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Impact of sprayer drone flight height on droplet spectrum in mountainous coffee plantation[1]

Impacto da altura de voo de drone pulverizador no espectro de gotas em café de montanha

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HIGHLIGHTS:

The parameters influenced by the flight height were $Dv_{0.1}$, numerical median diameter, and coverage percentage.
Lower coverage percentage values were observed at the working height of 4 m.
Since there is an increase in flight height, the droplet diameter decreases to the parameters $Dv_{0.1}$ and NMD.

ABSTRACT: Weather conditions and sprayer operating parameters influence spray quality. Unmanned aerial vehicles are considered a modern, useful, and very efficient technological tool in the application of pesticides, as they carry out punctual spraying, and reduce environmental and public health problems. The objective of this study was to characterize the spraying quality carried out with an unmanned aerial vehicle as a function of flight height and target position in a coffee plantation in a mountainous region. Three flight heights (2.5, 3.0, and 4.0 m) were used, and the targets were placed at the top and bottom of the plant. For each plant, six water sensitive papers were placed on top of the plant and six were placed at the bottom. CIR 1.5 software was applied to determine the coverage percentage, drop density, volume median diameter, volumetric diameter corresponding to 10 and 90%, numerical median diameter, and relative amplitude. The results showed that the flight height only influenced the parameters of the volumetric diameter corresponding to 10% of the volume, numerical median diameter, and coverage percentage. The target position on the canopy influenced all the evaluated spraying parameters. In mountainous coffee plantations, the spraying system using unmanned aerial vehicle spraying is more efficient for the lower part of the plant.

Key words: coverage percentage, drop density, droplet size

RESUMO: Condições climáticas e parâmetros operacionais dos pulverizadores influenciam a qualidade da pulverização. Os veículos aéreos não tripulados são considerados uma ferramenta tecnológica moderna, útil e bastante eficiente na aplicação de defensivos agrícolas, uma vez que realizam pulverizações pontuais, reduzindo problemas ambientais e de saúde pública. O objetivo deste estudo foi caracterizar a qualidade da pulverização realizada com um veículo aéreo não tripulado em função da altura de voo e a posição do alvo em lavoura de café de região montanhosa. Utilizou-se três alturas de voo (2,5; 3,0; e 4,0 m) e os alvos foram colocados na parte inferior e superior da planta. Em cada planta utilizou-se 12 etiquetas de papel hidrossensível no total, seis para a parte inferior e seis para a parte superior. O software CIR 1.5 foi aplicado para determinar a porcentagem de cobertura, densidade de gotas, diâmetro da mediana volumétrica, diâmetro correspondente a 10 e 90% do volume, diâmetro mediano numérico e amplitude relativa. Os resultados mostraram que a altura de voo apenas influenciou os parâmetros diâmetro volumétrico que corresponde a 10% do volume, diâmetro mediano numérico e porcentagem de cobertura. A posição do alvo no dossel influenciou todos os parâmetros de pulverização estudados. No café de montanha, o sistema de pulverização por veículo aéreo não tripulado é mais eficiente para a parte inferior da planta.

Palavras-chave: porcentagem de cobertura, densidade de gotas, tamanho de gota

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Introduction

The application of pesticides during cultivation to prevent pests and diseases is the main method to avoid productivity losses and guarantee the quality of agricultural products (Dhananjayan et al., 2020). From this perspective, the development of unmanned aerial vehicles (UAVs) has recently provided numerous possibilities in the application fields of pesticides (Radoglou-Grammatikis et al., 2020; Maddikunta et al., 2021). UAVs have various possible applications which offer the potential to revolutionize traditional systems of weed detection, production estimation, crop monitoring and the application of pesticides (Delavarpour et al., 2021; Mohamad et al., 2021).

Drone usage has the advantage of having a lower payload capacity, carrying out spraying punctually (Khan et al., 2021). It also reduces the rate of health-related problems, environmental problems, reduces the number of field workers and the farmer's workload, which is a significant part of the agricultural revolution (Liu et al., 2021; Rahman et al., 2021; Yao et al., 2021).

