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Evaluation of Remotely Piloted Aircraft for Agricultural Spraying in Corn Cultivation in the Brazilian Savannah

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Abstract

This study aimed to evaluate the quality of application using both RPA and ground techniques in corn cultivation using different spray nozzles in Brazilian savannah (*Cerrado*). The experiment was conducted using a completely randomized design, with four treatments and eight repetitions. The treatments involved two methods of application: aerial (RPA, 10 L ha^{-1}) and ground (backpack sprayer, 100 L ha^{-1}); and two types of nozzles: the standard flat fan nozzle XR 11001 and the air induction flat fan nozzle AirMix 11001. To study the quality of the application, the deposition was evaluated using a tracer and spectrophotometry, and the droplet spectrum, evaluated through the analysis of water-sensitive paper. Furthermore, a study on application quality was conducted using the Statistical Process Control methodology. The results demonstrated that with RPA, the deposition was higher, and the AirMix 11001 nozzle also stood out in this variable. No non-random behavior was observed in the deposition. Ground application showed the best performance in terms of target coverage and droplet density. The XR 11001 nozzle resulted in a higher droplet density. Overall, the XR11001 nozzle and the RPA application showed smaller volume median diameters (VMDs), indicating a higher potential for drift, which should be taken into account. Given the results obtained, it can be stated that the use of RPAs for agricultural spraying is viable for application.

Keywords: southeast region of Brazil, spray nozzles, unmanned aerial application systems (UAAS), *Zea mays* L.

1. Introduction

The corn plant (*Zea may*s L.) is native to Mexico and Central America and has adapted to various edaphoclimatic conditions (Osorio-Santiago et al., 2022). Its uses are diverse, including as food, fodder, feed, and fuel, making it a standout and a high-value crop (Aakash et al., 2022). In corn production, the occurrence of pests and diseases can compromise productivity, leading to economic losses (Ferreira & Miranda, 2020). The most economically significant pest species in the Neotropical region of South America are the corn leafhopper (*Dalbulus maidis*) (T. G. da Cunha et al., 2023; Oliveira & Frizzas, 2022) and the lepidopterans, such as the sugarcane borer (*Diatraea saccharalis* F.) (Francischini et al., 2019; Horikoshi et al., 2022; Marques et al., 2019) and the fall armyworm (*Spodoptera frugiperda* W.) (F. S. A. Amaral et al., 2020; Juárez et al., 2012).

To control pests and diseases, the primary method involves the use of plant protection products. Tudi et al. (2021) reported that these products are indispensable in agricultural production. To put it into perspective, approximately one-third of agricultural products are produced as a result of the application of plant protection products. Without the use of these products, there would be an estimated 32% decrease in cereal production. Therefore, they play a crucial role in reducing plant protection problems and increasing crop yields. Thus, they have significantly contributed to reducing food shortages and providing quality food.

In this context, where plant protection products are of paramount importance, and at a time when the global community is striving for more sustainable agricultural practices, one of the primary focuses is on effective pest management to enhance crop productivity (Singh et al., 2020). Effective management refers to the prevention of waste, meaning that the applied product should reach its target uniformly, thus controlling pests or diseases efficiently and with minimal risk to the environment. According to D. Wang et al. (2022), advancements in evidence-based technologies provide new opportunities to address the challenges associated with sustainable agriculture.

One of the latest technologies being used in this regard is the remotely piloted aircraft (RPA). It is a type of aircraft that can fly autonomously without a pilot on board, and the aircraft's movement is remotely controlled by the operator (Reddy Maddikunta et al., 2021). The droplet generators commonly used for RPA applications mainly consist of pressure nozzles and centrifugal atomizers (Yang et al., 2023). An RPA sprayer that uses hydraulic nozzles forms droplets under pressure, using a spray pump. The RPAs used for this purpose can vary according to their speed, payload, and number of spray nozzles (Velusamy et al., 2022).

RPAs are primarily used to replace conventional backpack sprayers, hydropneumatic sprayers, manned aerial sprayers, and also to perform spraying tasks in areas difficult to access by ground machines, such as mountainous regions and disorganized orchards that do not follow planting lines (C. Wang et al., 2022). Although the use of RPAs is increasingly being adopted for aerial applications, there is still uncertainty about their effectiveness in terms of deposition uniformity and application efficiency (Richardson et al., 2020).

The spraying with the application via RPA is affected by the relationship between the nozzle design and the plant protection product (Dong et al., 2023). The main features primarily include the size and speed of the droplets (S. Li et al., 2021). According to S. Wang et al. (2023), the nozzle is the most critical component of a sprayer for the application of plant protection products. Cerruto et al. (2021) stated that the correct spray droplet spectrum ensures the necessary dose on the target, minimizing losses due to drift.

RPAs, not unlike other sprayers, require appropriate equipment. The nozzles used in multi-rotor RPAs are mounted on the arms where the rotors with propellers are located, or on a bar positioned transversely in the direction of flight. Therefore, they are located below the rotors. The intensity of the airflow from the rotors, which tends to affect spraying, cannot be freely adjusted as it primarily depends on the equipment weight and flight height. Therefore, selecting the appropriate nozzles for treatment is of utmost importance (Chojnacki & Pachuta, 2021).

The standard flat fan spray nozzle is commonly used in the spraying process for pest and disease management in agriculture. These, however, produce various droplet sizes. Consequently, many small droplets, which are associated with spray drift, are carried by the wind and deposited outside the desired application area (Sijs et al., 2023). Air induction nozzles may be an alternative in the application. In this type of nozzle, the mixture to be applied passes through a narrow section of the channel, resulting in the Venturi effect, creating a negative pressure inside the nozzle body. This causes the air to be drawn into the interior through holes present in it and mixed with the liquid before exiting through the nozzle. The spray generated contains droplets with air bubbles, consequently producing fewer fine droplets (Doruchowski et al., 2017). Kasbi et al. (2023) report the suitability of air induction nozzles compared to standard flat fan nozzles, due to the chaotic movement conditions characteristic of RPA spraying, where there is a turbulent downward air flow. This leads to greater droplet disintegration and increases the potential for drift while compromising coverage.

