropriately to achieve the control objective. Residual pesticide deposition is affected by both the concentration of the active ingredient in the spray solution and the position of the leaf within the canopy of the target crop (Wu *et al*., 2020).

CONCLUSIONS

1. Application rates between 10 and 15 L ha^{-1} did not significantly affect droplet density in either canopy

layer. Coverage was higher in the upper canopy layer than in the lower canopy layer, with a 2.2-fold increase between the 5 and 15 L ha^{-1} rates;

2. Droplet deposition was higher at the application rates of 10 and 15 L ha^{-1} and was significantly lower in the lower canopy layer. Volumetric median diameter was, on average, 13% lower in the lower canopy layer regardless of application rate;
3. Mean residual abamectin deposition was 0.670 mg kg^{-1} at the application rates of 10 and 15 L ha^{-1}, approximately three times higher than at 5 L ha^{-1}. Residual deposition was also higher in the upper canopy layer than in the lower canopy layer;
4. The values of coverage, droplet density, droplet deposition, volumetric median diameter, and residual abamectin deposition indicated good spraying quality for insecticide application with RPAs. However, further experiments are needed to evaluate the biological efficacy of insecticides applied with RPAs in dense conilon coffee crops.

DATA AVAILABILITY STATEMENT

The research data is only available upon request to the corresponding author.

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