The application droplet spectrum using UAVs has a greater risk of drift, depending on the height and diameter of the droplet coming from the spray nozzles (Wang et al., 2020). Drifting drops can damage sensitive crops, affect natural pests, reduce pollinator populations, cause environmental contamination, and threaten human and animal health (Grella et al., 2020; Langkamp-Wedde et al., 2020; Tudi et al., 2021).

The advantage over manned aerial vehicles is that UAVs can spray at lower heights, using lower speeds, which provides a reduction in drift (Li et al., 2019). Although studies using UAVs spraying on agricultural crops are found in the literature, there is no report with the use of this technology in mountainous coffee plantations, where labor is scarce, and the production area is difficult to mechanize. Therefore, the objective of this study was to characterize the spraying quality performed with an UAV as a function of flight height and target position in a coffee plantation in a mountainous region.

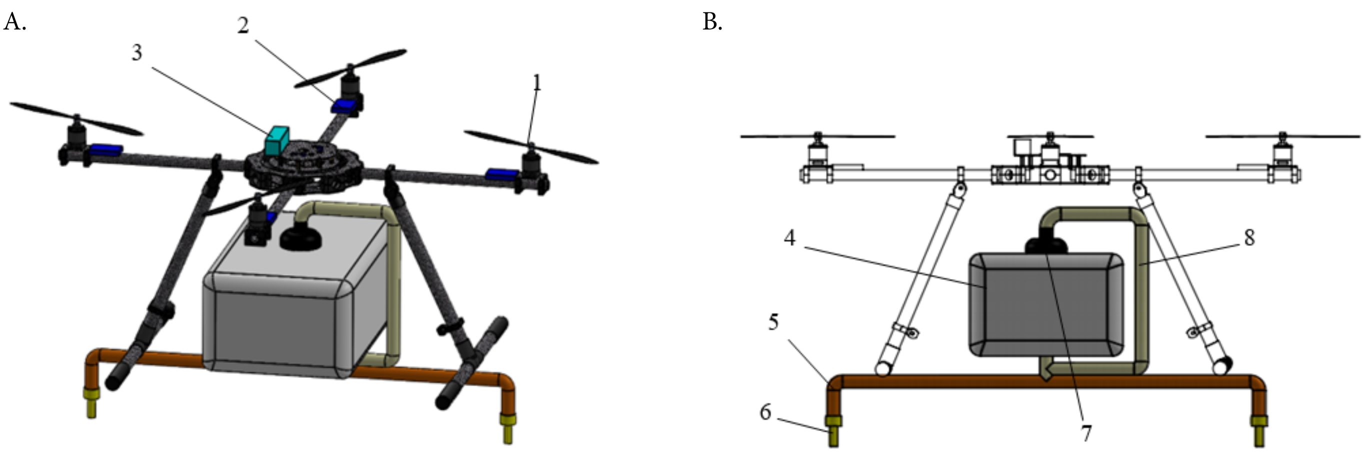
Material and Methods

The experiments were carried out at an agricultural experimental station located in Viçosa, Minas Gerais state, Brazil (latitude 20° 45' 14" S, longitude 42° 52' 53" W, and altitude of 648 m). The crop tested was arabica coffee (*Coffea arabica* L.) planted in a mountain region, with a plant spacing of 0.8 m and row spacing of 1.5 m. The average plant height of the coffee trees was 1.70 m over the entire area.

As shown in Figure 1, the UAV model used in the experiment had four 680 kV (RPM/V) rotors (1) connected to 40 A electronic speed controllers (ESCs) (2). The UAV was powered by a 14,400 mAh Li-Po battery (3). The flight time was 7 min with a full tank of 2 L (4). Flight speed was approximately 1.5 m s^{-1}. The equipment had a spray bar (5) with two large-angle, flat-jet hydraulic nozzles, model TT 11002-VP (TeeJeet®, Cotia, São Paulo state, Brazil) (6), spaced at 30 cm. The working pressure was 0.3 MPa provided by a hydraulic pump (7) conditioned inside the tank, taking the spray solution to the nozzles, through silicone hoses (8) coupled to the spray bar. Pure water was used to carry out the sprays.