As stated, understanding the characteristics of the spray droplet spectrum and deposition under working conditions is essential to guide the most appropriate choice of spray nozzle and the technology to be used in relation to the target structure and local environmental conditions. Deposition is an extremely important index for evaluating the quality of spraying via RPAs. One method of evaluating this deposition is to obtain it indirectly through a calculation based on the analysis of the amount of tracer added to the spray (Gao et al., 2019). In addition to deposition, the droplet spectrum is also of great interest for evaluating the quality of the application, as through this analysis it is possible to characterize the size and distribution of sprayed droplets, aiming for greater control of the application. One way to analyze the droplet spectrum is through artificial targets, water sensitive papers (WSPs), where the WSPs are subsequently processed and analyzed with specific imaging systems, and thus obtain some indicators such as the droplet size, target coverage and droplet density (Xun & Gil, 2024).Therefore, the present study aimed to evaluate the application quality with the remotely piloted aircraft in corn cultivation using different spray nozzles and the ground application was also carried out in order to allow the discussion of the new technique with an already widespread (conventional) technique.

2. Materials and Methods

2.1 Study Area

The field trial was conducted in a cornfield at the Experimental Farm of the Glória Campus of the Federal University of Uberlândia (UFU), with the coordinates of 18°57’07” south latitude and 48°12’46” west longitude, in the city of Uberlândia, Minas Gerais, Brazil, during the month of January 2023. The local average altitude of the experimental area is 867 m and the characteristic climate of the region is of the Aw tropical humid megathermic type, according to the Köeppen classification, has hot and humid summers and cold and dry winters. The average monthly air temperature ranges from 20.9 to 23.1 °C. The average annual rainfall is 1,500-1,600 mm (Rodrigues & Lima, 2019).

The experimental area where the applications were performed (Figure 1) consisted of four plots. Where applications were performed via remotely piloted aircraft (RPA), the plots were 50 m long and 20 m wide, totaling an area of 1000 m². The plots that received applications with the CO_2 pressurized backpack sprayer were 40 m long and 6 m wide, totaling 240 m². In each plot where the application was carried out with RPA, for sampling, 5.0 m were disregarded on each of the lateral edges and the ends of the length. In the plots where ground applications were made, 1.0 m was disregarded on each of the edges, to ensure that the sprayer speeds were constant. The distance between the plots was 10 m (buffer zone). The working swath width for aerial application was 4 m, based on the study conducted by Cunha e Silva (2023); for the ground application, it was 2 m.

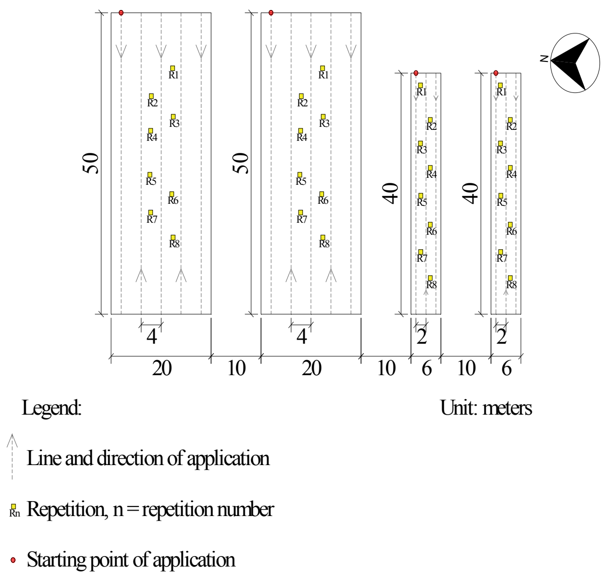

Figure 1. Experimental arrangement

As can be seen in Figure 1, the repetitions of each treatment were positioned within each plot. When conducting an experiment with RPA, where the plots are usually larger in area, repetitions by blocks is unfeasible. Therefore, this arrangement is justified and has been used by various research groups (Chen et al., 2021; Meng et al., 2018; G. Wang et al., 2019a). Biglia et al. (2022) reported that this allows the minimization of the variation of environmental conditions between repetitions, making the obtained data comparable. The application took place at the V8 vegetative phenological stage, on January 11, 2023, 47 days after sowing (DAS).

2.2 Cultivar

For subsequent application, the experimental area was cultivated with hybrid corn XB 6016 Vip 3, from Semeali Seeds (Birigui, São Paulo), sown on November 25, 2022, with a row spacing of 0.50 m and a density of 66,000 plants^{-1}. The average plant height on the day of application was 1.15 m (Figure 2).

Figure 2. Experimental field with corn cultivation, XB 6016 Vip 3 cultivar

2.3 Equipment

The agricultural sprayers used in the application were the remotely piloted aircraft (RPA) AGRAS MG-1P (DJI, China), with a 10 L spray tank, 4 spray nozzles, and 8 motors (130 rpm/volts). More specifications can be found in Table 1. A CO_2 pressurized backpack sprayer equipped with a bar with four nozzles spaced 0.5 m apart was also used.

Table 1. Specifications of the remotely piloted aircraft

Parameter	Description
Operation Method	Remote Control
Dimensions (mm)	1471 x 1471 x 482 (dimensions with arms open)
Work capacity (ha h^{-1})	2,80 - 4,05
Spraying System	Atomized spraying
Tank capacity (L)	10
Number of nozzles	4
Application Range (m)	4 - 6 (with application from 1.5 - 3.0 m from the crop)
Altitude detection accuracy (m)	0.1
Maximum operating speed (m s^{-1})	8
Positioning mode	GPS* or manual

Note. *GPS = Global positioning system.

Source: DJI, 2016.

The nozzles used in the application were as follows: extended range flat fan XR 11001, from Teejet® Technologies (Illinois, USA) and air induction flat fan AirMix 11001 from Agrotop® Spray Technology (Obertraubling, Germany).

For the application via remotely piloted aircraft, the application rate was 10 L ha^{-1}, the speed and flight height were 22.4 km h^{-1} and 2.0 m above the top of the plants, respectively. In ground spraying, for both nozzles, the working pressure was 200 kPa, the flow rate of each nozzle was 0.33 L min^{-1}, the displacement speed was 4.0 km h^{-1}, the application rate was 100 L ha^{-1}, and the application height was 0.5 m above the upper part of the plants.

During the experiment, the weather conditions in the area showed relative humidity ranging from 61.0% to 74.0%, with an average of 69.5%. The air temperature varied between 30.1 to 32.2 °C, with an average of 30.9 ºC, and the wind speed was between 3.2 to 5.0 km h^{-1}, with an average of 4.5 km h^{-1}. These measurements were taken using a portable digital thermo-hygrometer-anemometer, model KR825, brand AKROM® (São Leopoldo, Brazil).

The experiment had a completely randomized design (CRD) with two factors (nozzle and application method), totaling 4 treatments and eight repetitions. The treatments included the XR 11001 and AirMix 11001 nozzles, previously characterized, and the application methods were aerial (via remotely piloted aircraft) and ground (via CO_2 pressurized backpack sprayer).

