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Scientific Article

Glyphosate application using a RPA with different spray nozzles and flight heights

Aplicação de glifosato utilizando ARP com diferentes pontas de pulverização e alturas de voo

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ABSTRACT – Conventional herbicide application methods can be inefficient, and remotely piloted aircraft (RPA) provide a viable alternative. This study evaluated application quality and weed control efficacy using an RPA and an electric backpack sprayer. A randomized block design with eight replications was used. Treatments consisted of two spray nozzle types (standard flat fan and air-induction flat fan) and two RPA flight heights (3.0 and 4.0 m), plus an untreated control and a standard treatment with a backpack sprayer. The spray mixture contained water, brilliant blue dye, glyphosate, and an adjuvant. RPA treatments achieved higher spray quality on the weed canopy and reduced soil losses compared with the backpack sprayer. Both methods resulted in effective weed control at 21 days after application, particularly the RPA treatments with flat fan nozzles at 3.0 and 4.0 m flight heights. RPA equipped with flat fan nozzles at a 3.0 m flight height achieved weed control efficacy equivalent to that of the electric backpack sprayer (98.5%), demonstrating that RPA technology represents a viable alternative for total-area weed management.

Keywords: Application technology. Unmanned aerial vehicle. Drone. Efficacy. Droplet deposition. Weeds.

RESUMO – Métodos convencionais de aplicação de herbicidas podem apresentar baixa eficiência, e o uso de aeronaves remotamente pilotadas (ARP) surge como uma alternativa viável. Este estudo avaliou a qualidade de aplicação e a eficácia no controle de plantas daninhas utilizando uma ARP e um pulverizador costal elétrico. Foi utilizado um delineamento experimental em blocos casualizados, com oito repetições. Os tratamentos consistiram de dois tipos de pontas de pulverização (jato plano padrão e jato plano com indução de ar) e duas alturas de voo da ARP (3,0 e 4,0 m), além de uma testemunha sem aplicação e de um tratamento padrão com pulverizador costal. A calda de pulverização continha água, corante azul brilhante, glifosato e adjuvante. Os tratamentos com ARP apresentaram maior qualidade de pulverização sobre o dossel das plantas daninhas e menores perdas para o solo em comparação ao pulverizador costal. Ambos os métodos proporcionaram controle eficaz de plantas daninhas aos 21 dias após a aplicação, com destaque para os tratamentos com ARP equipada com pontas de jato plano nas alturas de voo de 3,0 e 4,0 m. A ARP equipada com pontas de jato plano operando a 3,0 m de altura de voo apresentou eficácia de controle equivalente à do pulverizador costal elétrico (98,5%), demonstrando que essa tecnologia representa uma alternativa viável para o manejo de plantas daninhas em área total.

Palavras-chave: Tecnologia de aplicação. Veículo aéreo não tripulado. Drone. Eficácia. Deposição de gotas. Plantas daninhas.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

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INTRODUCTION

Weeds are responsible for significant yield losses in agricultural crops, with global economic losses estimated at approximately US$32 billion annually and affecting approximately 1,800 weed species in plant production (DAS et al., 2024). This interference results from biotic and abiotic factors and occurs directly through competition, allelopathy, and parasitism or indirectly by hindering harvesting and cultural practices and by harboring pests, fungi, and nematodes (BARROSO; MURATA, 2021).

In agriculture, conventional herbicide application methods rely on ground-based equipment, such as backpack or tractor-mounted hydraulic sprayers. However, these systems may present operational limitations, including lower efficiency, higher labor requirements, restrictions imposed by field topography, and risks to human health, especially when recommended operational parameters and the proper use of personal protective equipment are not strictly followed (KUMAR et al., 2022; VITÓRIA et al., 2023).

Remotely piloted aircraft (RPA), also known as unmanned aerial vehicles (UAVs) or drones, represent an emerging technology in agricultural pest management. These autonomous or remotely controlled systems are equipped with precision spray systems and can operate with greater flexibility than conventional ground-based equipment. RPA offer significant advantages over conventional sprayers, including higher operational efficiency, lower application rates, water savings, reduced risk of human contamination, suitability for steep slope areas and muddy fields, and elimination of limitations imposed by field

topography, turning space, and crop canopy (CRAUSE et al., 2023; MODI et al., 2026; CHEN et al., 2026).

However, despite their numerous advantages, RPA systems present important operational and technical limitations that must be carefully considered for successful implementation in agricultural environments. The need for specialized labor and technical expertise constitutes a significant barrier, especially in regions where trained operators are scarce or unavailable. In addition, the limited load capacity restricts the volume of spray solution carried per flight, increasing operational time and labor demand in large-scale applications.

Additional constraints include battery autonomy and the high potential for drift when operational parameters such as droplet size, application swath, flight path, speed, and flight height and weather conditions, particularly wind speed and direction, are not properly controlled. These factors reduce application efficiency and effective droplet deposition on target weeds while increasing off-target losses (GUO et al., 2020; VITÓRIA et al., 2025; MA et al., 2026). Therefore, optimization of operational parameters, such as spray nozzle type and flight height, is essential to maximize application quality and herbicide efficacy while minimizing environmental impacts.

Recent studies have demonstrated the potential of RPA systems for herbicide application in different crops and weed species. Ahmad et al. (2020) and Jeevan et al. (2023) reported higher droplet deposition and greater application efficiency of these systems compared with manual methods in rice crops. Similarly, research involving glyphosate application has reported effective weed control using RPA equipped with different nozzle types (LOPES et al., 2024; CARNEIRO et al., 2024).

