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CHARACTERIZATION OF SPRAY APPLICATION WITH A 110015 AD NOZZLE USING A REMOTELY PILOTED AIRCRAFT: EVALUATION OF FLIGHT ALTITUDE AND COLLECTOR TYPE

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Abstract.

Remotely piloted aircraft (RPA) spray systems represent an innovative technology in modern agriculture, offering pesticide application with high precision and operational efficiency. A comparative study of different collector substrates is essential for precision agriculture, as each substrate exhibits specific droplet absorption and retention properties that significantly affect the evaluation of spray performance and pesticide deposition efficacy. Investigating the interaction of sprayed droplets with different surfaces allows for the refinement of technical recommendations for equipment selection and application procedures. This leads to considerable gains in agricultural productivity, reduced environmental impact, and improved economic feasibility, while also enabling the adoption of lower-cost, more readily available alternative substrates. This study aimed to evaluate the operational efficiency of applications using an RPA equipped with a 110015 AD nozzle, analyzing the impact of two flight altitudes and two collector types. The experiment followed a 2 × 2 factorial design with five replications, totaling 20 experimental units. The treatments consisted of two flight altitudes (3 and 5 m) and two collector types (water-sensitive paper and cardstock). The experiment was conducted at the Experimental Farm of the State University of Minas Gerais (UEMG) in Ituiutaba, Minas Gerais, Brazil. Applications were performed using a DJI AGRAS T10 RPA with a programmed application rate of 10 liters per hectare ($L\ ha^{-1}$). The spray solution comprised a mixture of water, dye, and an adjuvant. The water-sensitive paper and cardstock collectors, with identical dimensions of 26 × 76 mm, were strategically positioned in the application area at 50 cm intervals to capture the sprayed droplets. After collection, the papers were scanned and analyzed using Gota software (EMBRAPA, 2000), which quantifies and characterizes the deposited droplets. It provides precise data on droplet number, diameter, dispersion, volume, density, coverage, and volumetric median diameters (DV10, DV50, and DV90). The relative span of the droplet distribution was also calculated. Statistical analysis was performed using analysis of variance (ANOVA), and means were compared using Tukey's test at a 5% significance level ($p < 0.05$). The results revealed a significant interaction between flight altitude and collector type for the volumetric median diameters (DV10, DV50, and DV90). For DV10, the 5 m flight altitude resulted in smaller droplets on water-sensitive paper compared to cardstock, a pattern that was consistent for DV50 and DV90. However, the relative span did not differ among treatments, indicating homogeneity in droplet size distribution for both collector types. This finding is promising, as it suggests that an alternative material, such as cardstock, provides comparable uniformity to standard water-sensitive paper.

Keywords.
alternative materials, application quality, droplet characterization, flight height, precise application.

Introduction

Spray systems using remotely piloted aircraft (RPA) represent an innovative and promising technology in modern agriculture. The use of RPAs provides high precision, operational efficiency, and the ability to access areas that are difficult to reach with conventional machinery (Santos et al., 2019; Delavarpour et al., 2023). Aerial application with drones enables the reduction of the applied spray volume, minimizing the waste of agricultural pesticides and the environmental impacts associated with drift (Lan, 2025). To ensure application efficacy, the characterization of sprayed droplets is a crucial factor. The size, density, and uniformity of the droplets determine target coverage and chemical absorption by plants (Salyani et al., 2013). Traditionally, water-sensitive paper is the standard substrate used to collect and analyze spray droplets, as it changes color upon contact with water, allowing precise quantification of the droplet spectrum (Wu et al., 2025). However, its high cost and extreme sensitivity to ambient humidity limit its large-scale use. The search for alternative materials, such as cardstock paper, emerges as a viable strategy to reduce costs in application technology evaluations, provided they exhibit droplet retention and spreading properties comparable to water-sensitive paper. The interaction between sprayed droplets and the collector surface directly affects the measured parameters, making the comparative study of different substrates essential (Garcera et al., 2014; Forster et al., 2014).