2.4 Evaluations

2.4.1 Deposition

Deposition in the crop was quantified by adding a tracer to the spray, consisting of Brilliant Blue food dye (FD&C Blue n.1), internationally cataloged by the Food, Drug & Cosmetic, at a dose of 0.5 kg ha^{-1}. The applied spray was composed of water and tracer. For the RPA, a flight plan was made before the application, according to the plots, the application rate and swath, the desired flight height, and the displacement speed, so that the flight could be carried out from a previous programming. The application was conducted with the spray mixture in the tank of the sprayers. The RPA flight was conducted in a *back-to-back* manner.

After the application, samples were taken from the upper (last fully expanded leaf) and lower (first leaf) parts of the crop, with one leaf being removed from each part of the plant (Figure 3). The samples were collected at eight random points, respecting the useful area. The leaves were stored according to the height and corresponding position of each repetition and plot, in previously identified plastic (PVC) bags. These were sealed and placed in containers with thermal and light insulation, then transported to the Agricultural Mechanization Laboratory of the Federal University of Uberlândia (Uberlândia, Minas Gerais), where subsequent analyses were conducted.

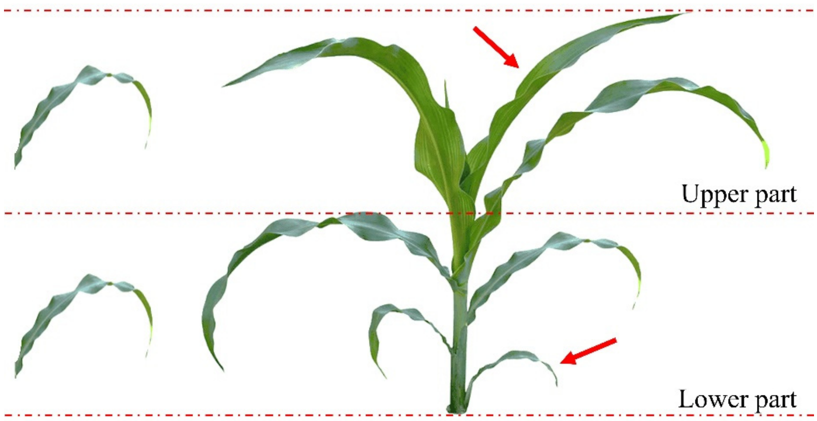

Figure 3. Leaf sampling pattern to assess deposition

Note. The red arrows indicate leaf sampling. Lower part: first leaf. Upper part: last leaf.

In the laboratory the leaf deposit was extracted from the samples. For this, 100 mL of deionized water was added to each plastic bag with the samples, and then the plastic bags with the solution were shaken for complete homogenization using a pendulum shaking table model TE240/I from Tecnal company (Piracicaba, Brazil), set at 250 rpm for 15 minutes, in order to extract all the tracer present in the samples.

From the solutions formed, the tracer was quantified using the absorbance values obtained by spectrophotometry, which constitutes determining the concentration of a substance by measuring the relative absorption of light, i.e., it shows the light energy absorbed by the sample at a specific frequency. The spectrophotometer used in the experiment was a Bioespectro (Curitiba, Brazil) model SP-220, with a tungsten halogen lamp, and glass cuvettes with a 10 mm optical path, at a wavelength of 630 nm for the color blue.

The absorbance values were converted into tracer concentration in μg L^{-1} using a previously determined calibration curve based on solutions with known tracer concentrations. The amount of tracer deposited was then determined relative to the quantity of extraction solution used to wash the leaves. Afterward, the tracer's mass was divided by the leaf area, measured in cm^2 for each sample (one leaf for each part of the plant evaluated), to determine the deposition in μg cm^{-2}. The leaf area was measured with a Licor® LI 3100C leaf area meter (Lincoln, USA).

2.4.2 Droplet Spectrum

Syngenta® water-sensitive papers (Basel, Switzerland) measuring 76 x 26 mm was used to analyze the droplet spectrum. For this, two of these papers were used per plot, on the upper and lower parts of the crop, for each repetition (Figure 4a and 4b). Metal clips were used to attach them to the plants in order to simulate the appearance of a leaf.

(a) (b)

Figure 4. Detail and positioning of the water-sensitive papers: (a) Water-sensitive paper attached to the plant; (b) How the water-sensitive paper was sampled in the different parts of the plant

Soon after application in each plot, the papers were collected and placed inside properly identified paper envelopes and transported to the laboratory. Using the DropScope® system from SprayX (São Carlos, Brazil) the papers were processed with scanning and the data analyzed.

The coverage (%), droplet density (droplets cm^{-2}), volume median diameter (VMD, µm), relative amplitude (RA), and percentage of volume in droplets smaller than 100 µm (% < 100 µm) were analyzed.

2.5 Statistical Analysis

In this study, the assumptions of the linear model were studied, using the Shapiro-Wilk (W) tests to assess the normality of the residuals, the Levene (L) tests for homogeneity of variances, and the Durbin-Watson (DW) test for independence of the residuals. After ensuring that these variable assumptions were met, a variance analysis study was conducted using a completely randomized design (CRD) with four treatments and unbalanced repetition for the droplet spectrum variables.

Data were transformed with square root or logarithmic when the assumptions of the linear model were not met. When the assumptions were not met even after transformation, non-parametric statistics such as the Kruskal-Wallis test (Morais, 2001) were used, and the data position measure was represented using medians due to non-normality.

Additionally, to assess whether the process of spray deposition within each plot was within acceptable variability, that is, to verify the quality of the deposition, control charts were created. Monitoring by statistical process control (SPC) is a very useful and effective methodology for detecting abnormal changes in a process (Xu & Deng, 2023). The analysis was conducted for the upper and lower parts of the crop. Individual measurements of each treatment were used to construct the individual control charts. For the control charts measuring the variability between two consecutive measurements, the moving range was used, as described by Montgomery (2017).

The analyses were conducted using R software version 4.2.2 (R CORE TEAM, 2020), and the control charts were created using Minitab® software version 16.2 (MINITAB Inc., 2010).

3. Results and Discussion

3.1 Deposition

Deposition is a highly relevant factor as it indicates the amount of spray or product deposited per unit area. Table 2 shows the average values of the tracer deposition. At the upper part of the plant, the aerial application via remotely piloted aircraft (RPA) showed a higher average deposition of 3,900 µg cm^{-2} than that observed in the ground application, which showed 2,494 µg cm^{-2}. A higher deposition mass implies a lower loss of applied product, whether due to drift or runoff.