However, most of these studies have focused on specific crops (rice and wheat) or on isolated weed species under controlled conditions, which limits extrapolation of the results to total-area management. Furthermore, the interaction between operational parameters, including the combined effects of flight height and spray nozzle type, on both application quality and weed control efficacy remains poorly understood. This knowledge gap is relevant because proper optimization of these parameters is essential to expand the practical adoption of RPA technology in different agricultural systems and to ensure consistent herbicide efficacy under varying field conditions and weed communities.

Many studies have evaluated the use of RPA for applying pesticides and foliar fertilizers to agricultural crops. However, the present study focused on specific aspects to fill theoretical gaps related to application quality and weed control efficacy in total-area applications. Several studies have focused on the effects of different operational parameters of RPA on herbicide applications, but the results are not always applicable to weed control in total-area management. The hypothesis of this study was that flight height and spray nozzle type affect the quality of herbicide application and weed control efficacy in total-area treatments.

The objective of this study was to evaluate the application quality and weed control efficacy in total-area application, using an RPA with different spray nozzle types and flight heights compared with an electric backpack sprayer.

MATERIAL AND METHODS

The experiment was conducted at the experimental farm of the Centro Universitário Norte do Espírito Santo (Ceunes; Northern University Center of Espírito Santo) of the Universidade Federal do Espírito Santo (UFES), in São Mateus, ES, Brazil (18°40'25"S, 40°51'23"W). The soil of the area was classified as a Typic Hapludult (Argissolo Vermelho -Amarelo Distrófico típico) (SOIL SURVEY STAFF, 2022) with a sandy loam texture. The region's climate is classified as Aw (hot and humid), with a dry season in autumn and winter and a rainy season in spring and summer (ALVARES et al., 2013).

Phytosociological surveys were performed using the inventory method with a 1.0 × 1.0 m square polyvinyl chloride frame that was randomly placed at ten locations in the experimental area. The weeds with the highest incidence in each sampled frame were identified. Dicotyledonous weeds occurred at lower incidence and were represented mainly by *Bidens pilosa* and *Solanum americanum*. Monocotyledonous weeds occurred at higher incidence and were represented mainly (in descending order of incidence) by *Urochloa decumbens*, *Cenchrus echinatus*, *Panicum maximum*, and *Rhynchelytrum repens*. Weed canopy height ranged from 0.5 to 1.10 m during the experiment.

An electric backpack sprayer (DJB-S 20; Jacto®, Pompeia, Brazil) equipped with an air-induction flat fan nozzle (AI11002 VS; Teejet®, Glendale Heights, USA) was used according to local standards for postemergence herbicide application. Applications were performed at a speed of approximately 1.0 m s^{-1} with the spray boom 0.50 m above the weed canopy. The application rate was approximately 100 L ha^{-1} at a working pressure of 200 kPa, resulting in a flow rate of 0.65 L min^{-1} and a swath width of 1.05 m.

The remotely piloted aircraft (RPA) used was a DJI Agras T10 (SZ DJI Technology, Shenzhen, China) with a 10.0 L capacity, which was calibrated before the applications. The RPA spray nozzles were spaced equidistantly at 1.0 m and oriented perpendicularly to the aircraft axis. A theoretical swath width of 3.0 m, flight speed of 5.0 m s^{-1}, and application rate of 10.0 L ha^{-1} were used in all treatments.

The experiment was conducted in two phases: the first consisted of application quality data acquisition and the second consisted of herbicide application and evaluation of weed control efficacy.

A randomized block design was used, with treatments arranged in strip plots. Because the strips were not laterally replicated, the experiment was considered as pseudo-replicated, and statistical analyses were performed under the assumption of spatial homogeneity of the weed community, which had been previously verified through a phytosociological survey. The first factor was spray nozzle type: XR110015 (standard flat fan; TeeJet®, USA) and ADIA015 (air-induction flat fan; Magnojet®, Brazil). The second factor was RPA flight height (3.0 and 4.0 m). An untreated control and a standard treatment with the electric backpack sprayer were also included. Spray application quality was assessed at eight sampling points within each strip plot; these points represented subsamples within the same experimental unit. The experimental treatments are shown in Table 1.

Table 1. Experimental treatments.

Treatment	Spray nozzle type	Flight height (m)	Application rate (L ha^{-1})	Droplet classification
T1	Control (no application)			
T2	ADIA015	3.0	10.0	Coarse to ultra-coarse
T3	ADIA015	4.0		
T4	XR110015	3.0		Fine to medium
T5	XR110015	4.0		
T6*	AI11002	0.50	100.0	Coarse to ultra coarse

*Standard treatment (electric backpack sprayer).

The area used for the applications measured 6,000 m² (100 × 60 m) in both experimental phases, with experimental units of 1,000 m² (100 × 10 m); only the central portions of the experimental units were used for data collection.

Spray quality variables (droplet coverage, density, and deposition; volume median diameter; potential drift; and endo-drift) were evaluated using water-sensitive paper cards measuring 76 × 26 mm (WSPaper®, Presidente Prudente, Brazil). The cards were attached to polyethylene collectors fixed to 1.0-m-tall metal rods and positioned at the upper and lower canopy layers with a 45° inclination (Figure 1B). Eight targets spaced 10.0 m apart were placed in the central portion of each experimental unit (Figure 1A).

Droplet losses to the soil (endo-drift) were evaluated by placing an additional polyethylene collector at ground level on the rod to characterize droplets deposited on water-sensitive paper cards (Figure 1B). Actual droplet losses to the soil were estimated using artificial targets (acrylic plates measuring 0.16 × 0.08 m) placed at ground level, at the same height as the water-sensitive paper (Figure 1B).