To assess the quality of the pesticide application, twelve water-sensitive paper tags were used, six placed on the canopy of the coffee plant and six at the bottom, corresponding to a height of 0.9 and 1.4 m in relation to the ground level, respectively. Spraying was carried out at three flight heights (2.5, 3.0, and 4.0 m, as shown in Figure 2), measured from the ground, at the target positions placed at the top and bottom of the plant. The experiment was carrying out in a completely randomized design in a factorial scheme of 2 x 3 (two target positions on the plant x three flight heights), with four replicates. During data collection, weather conditions such as air temperature, relative air humidity and wind speed were monitored using a digital thermo-hygrometer model ITHT2210 (Instrutemp, São Paulo state, Brazil) and a digital thermometer model TAFR-180 (Instrutherm, São Paulo state, Brazil).

The UAV spraying performance was characterized by determining the coverage percentage, drop density, volume median diameter (VMD), volumetric diameter corresponding to 10 and 90%, numerical median diameter (NMD) and relative amplitude (SPAN). These parameters were determined using image analysis of the water-sensitive papers, using CIR 1.5 spray spectrum analysis software (Conteo y Tipificación de Impactos de Pulverización).



(1) 680 kV rotor, (2) electronic speed controller, (3) 14,400 mAh Li-Po battery, (4) 2 L tank, (5) spray bar, (6) model TT11002-VP wide-angle flat jet hydraulic nozzle, (7) hydraulic pump, and (8) silicone hoses

Figure 1. Isometric view of the UAV model used in the experiment (A) and front view detailing the spraying system (B)