Table 2. Tracer deposition (μg cm^{-2}) in corn cultivation promoted through ground and aerial (RPA) application using different nozzles

Application	Upper part deposition	
AERIAL APPLICATION - RPA	3.900 a	
GROUND APPLICATION	2.494 b	
Nozzle		
XR 11001	2.456 b	
AIRMIX 11001	3.939 a	
Assumptions	***W* = 0,95**; ***L*= 2.43**; ***DW* = 2.63**	
	Lower part deposition [1]	
	XR 11001 NOZZLE	AIRMIX 11001 NOZZLE
AERIAL APPLICATION - RPA	1.615 aA	1.241 aA
GROUND APPLICATION	1.087 bB	1.693 aA
Assumptions	***W* = 0.96**; ***L*= 1.82**; ***DW* = 2.61**	

Note. Means followed by distinct lowercase letters in the column and uppercase in the row differ from each other by the Tukey test at the 0.05 significance level; *W*, *L*, and *DW*: statistics of the Shapiro-Wilk tests for normality of residuals, Levene for homogeneity of variances, and Durbin-Watson for independence of residuals, respectively; bold values indicate normally distributed and independent residuals and homogeneous variances at the 0.05 significance level; [1] Significant interaction between factors; RPA=remotely piloted aircraft.

H. Zhang et al. (2023) stated that the downward air flow produced by the RPA's rotors, known as *downwash*, primarily influences droplet deposition and drift, thereby altering the characteristics of the spray. The deformations created in the target crop due to this airflow will manifest uniquely for different phenotypic parameters of the crops, and therefore, the deposition effect may also vary. Furthermore, the entry and adhesion of droplets in crops at different stages of development vary due to differences in crop height, density, and leaf area index (S. Guo et al., 2021). According to Zhan et al. (2022), the *downwash* effect can enhance the spray deposition on target crops, as observed in this study. In this regard, Hong, Zhao e Zhu (2018) explains that the strong airflow reduces the droplet's flight time and minimizes the impact of weather conditions on the application, which may enhance droplet deposition.

In general, Z. Wang et al. (2023) observed a higher deposition of spray on corn leaves (*Zea mays* L.) after aerial application via RPA than that after ground application via electric backpack sprayer. The application rates for RPA were 15 and 30 L ha^{-1}, while for ground application it was 450 L ha^{-1}. The average deposition significantly increased by 87.90% for the 15 L ha^{-1} treatments and by 46.70% for the 30 L ha^{-1} treatments compared to ground application. Further supporting these results, Hussain et al. (2022) also evaluated the deposition in corn cultivation at different plant heights. They observed that the average droplet deposition values for RPA application at rates of 15 and 30 L ha^{-1} were not statistically different. In summary, the deposition with RPA applications was higher than those with backpack sprayers (450 L ha^{-1}).

G. Wang et al. (2022) in a study of product applications in cotton cultivation (*Gossypium hirsutum* L.), observed that there was less deposition with the boom sprayer (450 L ha^{-1}) on the upper part of the crop, with approximately 0.12 μg cm^{-2}, than that using RPA applications with rates of 15.0; 22.5 and 30.0 L ha^{-1}, which showed deposition values ranging between 0.20 and 0.25 μg cm^{-2}. The authors also found that an RPA application rate of 15 L ha^{-1} is recommended when considering deposition, the effectiveness of plant protection products, work efficiency, and lower cost for mechanized harvest.

X. Wang et al. (2023) evaluated the application in rice cultivation (*Oryza sativa* L.), and the results showed that although the application rate of the backpack sprayer, 450 L ha^{-1}, was an order of magnitude greater than that of the RPA sprayer, 22.5 L ha^{-1}, the droplet deposition with RPA application was better than that of the backpack sprayer.

In terms of the nozzles used, the AirMix 11001 flat fan nozzle with air induction stood out for the highest deposition (3,939 µg cm^{-2}) on the upper part of the crop. At the lower part, in ground application also showed superior performance, with 1.693 µg cm^{-2}, demonstrating the good penetration capability of this nozzle in this application method. In this type of spray nozzle, during the spraying process, air is entrained using the Venturi effect and then mixed with the spray solution as the fluid flows through the nozzle, forming a gas-liquid stream. (Abdelmotalib et al., 2021). Its main feature is drift reduction, as it typically produces a thicker droplet spectrum (De Cauwer et al., 2023). These large droplets containing air bubbles produce smaller droplets upon hitting the target due to splash, which can contribute to greater deposition, as the rebound of these larger droplets is avoided. This is possibly what occurred in this study.

McCoy et al. (2022) observed that air induction nozzles, for an air-assisted application, resulted in a higher deposition on the upper part of the grapevine (*Vitis vinifera*) canopy, with 426 ng cm^{-2}, compared to the nozzle without air induction (380.1 ng cm^{-2}). S. Guo et al. (2022) in assessing the application via RPA in Nanguo variety pear (*Pyrus* L.) orchards, they also found a higher deposition for the air induction nozzle (IDK90015). When the application was conducted at a rate of 90 L ha^{-1}, it produced the highest deposition values of 0.719 and 0.488 µL cm^{-2} with and without adjuvant on the upper surface of leaves, respectively.

At the lower part of the crop, the interaction between the nozzles and application methods was significant. When the application was made with the XR 11001 nozzle, the RPA application showed a higher deposition (1,615 µg cm^{-2}) than the ground application (1,087 µg cm^{-2}), indicating that the application method altered the deposition. Shouji et al. (2021) reported that the atomization characteristics of the spray nozzles are greatly affected by the downward air flow, which could explain this difference in spray deposition.

Our findings suggest that it is possible to reduce the application rate without decreasing the spray deposition, and the use of the AirMix 11001 nozzle may offer better performance in spray deposition on corn crops at the V8 vegetative phenological stage.

Monitoring the various parts of the process of applying plant protection products is a significant challenge due to technological advancements and field conditions. However, it is crucial to ensure the application meets the expected quality. In this sense, control charts are a tool used to examine this quality. Typically, they are developed for a response variable, thus providing information that can be useful for improving or maintaining the process quality based on the studied variable (Mahmood et al., 2022). Figures 5 and 6 show the control charts for deposition on the upper and lower parts of the crop, respectively, based on the values obtained for each treatment.