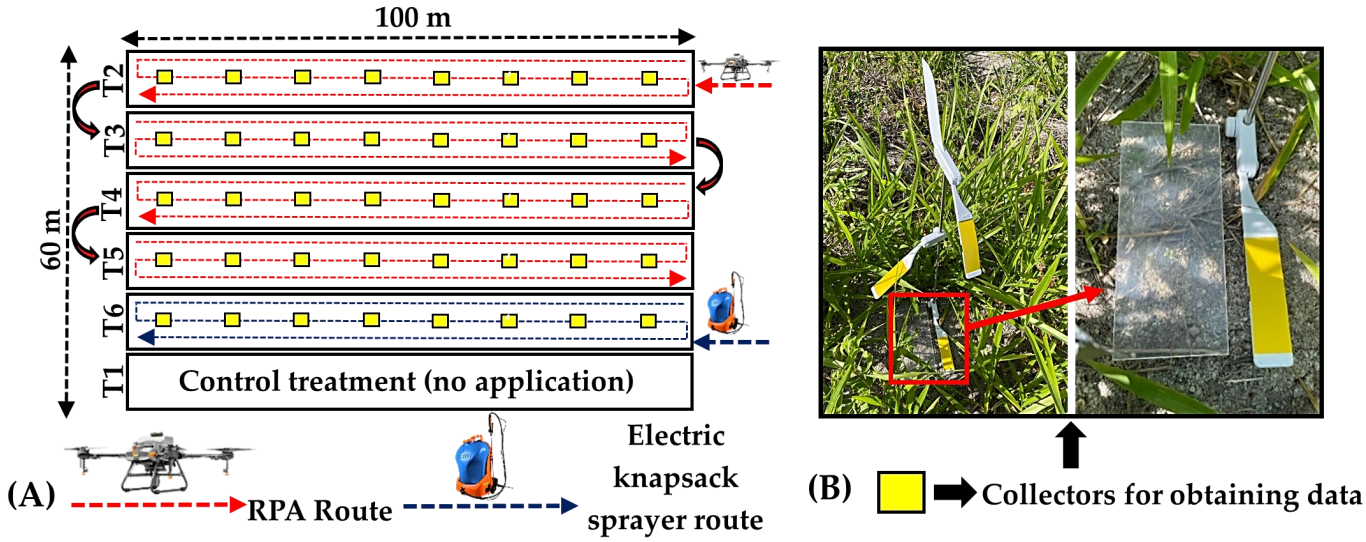


Figure 1. Experimental layout with treatments arranged in strip plots (A) and polyethylene collectors fixed to metal rods at the upper and lower weed canopy layers together with ground-level targets used to evaluate droplet losses to the soil (endo-drift) (B).

The spray solution consisted of water, brilliant blue dye tracer (MarcAzul®, Porto Alegre, Brazil) at 1.25 mL L^{-1}, and a non-silicone adjuvant (0.2% v v^{-1}) based on balanced polymers formulated specifically for aerial applications with low spray volumes (Helper Air®; ICL, São Paulo, Brazil).

Water-sensitive paper cards and artificial targets were collected five minutes after applications of each treatment to allow the solution to evaporate, leaving only the dye. The cards and targets were then placed in labeled kraft paper bags and sealed in plastic bags. The analyses were performed at the Laboratory of Mechanization and Agrochemicals (LMDA) of CEUNES/ UFES, São Mateus.

The DropScope® wireless system (SprayX, São Carlos, Brazil) was used to digitalize the water-sensitive paper cards for image analysis and data collection. This system includes software with a high-resolution image sensor that enables detailed analysis of overlapping droplets as small as approximately 25 µm. Despite the known limitations of water-sensitive paper cards, recent studies have confirmed the reliability of data obtained by scanning water-sensitive paper with the DropScope® system when analyzing droplet spectra from RPA applications (CUNHA; SILVA, 2023; RIBEIRO et al., 2023; RIBEIRO; VITÓRIA, 2024). The following parameters were determined: droplet coverage (%), droplet

density (droplets cm^{-2}), droplet deposition (µL cm^{-2}), volume median diameter (µm), and potential drift (percentage of volume applied in droplets smaller than 100 µm).

The dye was removed from the artificial targets in the laboratory by washing each sample with 50 mL of deionized water to estimate endo-drift. The samples were shaken for approximately 60 s, and the resulting solutions were analyzed for absorbance using a digital spectrophotometer (IL-226-NM -BI; Kasuaki®, China) capable of measurements in the visible range from 325 to 1,000 nm and equipped with a holographic flash monochromator. The spectrophotometer was set to measure absorbance at a wavelength of 630 nm. A calibration curve was prepared using seven standard solutions with known dye concentrations (0, 5, 10, 20, 25, 100, and 200 µL). Linear regression analysis of the standards resulted in a coefficient of determination of $R^2 = 0.999$, described by the equation $y = 0.0006x + 0.002$ relating concentration to absorbance.

Droplet deposition per unit area (µL cm^{-2}) was calculated from spectrophotometer readings, calibration curve data, and acrylic plate area using Equation 1:

$$\beta_{dep} = \frac{\left(\rho_{sample} - \rho_{blank}\right) \times F_{calibrate} \times V_{deposit}}{\rho_{spray} \times A_{target}} \quad (1)$$

where: β_{dep} = droplet deposition on the acrylic plates (µL cm^{-2}); ρ_{sample} = spectrophotometer reading of the sample; ρ_{blank} = spectrophotometer reading of the blank; $F_{calibrate}$ = calibration factor (µL L^{-1}); $V_{deposit}$ = liquid volume of the dilution (L); ρ_{spray} = sprayed dye concentration (g L^{-1}); and A_{target} = artificial target area (cm^2).