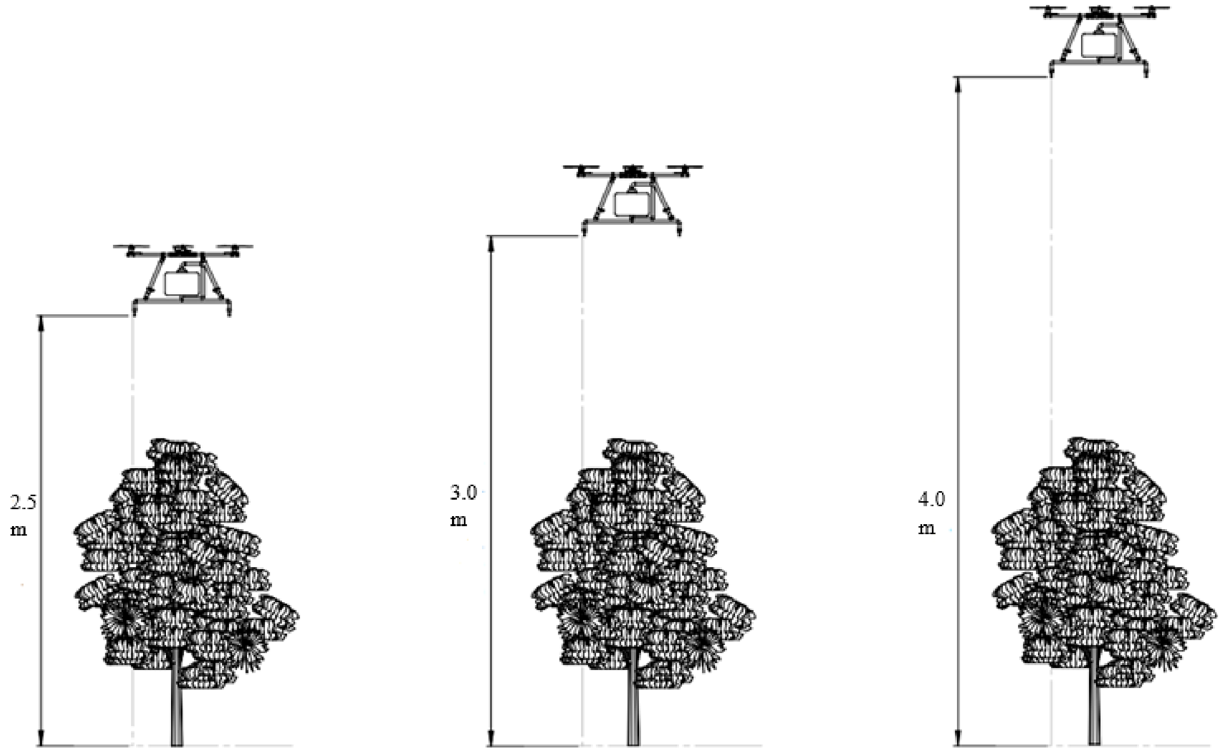


Figure 2. Schematic of pesticide application in the coffee plantation at a flight height of 2.5 m (A), 3.0 m (B), and 4.0 m (C)

After spraying, the water-sensitive papers were wrapped in duly identified paper envelopes and sent to the laboratory, where they were digitized using a digital camera with a resolution of 3,264 x 2,448 pixels.

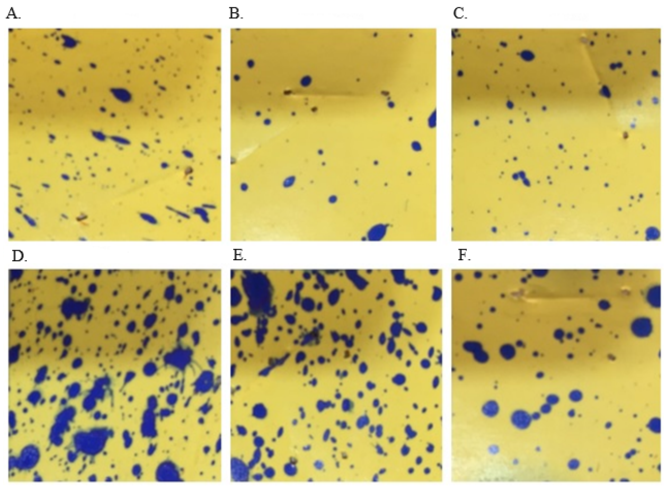
The data obtained in the CIR 1.5 software on the coverage percentage, drop density, volume median diameter (VMD), volumetric diameter corresponding to 10 and 90% ($Dv_{0.1}$ and $Dv_{0.9}$ respectively), numerical median diameter (NMD) and relative amplitude (SPAN), were submitted to analyze the variance using the F test at $p \leq 0.01$ and $p \leq 0.05$ and the means were compared using the t test ($p \leq 0.01$).

Results and Discussion

The water-sensitive paper tags distributed in the canopy of the plants were hit by the sprayed liquid in all positions. Figure 3 shows some samples of the water-sensitive paper used in the experiment. The blue dots indicate the area where the spray droplets encounter the papers, while the yellow area indicates the unsprayed sections. The averages of the parameters calculated by the software can be seen in Table 1.

It can be seen from Table 1 that the height only influenced the spraying parameters for the numerical median diameter (NMD), volumetric diameter that corresponds to 10% of the drops ($Dv_{0.1}$) and the coverage percentage. The influence of the target position on the plant where the spraying took place was significant for all parameters.

According to Li et al. (2021), the pesticide crop protection quality and performance using UAVs are comparable to conventional fixed-wing aircraft applications. However, the author claims that the droplet spectrum and short-term fate during application using UAVs offers a more effective and efficient protection to the crop, with minimal risk to the environment.



Blue dots - Area where the spray droplets encounter the papers; Yellow area – Unsprayed area

Figure 3. Samples of water-sensitive paper obtained in the experiment for flight height of 2.5 m with the paper at the bottom (A) of the plant and at the top (D), for flight height of 3.0 m with the paper at the bottom (B) of the plan and at the top (E), and for flight height of 4.0 m with the paper at the bottom (C) of the plant and at the top (F)

The numerical median diameter (NMD) is the droplet diameter that represents the central value in terms of droplet quantity in the application. The higher the NMD value of an application, the larger the drop diameter. It is noteworthy that the risk of drift is very low for the upper part of the plant canopy, due to NMD values above 100 µm (Marubayashi et al., 2021).