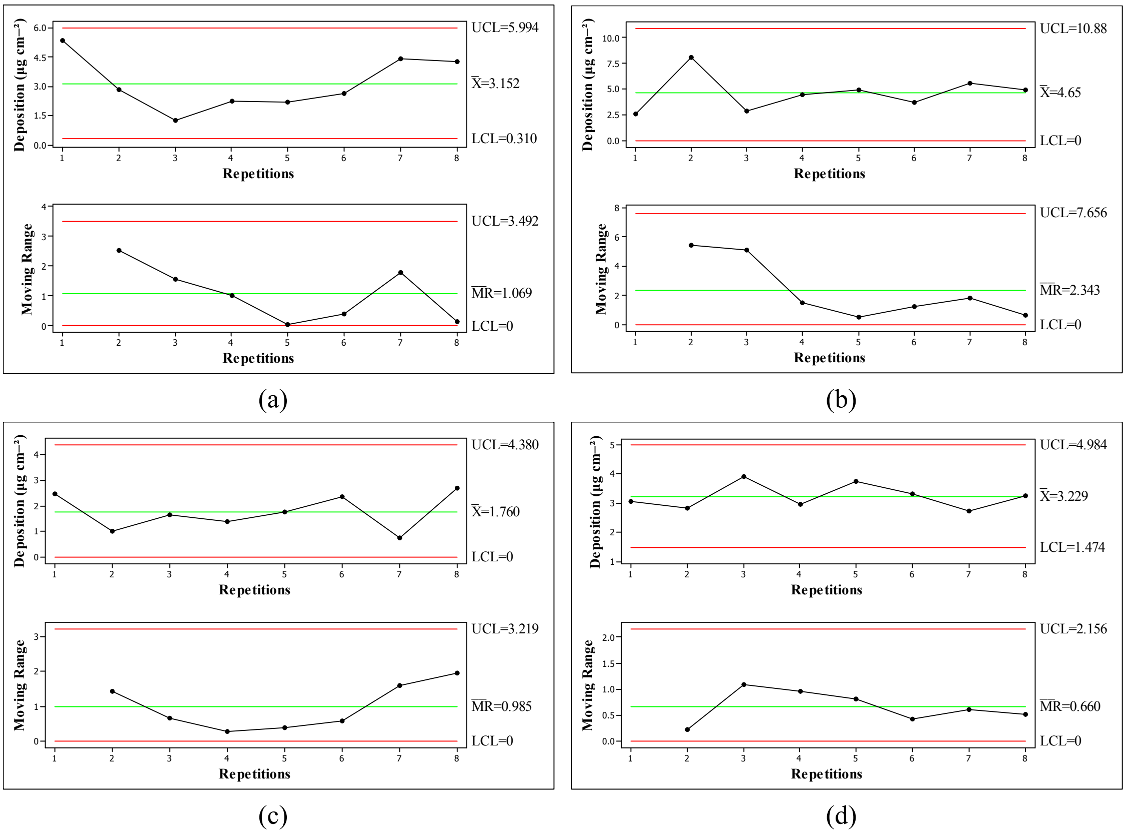

Figure 5. Control charts for tracer deposition (µg cm^{-2}) on the upper part of the corn crop: (a) RPA - XR 11001; (b) RPA - AirMix 11001; (c) GROUND - XR 11001; (d) GROUND - AirMix 11001

Note. UCL = Upper Limit, $\overline{X}$ = Treatment Mean, LCL = Lower Limit, $\overline{MR}$ = Moving Averages; RPA: Remotely Piloted Aircraft.

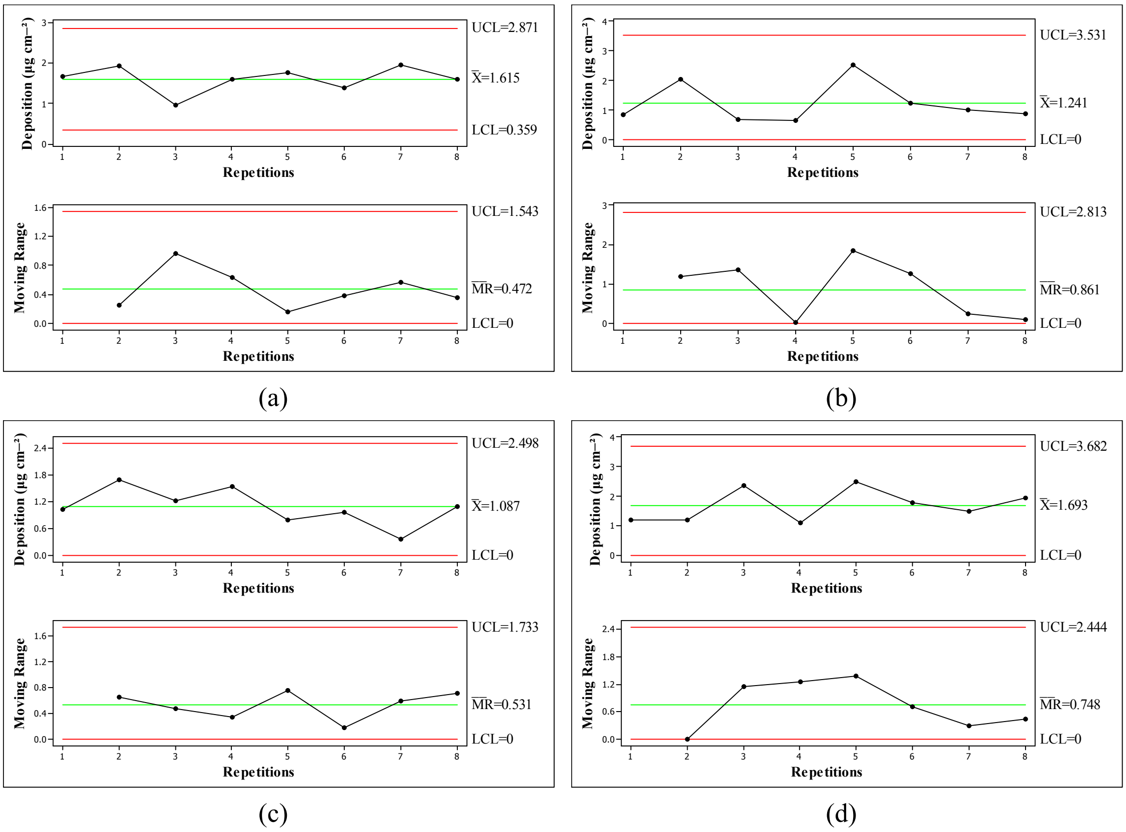

Figure 6. Control charts for tracer deposition (μg cm^{-2}) on the lower part of the corn crop: (a) RPA - XR 11001; (b) RPA - AirMix 11001; (c) Ground - XR 11001; (d) Ground - AirMix 11001

Note. UCL = Upper Limit, $\overline{X}$ = Treatment Mean, LCL = Lower Limit, $\overline{MR}$ = Moving Averages; RPA: Remotely Piloted Aircraft.