Weed control was evaluated after application of a spray solution consisting of water, the postemergence herbicide glyphosate (Roundup Original® Plus, soluble concentrate) at 3.0 L c.p. ha^{-1}, and a non-silicone adjuvant (0.2% v v^{-1}) based on balanced polymers formulated specifically for aerial applications with low spray volumes (Helper Air®; ICL, São Paulo, Brazil). Herbicide application and visual evaluations were performed according to the parameters described previously, using the same treatments and experimental design.

Control efficacy on the aerial parts of the weeds was visually assessed using the percentage scale described by Chen et al. (2023), which ranged from <60% to 100%. Evaluations were conducted at 10 and 21 days after application (DAA) using the inventory method with a 1.0 × 1.0 m sampling frame randomly placed five times in the central useful area of each experimental unit. At 21 DAA, the weeds inside the sampling frame were cut 5 cm above ground level, placed in labeled kraft paper bags, and separated by replication.

Shoot fresh weight (g m^{-2}) was determined by weighing the samples on a precision analytical balance (JKI®). The samples were then dried in a forced-air oven (Shel Lab®) at 60 °C until constant weight was reached, removed form the oven, and immediately weighed to obtain shoot dry weight (g m^{-2}).

Weed control efficacy (%) was calculated for each treatment by comparing shoot dry weight of the untreated control with that of the other treatments using Equation 2:

$$CE\ (\%) = \frac{SDW_{control} - SDW_{treatments}}{SDW_{control}} \times 100 \quad (1)$$

where: CE = weed control efficacy (%); $SDW_{control}$ = shoot dry weight of weeds in the untreated control (g m^{-2}); and $SDW_{treatments}$ = shoot dry weight of weeds in the herbicide-treated plots (RPA and electric backpack sprayer) (g m^{-2}).

Applications in both the first and second experimental phases were performed during the morning. Weather conditions were recorded during the applications using an automatic weather station (Davis®, Vantage Pro 2 wireless K6152) positioned approximately 100 m from the experimental area. Air temperature ranged from 24.7 to 28.1 ° C, mean relative humidity was above 60%, and wind speed ranged from 2.3 to 5.8 km h^{-1} during the applications. The methodology followed ISO 22866 (ISO, 2005), which specifies that air temperature during applications should be between 5 and 35°C, no more than 10% of wind speed measurements should be below 1.0 m s^{-1}, and wind direction deviation should remain 90° ± 30° relative to the application line.

The Shapiro-Wilk test was used to verify the normality of residuals. The data were then subjected to analysis of variance, and means were compared using Tukey's test. Dunnett's test was used, when necessary, to compare the RPA treatments with the untreated control and the standard treatment (electric backpack sprayer). All statistical analyses were performed using Rbio software (BHERING, 2017) at a 5% significance level.

RESULTS AND DISCUSSION

The interaction between flight height and spray nozzle type had no significant effect on the variables analyzed ($p \geq 0.05$). Therefore, the effects of the individual factors were analyzed separately for each variable (Table 2). Spray nozzle type significantly affected droplet density on the two weed canopy layers evaluated (upper and lower), indicating the importance of assessing application quality at different canopy positions. Coefficients of variation ranged from 27.33% to 80.47%, indicating a possible effect of RPA operating parameters combined with environmental conditions; however, this variation did not invalidate the statistical analysis.

Table 2. Analysis of variance of droplet coverage (COV; %), density (DEN; droplets cm^{-2}), and deposition (DEP; µL cm^{-2}) on the upper and lower weed canopy layers using a remotely piloted aircraft.

Variable	COV		DENS		DEP	
Canopy layer	Upper	Lower	Upper	Lower	Upper	Lower
A	0.66 ^{ns}	0.93 ^{ns}	0.63 ^{ns}	0.55 ^{ns}	0.58 ^{ns}	0.90 ^{ns}
N	0.36 ^{ns}	0.78 ^{ns}	<0.001***	<0.05*	0.52 ^{ns}	0.06 ^{ns}
A × N	0.73 ^{ns}	0.63 ^{ns}	0.37 ^{ns}	0.62 ^{ns}	0.71 ^{ns}	0.35 ^{ns}
CV (%) =	50.16	46.16	45.76	80.47	53.16	27.33

A = flight height; N = spray nozzle type; A × N = interaction between A and N. * and *** = significant at $p \leq 0.05$ and $p \leq 0.001$, respectively; ns = not significant; CV (%) = coefficient of variation.

The interaction between flight height and spray nozzle type was not significant for the application quality variables (droplet coverage, density, and deposition) assessed on the weed canopy. This finding may be attributed to the short distance between the data collection targets on the plants, which resulted from the low leaf volume in the upper and lower canopy layers and facilitated droplet distribution at both flight heights with the different spray nozzles. These results differ from those reported in previous studies that evaluated RPA applications on perennial and annual crops, where the plant canopy represented a significant barrier because of overlapping branches and leaves (CARNEIRO et al., 2024; RIBEIRO et al., 2025).

Flight height of 3.0 m resulted in higher mean droplet coverage and density in both the upper and lower weed canopy layers (Table 3). Differences between the means for the 3.0 and 4.0 m flight heights were less than 10%, confirming statistical equivalence between the treatments.

Droplet deposition at 3.0 m flight height followed the same pattern observed for droplet coverage and density, with higher means in both weed canopy layers compared with the 4.0 m flight height (Figure 2A). However, no significant differences were observed between factors (ANOVA).

Table 3. Mean droplet coverage (%) and density (droplets cm^{-2}) on the upper and lower weed canopy layers using a remotely piloted aircraft (RPA).