Besides the collector type, operational parameters such as flight altitude exert a strong influence on droplet deposition and drift. Inadequate flight altitudes can result in premature evaporation, product loss due to drift, and low coverage uniformity (Lou et al., 2018; Zhang et al., 2021). Studies indicate that the interaction between the airflow generated by the rotors (downwash) and flight altitude significantly alters droplet behavior before reaching the target (Guo et al., 2021). In this context, the present study aimed to evaluate the operational efficiency of applications using an RPA equipped with a 110015 AD nozzle, analyzing the impact of two flight altitudes and two collector types (water-sensitive paper and cardstock) on the characteristics of the droplet spectrum.

Materials and Methods

The experiment was conducted at the Experimental Farm of the State University of Minas Gerais (UEMG), located in the municipality of Ituiutaba, Minas Gerais, Brazil. The experimental area featured a flat topography and an absence of physical obstacles that could interfere with airflow during applications. The experimental design adopted was completely randomized, arranged in a 2 × 2 factorial scheme, with 5 replications, totaling 20 experimental units. The treatments consisted of the combination of two flight altitudes (3 and 5 meters) and two types of artificial collectors (water-sensitive paper and cardstock paper).

Applications were performed using a DJI AGRAS T10 Remotely Piloted Aircraft (RPA) model. The equipment was configured for an application rate of 10 liters per hectare (L ha^{-1}), using 110015 AD model spray nozzles (agricultural flat fan). The spray solution comprised a mixture of water, a marker dye, and an adjuvant, aiming to facilitate droplet visualization on the collectors. The artificial collectors, both water-sensitive paper and cardstock paper, were standardized with identical dimensions of 26 × 76 mm. They were fixed horizontally on appropriate supports and distributed strategically in the application area, spaced 50 cm apart, perpendicular to the RPA's flight line, to capture the sprayed droplets across the entire deposition swath.

After the applications, the droplets were allowed to dry completely. Then, the collectors were carefully gathered, placed in paper envelopes to prevent contamination or mechanical damage, and transported to the laboratory. The papers were scanned using a camera. The scanned images were processed and analyzed using the Gota software (EMBRAPA, 2000). The program quantified and characterized the deposited droplets, providing precise data on the number of droplets, volumetric median diameter (DV10, DV50, and DV90), droplet density, and relative span (Span) of the droplet size distribution. The obtained data were subjected to analysis of variance (ANOVA) by the F test. When significance was observed, treatment means were compared by Tukey's test at a 5% probability of error ($p < 0.05$), using appropriate statistical software.

Results and Discussion

The results presented in Tables 1 and 2 demonstrate that the variables number of droplets (NG), mean droplet diameter (DMG), dispersion (D), volume (V), droplet density (DG), coverage, and relative span (AR) were not significantly influenced by flight altitude, collector type, or the interaction between these factors ($p > 0.05$). These results indicate that, under the evaluated conditions, the spraying performed with the remotely piloted aircraft showed similar behavior between the 3 and 5 m altitudes, regardless of the substrate used for collection.

Table 1. Number of droplets (NG), mean droplet diameter (DMG), Droplet dispersion (D), Volume (V), and Droplet density (DG) data.

Source of Variation	NG	DMG	D	V (L ha^{-1})	DG (nº cm^{-2})
Altitude of 3 m	231.44	70.61	0.946	22.28	2.39
Altitude of 5 m	287.21	66.82	0.887	18.79	2.03
Water-sensitive paper	259.05	60.13	0.910	22.63	2.33
Cardstock paper	259.60	77.30	0.923	18.45	2.08
P-value - Altitude	0.16^{NS}	0.72^{NS}	0.11^{NS}	0.18^{NS}	0.31^{NS}
P-value - Paper	0.98^{NS}	0.12^{NS}	0.71^{NS}	0.11^{NS}	0.48^{NS}
P-value Altitude×Paper	0.94^{NS}	0.36^{NS}	0.93^{NS}	0.28^{NS}	0.08^{NS}
CV (%)	32.74	34	8.39	27.05	35

* Significant (p<0.05); NS = not significant.