No patterns of non-randomness were observed for the different types of nozzles and application techniques evaluated, as deposition values were within the upper (UCL) and lower (LCL) control limits. This corresponds to casual causes of randomness variation, relative to the average process value, indicating that the process is under control. Therefore, the applications were consistent in terms of deposition within the statistical process control (SPC), exhibiting natural variability.

According to Hadian e Rahimifard (2019), the process is deemed "out of control" when points on the control chart shift beyond the upper or lower limit. Consequently, the process varies beyond a projected measure over certain periods or spaces. The presence of uncontrollable conditions should prompt a more in-depth analysis aimed at identifying specific causes for subsequent pursuit of solutions and/or corrections.

For the deposition on the upper part of the crop (Figure 5), the greatest variations occurred in applications via RPA. When this technique was employed using the AirMix 11001 nozzle (Figure 5b), the deposition value in the second repetition (observation) was 8.081 μg cm^{-2}, while the average was 4.650 μg cm^{-2}. This recorded the highest variation between the observation and the average value, with a range of 3.431 μg cm^{-2}. The ground application using the AirMix 11001 nozzle (Figure 5d) resulted in the least variation between the observed deposition values and the average, with the third repetition (3.915 μg cm^{-2}) marking the point of greatest variation.

Regarding the deposition on the lower part of the crop (Figure 6), the greatest variation was also for the RPA application with the AirMix 11001 nozzle (Figure 6b). In the fifth repetition, the deposition was 2,513 μg cm^{-2}, and the average was 1,241 μg cm^{-2}, showing a range of 1,272 μg cm^{-2}. The application via RPA with the XR 11001 nozzle (Figure 6a) showed the least variation between the data and the average.

Overall, based on the results, it is reasonable to say that the least variation in deposition data was with ground application, even though the process is under control for both application methods. This smaller variation between observations did not imply greater deposition in the crop, as previously discussed (Table 2), where RPA applications were more prominent. The identification of potential abnormalities aids in enhancing the system's efficiency. Reducing variability around target values can result in minimizing costs, waste, and rework, thereby improving performance.

3.2 Droplet Spectrum

The degree of target coverage from the spray application is defined as the ratio between the surface area covered by the spray and the total surface area of the sampler (Cieniawska et al., 2022). The coverage on the upper part of the crop was influenced by the application technique used, as shown in Table 3. The ground application covered the target approximately 10 times more, with 9.95% coverage as compared to that of the RPA application, which achieved 0.95% coverage. As expected, coverage decreased due to the lower application rate. Hunter et al. (2019) also observed a consistent decrease in coverage as the application rate reduced. At a speed of 1 m s^{-1} with a rate of 151 L ha^{-1}, the coverage for different nozzles varied between 31% and 61%. When the speed was 7 m s^{-1} and the rate was 22 L ha^{-1}, the coverage varied between 13% and 22%. Other studies also confirmed the proportionality of coverage and application rate (Ferguson et al., 2016; G. Wang et al., 2019b).

Table 3. Coverage (%) and density (droplets cm^{-2}) of droplets obtained on the upper and lower parts of the corn crop promoted by ground and aerial (RPA) application using different nozzles

	Upper part	
Application	Coverage [1] (%)	Density [2] (droplets cm^{-2})
AERIAL APPLICATION – RPA	0.95 b	26.73 b
GROUND APPLICATION	9.95 a	170.63 a
Nozzle		
XR 11001	4.50 a	137.44 a
AIRMIX 11001	6.76 a	62.13 b
Assumptions	**W = 0.95**; **L = 1.99**; **DW = 2.09**	**W = 0.96**; **L = 0.60**; **DW = 1.96**
	Lower part [3]	
	Coverage [1] (%)	
	XR 11001 NOZZLE	AIRMIX 11001 NOZZLE
AERIAL APPLICATION – RPA	0.70 aA	0.42 bA
GROUND APPLICATION	2.29 aB	5.14 aA
Assumptions	**W = 0.97**; **L = 2.99**; **DW = 2.23**	
	Density [2] (droplets cm^{-2})	
	XR 11001 NOZZLE	AIRMIX 11001 NOZZLE
AERIAL APPLICATION – RPA	31.18 aA	4.54 bB
GROUND APPLICATION	66.92 aA	39.96 aA
Assumptions	**W = 0.99**; **L = 0.39**; **DW = 2.07**	

Note. Means followed by distinct lowercase letters in the column and uppercase in the row differ from each other per the Tukey test at the 0.05 significance level; *W*, *L*, and *DW*: statistics of the Shapiro-Wilk tests for normality of residuals, Levene for homogeneity of variances, and Durbin-Watson for independence of residuals, respectively; bold values indicate normally distributed and independent residuals and homogeneous variances at the 0.05 significance level; [1] Square root transformation; [2] Logarithmic transformation; [3] Significant interaction between factors; RPA: Remotely Piloted Aircraft.

On the lower part of the crop, the interaction was significant between the nozzles and application methods for coverage and droplet density. The ground application with the XR 11001 nozzle (2.29%) and the RPA application with the AirMix 11001 nozzle (0.42%) showed less coverage than the ground application with the AirMix 11001 nozzle (5.14%). This result indicates that ground application, with a higher application rate (100 L h^{-1}), using the AirMix 11001 flat fan nozzle with air induction, provides better coverage on the lower part of the crop. Dafsari et al. (2021) reported that air injection into droplets can lead to improved coverage. This happens due to the presence of air in the droplets, which causes their disintegration on the target surface. This disintegration into several smaller droplets increases coverage. According to Hołownicki et al. (2021), the use of air induction nozzles, which can result in high spray coverage on targets, may be a good solution for applying plant protection products to minimize environmental impact without compromising their effectiveness in control.

Vera-Vaca et al. (2023) evaluated RPA aerial application in corn cultivation at the R2 reproductive stage, finding a coverage of less than 3.00%. Yongjun et al. (2017) also did evaluations of corn cultivation. They found that when the crop reached a height of 1.20 m, coverage varied between 0.49 and 5.87% on the upper part of the crop and 0.08 to 2.13% on the lower part for different flight heights (1.0, 1.5, and 2.0 m) and flight speeds (2, 4, and 6 m s^{-1}). These results corroborate those found in this study.