Variable	Droplet coverage (%)			Droplet density (droplets cm^{-2})		
			Flight height (m)			
Canopy layer	Upper	Lower	Mean	Upper	Lower	Mean
3.0 m	1.20	0.72	0.96	16.68	7.90	12.29
4.0 m	1.07	0.71	0.89	14.88	10.13	12.51
			Spray nozzle type			
ADIA015	1.00	0.70	0.85	4.80 b	4.52 b	4.66
XR110015	1.27	0.74	1.01	27.05 a	13.22 a	20.13

XR110015 = flat fan nozzle; ADIA015 = air-induction flat fan nozzle. Means followed by different letters in the same column differ significantly by Tukey's test at $p \leq 0.05$.

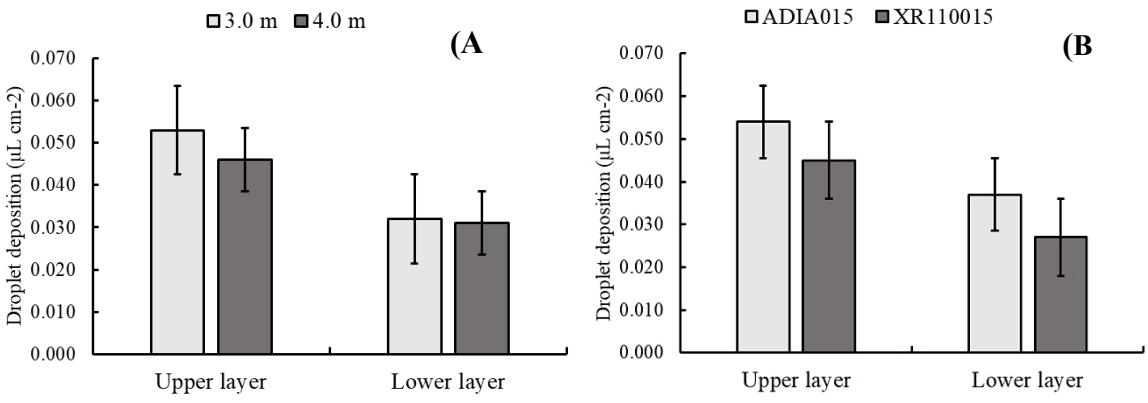


Figure 2. Effect of flight height (A) and sprays nozzle type (B) on droplet deposition (DEP; µL cm^{-2}) in the upper and lower weed canopy layers using a remotely piloted aircraft.

The analysis of the individual effects of the factors showed that the lower flight height (3.0 m) resulted in significantly higher droplet coverage, density, and deposition in both the upper and lower canopy layers. This result is consistent with reports by Crause et al. (2023) for lower flight heights. Although higher flight heights may occasionally increase droplet deposition per unit area, the stronger downward airflow generated by the RPA rotors near the canopy can increase the droplet runoff from leaves and losses to the soil (VITÓRIA et al., 2022; MA et al., 2026). However, increasing flight height increases droplet exposure to wind, thus increasing the risk of drift, reducing deposition efficiency on the target, and decreasing droplet penetration into the lower canopy layers because of the reduced effect of downward airflow from the RPA rotors (CUNHA; SILVA, 2023; VITÓRIA et al., 2025).

Flat fan nozzles (XR110015) produced higher mean droplet coverage on both weed canopy layers, although the difference was not significant compared with air-induction flat fan nozzles (ADIA015) (Table 3). Mean droplet density differed significantly between nozzle types and was directly proportional to droplet coverage; the highest mean droplet density was obtained with the XR110015 nozzles and was 4.32 times greater than that obtained with the ADIA015 nozzles.

Overall, air-induction spray nozzles (ADIA015 and AI11002) used in the RPA and electric backpack sprayer treatments, respectively, resulted in larger volume median diameter (VMD), regardless of weed canopy layer. VMD and potential drift (PD) were determined from water-sensitive paper cards placed in the weed canopy, whereas VMD and endo-drift (soil losses, µL cm^{-2}) were determined from water-sensitive paper cards and acrylic plates placed at ground level, respectively. The highest PD was observed with the XR110015 nozzles at both flight heights (T4 and T5) (Figure 3A); PD values with the ADIA015 nozzles were 8.13 and 5.07 times lower, respectively. For endo-drift, the standard treatment (T6) resulted in the lowest volume deposited on the soil (0.408 µL cm^{-2}) and differed from the RPA treatments, which deposited 0.367 µL cm^{-2} (T2), 0.376 µL cm^{-2} (T3), 0.382 µL cm^{-2} (T4), and 0.387 µL cm^{-2} (T5) (Figure 3B).