The distribution uniformity and droplet size are some of the main parameters that must be quantified during spraying to assess the system (Qin et al., 2016). In this study, the VMD presented higher values in the targets placed in the upper part

Table 1. Average values of spray parameters for combinations of spray height and target position on the plant

Height (m)	Target position on the plant			
	Top	Bottom	Top	Bottom
	VMD (μm)		$Dv_{0.1}$ (μm)	
2.5	447 ± 80 aA	305 ± 174 aB	230 ± 33 aA	149 ± 65 aB
3.0	584 ± 61 aA	321 ± 120 aB	265 ± 32 aA	160 ± 52 aB
4.0	551 ± 131 aA	279 ± 100 aB	223 ± 86 aA	86 ± 20 bB
	$Dv_{0.9}$ (μm)		NMD (μm)	
2.5	781 ± 185 aA	689 ± 224 aB	110 ± 37 aA	86 ± 14 aB
3.0	864 ± 127 aA	496 ± 128 aB	143 ± 59 aA	76 ± 13 aB
4.0	789 ± 246 aA	496 ± 154 aB	84 ± 20 bA	62 ± 3 bB
	SPAN		Drop density (drops cm^{-2})	
2.5	1.11 ± 0.27 aA	2.06 ± 0.83 aB	72 ± 14 aA	162 ± 72 aB
3.0	0.96 ± 0.22 aA	1.12 ± 0.32 aB	89 ± 19 aA	118 ± 52 aB
4.0	0.95 ± 0.22 aA	1.87 ± 0.54 aB	98 ± 57 aA	164 ± 80 aB
	Coverage percentage (%)			
2.5	9.7 ± 2.7 aA	6.0 ± 2.4 aB		
3.0	14.1 ± 2.2 aA	5.0 ± 2.5 aB		
4.0	7.6 ± 2.5 bA	3.5 ± 0.9 bB		

VMD - Volume median diameter; NMD - Numerical median diameter; SPAN - Relative amplitude; $Dv_{0.1}$ and $Dv_{0.9}$ - Volumetric diameter corresponding to 10 and 90% of the drops, respectively; Means followed by the same lowercase letter in the column and the same uppercase letter in the row for each parameter evaluated do not differ statistically according to t test at $p \leq 0.01$; Means are followed by standard deviation

of the coffee plant. Smaller drops have greater penetration capacity in the plant canopy, which explains the higher VMD values. Reis et al. (2010) used an experimental agricultural aircraft to spray soybean plants, obtaining an average VMD at the top of the plant of 144.5 μm, approximately 3.5 times smaller compared with the values obtained in the present research. In more recent studies, Wen et al. (2020), evaluating the droplet spectrum of a UAV spray, obtained a VMD of 128.3 μm, for a height similar to that used in the present study. Meng et al. (2022a), spraying an area of citrus, obtained top VMD values between 197 and 343 μm, and the bottom values ranged from 212 to 246 μm, similar to this study.

UAVs are different from a conventional agricultural aircraft and have specific characteristics for pesticide applications. The air movement caused by the UAV propellers directly influences the generation, dispersion, evaporation, and deposition of the droplets on the target. In a study by Zheng et al. (2018), through simulation in CFD (Computacional Fluid Dynamics), the dynamics of the air flow caused by the propellers of a UAV sprayer was evaluated. They found that the increase in flight height causes limitations on factors such as spray range, uniformity of deposition and spray penetration into the plant canopy. This affects the droplet spatial distribution and therefore influences the spraying effectiveness. Although they observed that the flight height influenced the spraying efficiency, in this study this behavior was not observed.