The literature provides varying reports regarding the influence of coverage percentages on efficacy. Lewis e Hamby (2020) observed that optimizing coverage is a crucial component of sugarcane (*Saccharum officinarum* L.) pest management. Nansen et al. (2021) reported that inconsistent and low coverage is particularly concerning when contact insecticides are applied. Greater coverage increases the likelihood of contact between the target and the product.

However, a high percentage of coverage does not necessarily mean that the concentration of plant protection products is sufficient to control the pest or disease (Menger et al., 2020). Arakawa e Kamio (2023) found that the application of ultra-low volume plant protection products using RPAs can be effective in protecting chestnut trees (*Castanea* sp.). The authors' findings suggest that a higher concentration of the acaricide fluvalinate (100 times less diluted than in hydro-pneumatic spraying) may be more effective or have a higher likelihood of maintaining its effectiveness. In this experiment, the spray mixture from the RPA was more concentrated, which, despite lesser coverage, could result in biological efficacy. Doruchowski et al. (2017) observed that while applying insecticides on apple trees (*Malus domestica* (Borkh.)), the differences in coverage between treatments did not reflect in the efficacy of aphid and mite control. Possibly, the systemic action mode of the insecticides compensated for any potential difference in coverage produced. Thus, it is verified that the coverage should be studied with caution.

Regarding the density results, on the upper part of the corn crop, the value was substantially higher for ground application, with 170.63 droplets cm^{-2}, while the RPA application achieved 26.73 droplets cm^{-2}. The application rate may have influenced the number of droplets on the evaluated surface. This outcome was also observed by C. Shan et al. (2021), where the droplet density increased with the rise in application rate. In this study, the authors observed that for a spray rate of 7.5 L ha^{-1}, the droplet density varied from 4.4 to 9.9 droplets cm^{-2} for different droplet sizes (100, 200, and 300 μm). However, at a volume of 30 L ha^{-1}, the droplet density varied between 8.8 and 40.0 droplets cm^{-2}. Furthermore, C. Wang et al. (2022) observed that the application via RPA may present a finer droplet spectrum. These fine droplets exhibit the characteristic of moving slower than the coarse droplets in the downward air flow and follow a long, winding path. As they rotate, the fine droplets have the potential to encounter more surfaces, providing more opportunities to deposit on the underside of the leaf.

C. Shan et al. (2022) evaluated the application of RPA in corn cultivation with different application rates (7.5-30.0 L ha^{-1}), observing an average droplet density of 18 droplets cm^{-2}. Cunha e Silva (2023) also analyzed application on corn cultivation at the V5-V6 vegetative stage with a density ranging from 26 to 39 droplets cm^{-2} for the RPA application. Values close to those found in this study.

For the nozzles used in the applications, the XR 11001 nozzle stood out with 137.44 droplets cm^{-2}, while the AirMix 11001 flat fan nozzle with air induction showed a density of 62.13 droplets cm^{-2}. Mur et al. (2018), testing applications with different nozzles in soybean (*Glycine max* (L.) Merrill), also observed a lower droplet density for the AI 110015 air induction nozzle (Hypro®, Cambridge, England) on the upper part of the crop. As will be seen later, the AirMix 11001 nozzle produced bigger droplets than the XR 11001 nozzle, which may explain the lower droplet density for this nozzle. Sayinci, Demir e Açik, (2019) in estimating droplet density for different spray nozzles, found that coarse droplets produce fewer droplets than do fine ones. Similarly, based on the findings from the lower part of the crop, the AirMix 11001 nozzle showed a lower droplet density in the RPA application, approximately 4.54 droplets cm^{-2}, compared to application with the XR 11001 nozzle, which showed 31.18 droplets cm^{-2}.

The AirMix 11001 nozzle showed a significant difference in density for the different application methods, particularly on the lower part of the crop. The ground application method had a higher density (39.96 drops cm^{-2}), approximately eight times greater than the RPA application (4.54 drops cm^{-2}). As previously discussed, the higher application rate intensified the droplet density. Regarding the lower part of the crop, this nozzle was more influenced by the application rate.

As outlined by Zhu, Salyani e Fox (2011), *Syngenta Crop Protection AG* (Basel, Switzerland) recommends at least 20-30 droplets cm^{-2} for pre-emergent insecticide or herbicide applications, 30-40 droplets cm^{-2} for post-emergent herbicide applications, and 50-70 droplets cm^{-2} for fungicide applications, in order to achieve satisfactory results. Considering that the spray from an ultra-low volume application is more concentrated, and that the droplets of the spray with the plant protection product have an osmotic and diffusion effect on plants, individual droplets on plant leaves indicate an effective control (X. Zhang et al., 2020). L. Li et al. (2022) report that further research is needed to determine the consistency of droplet density and coverage that will favor disease and pest control, due to the higher concentration of the product and lower application rate.

The comparison of the effects of applications on the volume median diameter (VMD), relative amplitude (RA), and percentage of volume in droplets with a diameter less than 100 μm can be seen in Table 4. The RPA application was characterized by fine droplets on the upper and lower parts of the crop, with VMDs of 216.74 and 223.20 μm, respectively. The ground application exhibited medium spectrum droplets (261.75 μm) on the upper part of the crop and fine droplets on the lower part (220.04 μm). The droplets were categorized based on the droplet spectrum classification of the American Society of Agricultural and Biological Engineers (ASABE, 2009).

Table 4. Volume Median Diameter (VMD, μm), Relative Amplitude (RA), and the percentage of volume in droplets smaller than 100 μm obtained in the upper and lower parts of the corn crop, promoted through ground and aerial (RPA) application using different nozzles

	Upper part		
Application	VMD [1,4] (μm)	RA [1]	% < 100 μm [2]
AERIAL APPLICATION – RPA	216.74 b	1.03 a	15.43 a
GROUND APPLICATION	261.75 a	1.19 a	4.47 b
Nozzle			
XR 11001	158.72 b	1.17 a	15.68 a
AIRMIX 11001	326.64 a	1.05 a	0.98 b
Assumptions	**W = 0.97**; **L = 2.91**; **DW = 2.06**	**W = 0.98**; **L = 0.57**; **DW = 1.87**	W = 0.71; **L = 0.97**; **DW = 2.40**
	Lower part		
Application	VMD [1,3] (μm)	RA [1]	% < 100 μm [1,4]
AERIAL APPLICATION – RPA	223.20 a	0.79 a	10.95 a
GROUND APPLICATION	220.04 a	0.89 a	5.89 b
Nozzle			
XR 11001	154.45 b	0.85 a	15.23 a
AIRMIX 11001	288.79 a	0.83 a	1.61 b
Assumptions	**W = 0.96**; **L = 0.93**; **DW = 2.13**	**W = 0.95**; **L = 0.83**; **DW = 2.30**	**W = 0.96**; **L = 2.35**; **DW = 2.69**

Note. [1] Means followed by different lowercase letters in the column differ from each other per the Tukey test at the 0.05 significance level; [2] Medians followed by different lowercase letters in the column differ from each other per the Kruskal-Wallis test at the 0.05 significance level; W, L, and DW: statistics of the Shapiro-Wilk tests for normality of residuals, Levene for homogeneity of variances, and Durbin-Watson for independence of residuals, respectively; bold values indicate normally distributed and independent residuals and homogeneous variances at the 0.05 significance level; [3] Logarithmic transformation; [4] Square root transformation; RPA: remotely piloted aircraft.