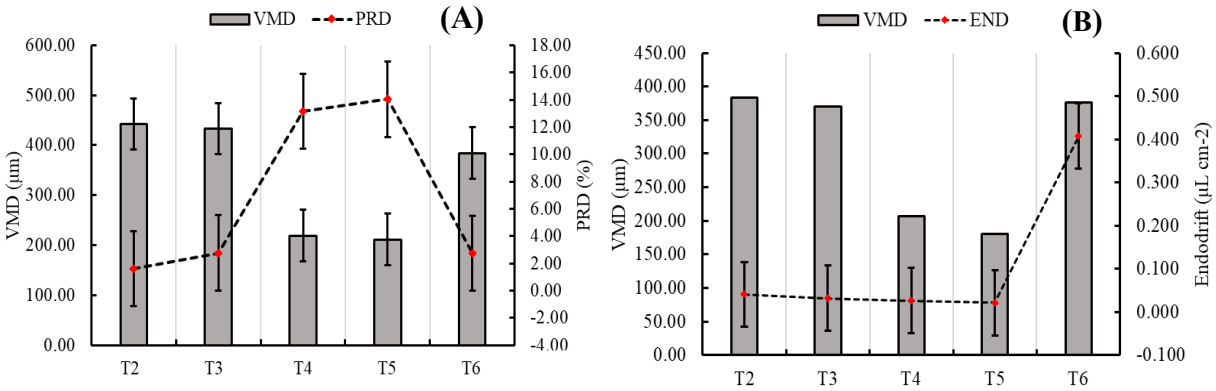


Figure 3. Relationship between volume median diameter (VMD; µm) and potential drift (PD; %) (A) and endo-drift (END; µL cm^{-2}) (B), regardless of weed canopy layer. Data include applications using a remotely piloted aircraft with different spray nozzle types and flight heights [ADIA015 at 3.0 m (T2) and 4.0 m (T3); XR110015 at 3.0 m (T4) and 4.0 m (T5)] and standard application using an electric backpack sprayer (T6).

Flat fan nozzles (XR110015) increased droplet density by approximately 76.85% compared with air-induction flat fan nozzles (ADIA015) in the RPA treatments. The higher number of droplets per unit area produced by the flat fan nozzles can be explained by their smaller VMD, since smaller droplets favor penetration into the plant canopy and increase the efficacy of contact-action herbicides (RIBEIRO et al., 2025; MODI et al., 2026). However, as droplet size decreases, droplets become more susceptible to evaporation and primary drift when applied under unfavorable weather conditions (RIBEIRO; VITÓRIA, 2024; CHEN et al., 2026), as confirmed by the results of the present study. In contrast, air-induction flat fan nozzles contain a pre-orifice before the outlet that incorporates air into the droplets, thereby increasing droplet size, reducing the number of droplets per unit area, and minimizing primary drift (MINGUELA; CUNHA, 2010).

Lopes et al. (2024) reported similar results when flat fan spray nozzles were used to control *Urochloa decumbens*. The highest PD in RPA applications occurred with the XR110015 nozzles, although these nozzles produced lower endo-drift. The ADIA015 nozzles produced lower PD and endo-drift than the electric backpack sprayer. However, the higher flight height (4 m) resulted in greater PD than the lower flight height for both nozzle types. According to Guo et al. (2020), spray droplets disperse more readily as flight height increases.

The electric backpack sprayer (standard treatment) produced higher droplet coverage, density, and deposition on both weed canopy layers compared with the RPA treatments. These results indicate that at least one RPA treatment differed statistically from the standard treatment (Table 4). Droplet coverage with the standard treatment was 90% higher than those with the RPA treatments in both weed canopy layers (Table 4). Differences in droplet deposition between application methods were even greater. RPA treatments with the ADIA015 nozzles at both flight heights (3.0 and 4.0 m) resulted in significantly lower droplet deposition compared with the standard treatment: 17.20 and 17.85 times lower in the upper canopy layer and 19.30 and 16.90 times lower in the

lower layer, respectively. Similarly, the standard treatment resulted in significantly higher droplet deposition than the RPA treatments with XR110015 nozzles at both flight heights: 94.50% and 95.87% higher in the upper layer and 95.70% and 96.44% higher in the lower layer, respectively.

Differences in droplet density between the standard treatment and the RPA treatment with ADIA015 nozzles 3.0 and 4.0 m were 104.0 and 100.88 droplets cm^{-2} (upper canopy layer) and 70.87 and 68.25 droplets cm^{-2} (lower layer), respectively. RPA treatments with XR110015 nozzles at both flight heights exhibited mean droplet densities 72.45% and 77.33% lower in the upper canopy layer and 78.65% and 81.80% lower in the lower layer, respectively, compared with the standard treatment.

Table 4. Droplet coverage (COV; %), density (DENS, droplets cm^{-2}), and deposition (DEP, µL cm^{-2}) on the upper and lower weed canopy layers for remotely piloted aircraft (RPA) treatments compared with a standard treatment (electric backpack sprayer).

Electric backpack sprayer (standard treatment)				
Canopy layer	Upper		Lower	
COV	18.94		13.70	
DENS	107.75		73.60	
DEP	0.946		0.675	
RPA				
Spray nozzle type	ADIA015			
Flight height (m)	3.0		4.0	
Canopy layer	Upper	Lower	Upper	Lower
COV	1.01**	0.65**	1.00**	0.74**
DENS	3.69**	2.73**	6.87**	5.35**
DEP	0.055**	0.035**	0.053**	0.040**
Spray nozzle type	XR110015			
Flight height (m)	3.0		4.0	
Canopy layer	Upper	Lower	Upper	Lower
COV	1.40**	0.78**	1.16**	0.71**
DENS	29.68**	15.71**	24.42**	13.40**
DEP	0.052**	0.029**	0.039**	0.024**

ADIA015 = air-induction flat fan nozzles; XR110015 = flat fan nozzles. **Means significantly different from the standard treatment by Dunnett's test ($p \leq 0.01$).

The electric backpack sprayer used as the standard treatment produced significantly higher droplet coverage, density, and deposition on both weed canopy layers, with some variables showing means approximately 90% higher than those obtained with the RPA treatments. This result can be attributed to the higher application rate and flow rate provided by the air-induction flat fan nozzle (AI11002) used in the standard treatment. Additionally, ergonomic limitations for the operator represent one of the main disadvantages of backpack sprayers, especially in steep areas.