Table 2. Coverage, volumetric diameter 10% (D10%), volumetric diameter 50% (D50%), volumetric diameter 90% (D90%), and relative span (AR).

Source of Variation	Coverage	DV10	DV50	DV90	AR
Altitude of 3 m	2.74	470.58	814.24	1232.67	0.951
Altitude of 5 m	2.32	496.95	852.70	1236.31	0.885
Water-sensitive paper	2.76	501.28	848.06	1261.71	0.913
Cardstock paper	2.30	466.16	818.88	1207.27	0.923
P-value - Altitude	0.18^{NS}	0.50^{NS}	0.55^{NS}	0.96^{NS}	0.77^{NS}
P-value - Paper	0.14^{NS}	0.37^{NS}	0.65^{NS}	0.51^{NS}	0.77^{NS}
P-value Altitude×Paper	0.70^{NS}	0.03*	0.02*	0.01*	0.90^{NS}
CV (%)	26.21	17.70	17.09	14.72	8.34

* Significant (p<0.05); NS = not significant..

Although numerical differences were observed between some treatments, such as a higher number of droplets at the 5 m altitude and greater coverage at the 3 m altitude, these variations were not statistically significant, suggesting that these differences can be attributed to experimental variability. However, the absence of statistical differences does not necessarily imply that both collectors showed satisfactory performance or that the obtained deposition is adequate for phytosanitary applications. The mean droplet density observed in this study ranged between 2.03 and 2.39 droplets cm^{-2}, indicating low deposition on the collectors when compared to the values normally used as a reference for evaluating spray quality. In conventional applications, densities close to 30 droplets cm^{-2} are frequently associated with adequate levels of deposition (Washington, 1997; Ozkan & Gil, 2022).

For sprayings performed with remotely piloted aircraft at ultra-low volume, optimizing deposition must consider the reduced application volume and the high concentration of the spray solution, aspects that significantly differentiate these applications from conventional ones (Grella et al., 2022). Similarly, coverage rates between 10 and 15% are frequently used as a reference for conventional applications, whereas, for UAVs, coverage effectiveness depends on product concentration, the equipment's operational characteristics, and the biological target's physical properties. Thus, the low density and coverage values obtained in this study suggest that both collectors recorded reduced deposition, indicating that the absence of statistical differences between them does not necessarily imply equivalence regarding the application's agronomic quality. Additional studies with different spray nozzles, application volumes, and environmental conditions will be necessary to establish adequate deposition thresholds for applications with remotely piloted aircraft.

In contrast, the volumetric diameters DV10, DV50, and DV90 presented in tables 3, 4, and 5 indicate a significant interaction between flight altitude and collector type, showing that the response of these variables depends simultaneously on the two evaluated factors. The absence of an isolated effect for altitude or paper type reinforces that the interpretation must be carried out from the unfolding of the interaction.

Table 3. Mean values obtained for the breakdown of the volumetric diameter 10% (DV10%).

Factors		Paper	
		Water-sensitive	Cardstock
Altitude	3 m	534.20Aa	468.35Aa
	5 m	406.97Bb	525.34Aa
P-value	Paper/3 m	0.03 *	
	Paper/5 m	0.31 NS	
	Altitude/Water-sens	0.24 NS	
	Altitude/Cardstock	0.04*	
Least Significant Difference (LSD)	Paper	118.01	
	Altitude		

Means followed by the same lowercase letter in columns and uppercase in rows do not differ by Tukey's test ($p<0.05$).

Table 4. Mean values obtained for the breakdown of the volumetric diameter 50% (DV50%).