To obtain good pesticide application efficiency, it is essential that there is an efficient coverage of the upper and lower part of the coffee plant. Owing to the difficulty imposed by the leaf mass of the upper part of the plants, the pesticide coverage on the lower part is impaired. This phenomenon can be noticed on the water sensitive paper labels shown in Figure 3. Even with airflow assistance to move the canopy, the percentage of coverage in the upper part was on average 10.5%, almost double the 4.8% observed in the lower part. Yongjun et al. (2017) when evaluating the coverage percentage in a corn crop using a UAV at a height of 2.08 m and at different speeds, obtained values between 0.83 and 14.3% for the upper part of the plant and 0.09 to 4.6% for the lower part. Similar coverage percentages were obtained in both the present study and by Meng et al. (2022a). These authors verified the UAV sprayer application percentages of between 0.8 and 12.4% in citrus.

The relative amplitude (SPAN) had lower values for the upper part of the plant. SPAN is directly linked to the $Dv_{0.1}$ and $Dv_{0.9}$ and indicates the homogeneity of droplet size, where a homogeneous droplet spectrum has a SPAN value tending to zero. The upper part had an average SPAN value of 1.01 and the lower part the value was 1.68. According to Minguela & Cunha (2010), values below 1.4 for the relative amplitude (SPAN) of a drop population are acceptable. The turbulence caused by the UAV propeller may have contributed to the high SPAN value at the bottom, which was higher than the acceptable value.

Matthews (2000) defined a range of droplet densities necessary for the efficient applications of pesticides. For pre-emergence insecticide and herbicide applications, the recommended range is 20 to 30 drops cm^{-2}. For post-emergence herbicides and systemic fungicides, the recommended ranges are 30 to 40 and 30 to 50 drops cm^{-2}, respectively. Drop density above 70 drops cm^{-2} is indicated for contact fungicides. As shown in Figure 4, the contact fungicide is the most suitable product for application using UAVs under these experimental conditions, since approximately 82% of the values obtained in the observations were greater than 70 drops cm^{-2}. Ahmad et al. (2020), evaluating the effect of the operational parameters of a UAV sprayer for weed control, found drop densities between 87 and 116 drops cm^{-2}, values very close to those observed in the present study. When analyzing the droplet distribution produced by a UAV spraying in a citrus tree canopy, Meng et al. (2022b) found drop densities between 20 and 136 drops cm^{-2} in the different positions of the plant canopy. As in this study, these authors found higher droplet density values in the lower positions of the plant canopy.

The results of this study reinforced the potential of using UAVs to carry out spraying in mountainous coffee

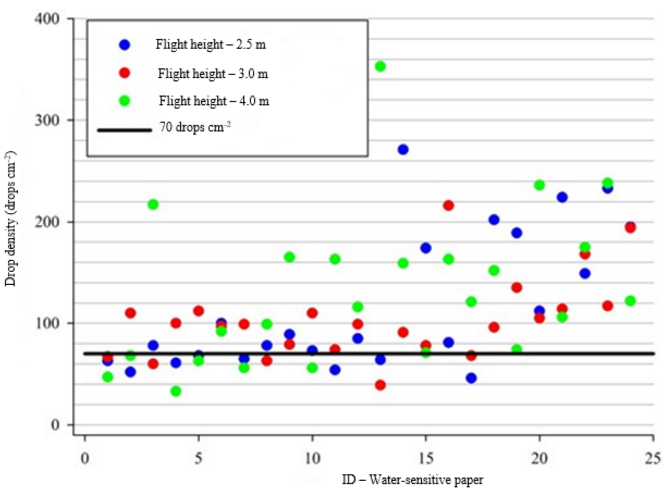


Figure 4. Observed droplet density values in the experiment

plantations. However, more scientific investigations must be conducted to improve the efficiency of this technology. The conditions under which this experiment was conducted did not include the study of the distribution of the pesticide along the working width. In agricultural pesticide applications, knowledge of the distribution profile of a specific liquid is of paramount importance for the optimization of spraying management. Therefore, a suggestion for future studies is the determination of the distribution uniformity in the sprayer UAV boom.

Conclusions

1. The flight height only influenced the parameters volumetric diameter corresponding to 10% of the volume, numerical median diameter, and coverage percentage.
2. The target position on the canopy influenced all the spraying parameters studied.
3. In mountainous coffee plantations, the spraying system using unmanned aerial vehicle spraying is more efficient for the lower part of the plant.

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