The standard treatment resulted in a higher percentage of weed control at 10 days after application (DAA), which was classified as acceptable according to the visual rating scale described by Chen et al. (2023). However, all RPA treatments significantly reduced the occurrence of target weeds, achieving control levels ranging from 71% to 86% (Figures 4 and 5). Weed control increased for treatments at 21 DAA. All RPA treatments produced mean control percentages 10% lower than that of the standard treatment (100% control) (Figure 4), which were considered effective.

The untreated control resulted in significantly higher weed shoot fresh weight, with differences of 7.10 to 8.50 g m^{-2} compared with means of the herbicide treatments (Figure 6). The highest weed control efficacy was obtained with the electric backpack sprayer and with RPA equipped with XR110015 nozzles at 3.0 m flight height, which provided 70% and 67% higher control, respectively, than the untreated control.

Weed control obtained with the electric backpack sprayer was superior at the first evaluation (10 DAA). This result was due to the high droplet deposition on both the upper and lower weed canopy layers. However, this method also caused greater endo-drift. The application rate used in the standard treatment was 10 times higher than that used with the RPA; therefore, a larger volume of spray solution containing glyphosate was available for absorption and translocation by the weeds through leaves and roots. Herbicide application technology must be efficient to minimize losses caused by drift, volatilization, and leaching, particularly those resulting from excessive endo-drift (BLANK; ROZENBERG; GAFNI, 2023). In the case of glyphosate, any active ingredient not absorbed by the weed roots can be adsorbed by clay minerals, iron oxides, or organic matter in the soil, thereby preventing leaching and soil contamination (PEREIRA et al., 2020).

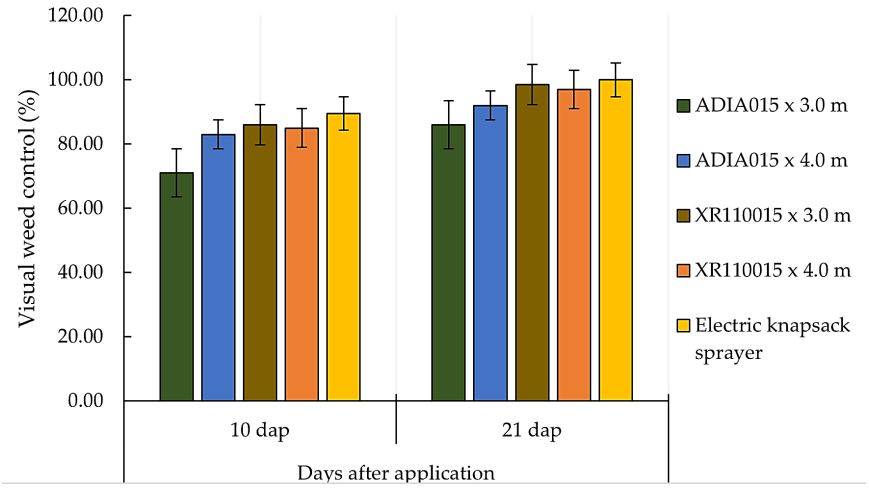


Figure 4. Weed control (%) at 10 and 21 days after application based on visual analysis in treatments applied using a remotely piloted aircraft with different spray nozzle types and flight heights (ADIA015 at 3.0 and 4.0 m; XR110015 at 3.0 and 4.0 m) and in a standard treatment using an electric backpack sprayer.