Factors		Paper	
		Water-sensitive	Cardstock
Altitude	3 m	911.26Aa	784.86Aa
	5 m	717.23Ab	920.54Aa
P-value	Paper/3 m	0.05 NS	
	Paper/5 m	0.15 NS	
	Altitude/Water-sens	0.18 NS	
	Altitude/Cardstock	0.04*	
Least Significant Difference (LSD)	Paper	196.33	
	Altitude		

Means followed by the same lowercase letter in columns and uppercase in rows do not differ by Tukey's test ($p<0.05$).

Table 5. Mean values obtained for the breakdown of the volumetric diameter 90% (DV90%).

Factors		Paper	
		Water-sensitive	Cardstock
Altitude	3 m	1377,20Aa	1146,22Aa
	5 m	1088,14Ba	1326,40Aa
P-value	Paper/3 m	0,02*	
	Paper/5 m	0.14 NS	
	Altitude/Water-sens	0.06 NS	
	Altitude/Cardstock	0.06NS	
Least Significant Difference (LSD)	Paper	250.37	
	Altitude		

Means followed by the same lowercase letter in columns and uppercase in rows do not differ by Tukey's test ($p<0.05$).

The unfoldings revealed distinct patterns between the collectors. For DV10, using water-sensitive paper, raising the flight altitude from 3 to 5 m promoted a significant reduction in the diameter of the smallest droplets, going from 534.20 to 406.97 µm. For cardstock paper, on the other hand, there was no significant difference between the altitudes, presenting values of 468.35 and 525.34 µm for 3 and 5 m, respectively. A similar trend was observed for DV50 and DV90, where the water-sensitive paper showed a reduction in volumetric diameters with the increase in flight altitude, while the cardstock showed a tendency for these values to increase. This differing behavior suggests that the physical properties of the substrates, such as absorption, spreading, and retention of the droplets, significantly influence the characterization of the deposited droplet spectrum. Therefore, part of the observed differences may be related to the collection method itself and not necessarily to changes in the actual spray pattern produced by the aircraft.

Despite these differences in volumetric diameters, the relative span (AR) remained close to 0.9 in all treatments and showed no significant difference ($p = 0.90$), indicating a relatively homogeneous distribution of the droplet spectrum regardless of flight altitude and collector type. Values close to 1 are normally associated with good uniformity in the distribution of droplet size, an important characteristic for reducing drift risks and favoring greater deposition uniformity. Similar results were reported by Lou et al. (2018) and Guo et al. (2021), who highlight the uniformity of the droplet spectrum as a determining factor for the efficiency of applications with remotely piloted aircraft. The coefficients of variation observed, ranging between 14.72 and 17.70% for the volumetric diameters, 26.21% for coverage, and reaching higher values for some deposition variables, indicate experimental precision compatible with spray trials conducted under field conditions, in which meteorological factors, turbulence generated by the rotors, and the droplet dynamics themselves contribute to increasing experimental variability.

In general, cardstock paper showed similar behavior to water-sensitive paper for most operational variables, especially the number of droplets, dispersion, droplet density, and coverage, indicating potential for use as a lower-cost alternative material in comparative deposition studies. However, considering the low absolute values of density and coverage obtained in this experiment and the differences observed for the volumetric diameters, its use should be interpreted with caution. These results are consistent with the observations of Garcera et al. (2014) and Forster et al. (2014), who highlight that alternative collectors can be used in spray evaluations, provided their physical properties are previously characterized and considered when interpreting the results. Thus, it is recommended to conduct new studies involving different spray nozzles, application volumes, flight altitudes, and environmental conditions to validate the use of cardstock paper in scenarios that provide agronomically adequate deposition levels and allow its use as a reliable substitute for water-sensitive paper.

Final Considerations

Flight altitude (3 and 5 meters) did not significantly influence the number and diameter of the droplets in the application with the remotely piloted aircraft equipped with 110015 AD nozzles, demonstrating deposition stability within the evaluated operational range. Cardstock paper presented statistically similar performance to water-sensitive paper in evaluating the number and diameter of droplets, confirming its technical viability as an alternative, low-cost material for characterizing the droplet spectrum in agricultural applications with drones.

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