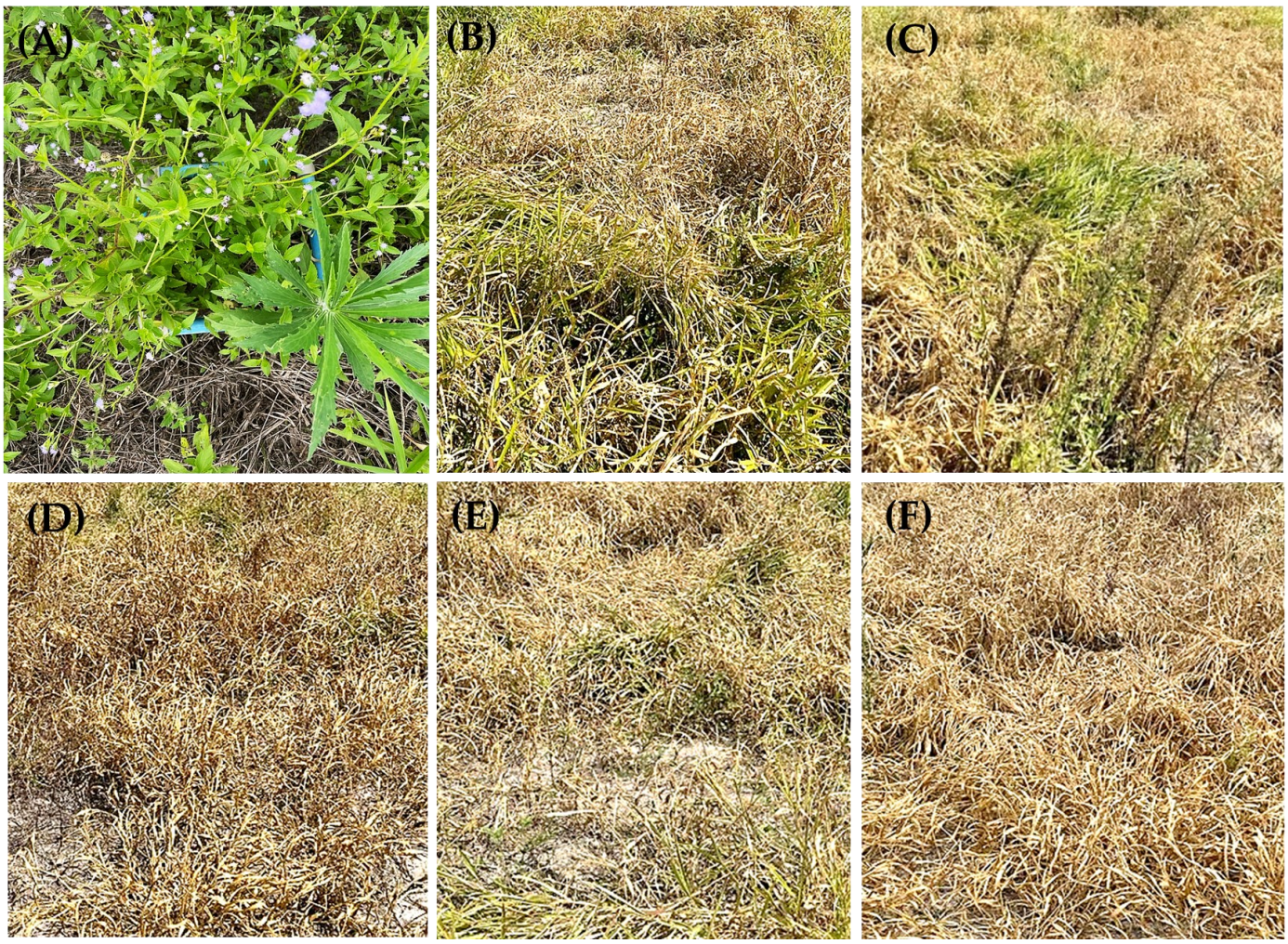


Figure 5. Weed control at 21 days after application. Treatments: untreated control (A); applications using a remotely piloted aircraft with different spray nozzle types and flight heights [ADIA015 at 3.0 m (B) and 4.0 m (C); XR110015 at 3.0 m (D) and 4.0 m (E)]; and standard application using an electric backpack sprayer (F).

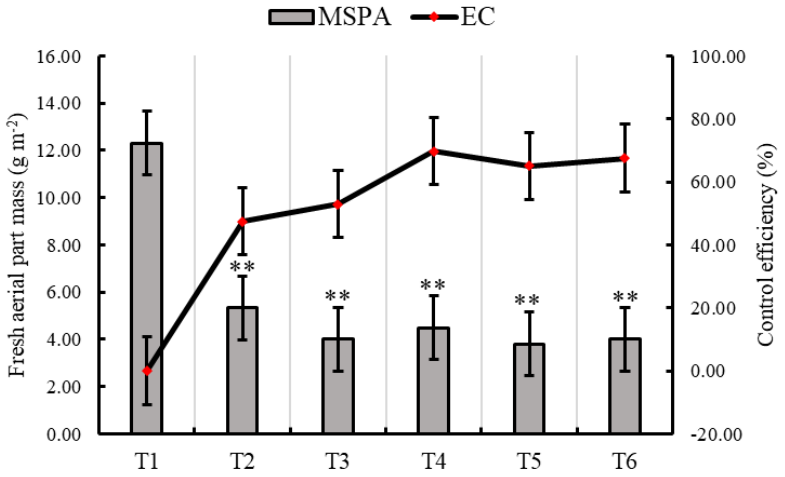


Figure 6. Weed shoot fresh weight (SFW) at 21 days after application and weed control efficacy (CE) relative to the untreated control (T1). Treatments: applications using a remotely piloted aircraft with different spray nozzle types and flight heights [ADIA015 at 3.0 m (T2) and 4.0 m (T3); XR110015 at 3.0 m (T4) and 4.0 m (T5)]; standard application using an electric backpack sprayer (T6). **Means significantly different from the control treatment by Dunnett's test ($p \leq 0.01$).

Although the RPA treatments produced lower droplet coverage, density, and deposition on the weeds, control efficacy at 21 DAA reached 92% with the ADIA015 nozzles at 4.0 m and 98.5% and 97% with the XR110015 nozzle at 3.0 and 4.0 m, respectively, indicating control efficacy similar to that obtained with the electric backpack sprayer. This result can be attributed to the higher concentration of active ingredient in each sprayed droplet, a consequence of the lower application rate used with the RPA. This characteristic is common in RPA applications because of their limited tank capacity, which requires lower application rates (VITÓRIA et al., 2023; RIBEIRO et al., 2023).

These results demonstrate the efficacy of RPA for total -area herbicide application in weed management; however, further research is needed to evaluate different operational parameters for pre- and postemergence applications of contact and systemic herbicides, as well as selective and burndown herbicides.

Jeevan et al. (2023) reported results similar to those of the present study regarding droplet deposition when applying herbicides to rice crops, as did Shan et al. (2021) and Kumar et al. (2022), who evaluated weed control in wheat crops applying halauxifen-methyl + florasulam and pyroxasulfone, respectively, and observed higher weed control efficacy and application quality with RPA compared with the backpack sprayer. Recently, Pranaswi et al. (2024) reported that the use of RPA for herbicide application supports Sustainable Development Goal 2 (Zero Hunger) of the United Nations by promoting sustainable crop protection and contributing to environmental safety.

CONCLUSIONS

Remotely piloted aircraft (RPA) equipped with flat fan spray nozzles at a 3.0 m flight height achieved weed control efficacy equivalent to that of the electric backpack sprayer (98.5% and 97% at 21 days after application), despite lower droplet deposition.

Air-induction flat fan nozzles at a 4.0 m flight height provided satisfactory weed control (92%) while minimizing spray drift, representing a practical alternative for total-area weed management.

These results indicate that RPA technology can effectively replace conventional ground-based application methods when operational parameters are properly optimized, while also reducing environmental impact and improving operator safety in challenging terrain.

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