Parma et al. (2022) evaluated applications via RPA in mung bean (*Vigna radiata* L.) cultivation and observed that this equipment produces smaller droplets. They reported that the pressure exerted by the *downwash* breaks down the droplet particles into a smaller size. This may explain the observation in the present study on the upper part of the crop. Gibbs, Peters e Heck (2021) also found a smaller average droplet size for RPA spraying (102 to 182 μm for the geometric mean diameter) than that for ground application (265 to 432 μm).

The VMD generated by the XR 11001 flat fan nozzle was 158.72 μm on the upper part of the crop and 154.45 μm on the lower part, with the droplets being characterized as fine. The AirMix 11001 flat fan nozzle with air induction showed average droplets on the upper and lower parts of the crop with VMD of 326.64 and 288.79 μm, respectively. According to manufacturers' catalogs, the XR 11001 nozzle can produce very fine to fine droplets, and the AirMix 11001 nozzle can produce fine to coarse droplets, within the nozzle's working range. X. Li et al. (2021) found that working with a VMD in the medium size category for a small payload RPA minimizes the production of small droplets prone to drift. Martin, Woldt e Latheef (2019) analyzing the droplet spectrum in a wind tunnel for different nozzles, observed a VMD of 161.4 μm for the XR 11001 nozzle, a value very close to that found in the present study.

The results showed that the AirMix 11001 air induction nozzle produced a larger VMD (326.64 and 288.79 μm). This was expected due to the nozzle's *design*, which allows for the formation of larger droplets, even though it has the same nominal flow rate as the XR 11001 nozzle. This occurs because these nozzles feature fluid chambers with openings connected to the outside. These small holes draw in air to the spray due to the Venturi effect, which reduces the pressure at the outlet hole and increases the droplet size (J. P. A. R. da Cunha et al., 2020). Gong, Li e Kang (2022) further reported that the inclusion of air is not the only reason for the generation of larger droplets. The length and area of the spray blade generated by air induction nozzles are smaller due to the bursting of air bubbles, which facilitates the formation of larger droplets.

Other authors have observed this same trend. Massola et al. (2018) evaluated different hollow cone nozzles (ATR-1.0 and TVI-800075) at different pressures (500, 600, and 700 kPa), and found that regardless of the working pressure, the nozzle with air induction had a larger VMD. Alves, Kruger e Cunha (2018) observed that the XR flat fan nozzle produced finer droplets than those produced by the AIXR flat fan nozzle with air induction for different sprays. Creech et al. (2018) found that the XR nozzle produced fine spray droplets (246-252 μm) for spray without adjuvant, while the air induction nozzles produced very coarse to ultra-coarse droplets (465-808 μm).

The droplet size, which is crucial for effective control, can be varied. Fine or coarse droplets can be used and are indicated in specific situations. Noting that larger droplets may not penetrate the physical barrier of the crop leaves, hindering penetration into the lower parts of the plants, and very fine droplets may be more susceptible to drift. According to G. Wang et al. (2020), reducing droplet size can optimize target coverage at lower application rates, such as 15 L ha^{-1}. However, this was not observed in the present study.

The uniformity of the droplet spectrum was characterized by the relative amplitude (RA). In this study, there was no significant difference between the treatments. A homogeneous droplet spectrum has a RA value tending towards zero (Souza et al., 2022). The results indicate a narrower range of droplets on the lower part of the crop, as the values are smaller (0.79 to 0.89). Zhang e Xiong (2021) suggested that values less than one (1) imply a narrow range in droplet size. The smaller variation of the droplets may result in a more easily controlled application. For instance, in an application requiring droplets close to 250 μm with a homogeneous droplet spectrum, a RA less than one, and a DMV of 250 μm, losses in the application can be avoided as the droplets presented values close to the required ones.

Cao et al. (2021) observed values ranging from 0.32 to 0.97 for the RA with the RPA application in rice cultivation (*Oryza sativa* L.). Rodrigues Neto et al. (2023), while studying applications with different rates (77 and 144 L ha^{-1}), found that the most heterogeneous droplet spectra were observed in applications with the lowest application volume (1.36 to 1.44). The rationale was that a higher concentration of products in lower application rates could alter the physical characteristics of the spray mixture, consequently affecting the uniformity of the droplets. Since no plant protection product was added to the spray mixture in this study, no difference was observed between the various application rates (10 and 100 L ha^{-1}).

Droplets smaller than 100 μm in diameter significantly contribute to drift losses. Drift is characterized by droplets that are not deposited on the target. Vambol et al. (2020) reported that a 100 μm droplet may be subject to significant deviations. The same authors also reported that water droplets smaller than 150 μm evaporate approximately 27% faster than do larger droplets. This happens due to the change in air flow that occurs with smaller droplets. Above 150 μm, the airflow separates from the droplet base, and evaporation does not occur in this area. On the other hand, the flow is involved around droplets smaller than 150 μm, and evaporation occurs across the entire surface.

Applications via RPA resulted in a higher percentage of droplets smaller than 100 μm, with a median of 15.43% on the upper part of the crop and an average of 10.95% on the lower part. The use of RPA can produce finer droplets at a faster flight speed and greater target distance, contributing to a drift risk (C. Wang et al., 2023). Y. Li et al. (2023) found that 25.98% of droplets were less than 100 µm for RPA application using the SX11002VS nozzle in a mango orchard (*Mangifera indica* L.). The ground application showed a median of 4.47% of droplets smaller than 100 µm on the upper part and an average of 5.89% on the lower part, indicating a lower drift potential.

Regarding the spray nozzles, the XR 11001 nozzle produced a higher percentage of droplets smaller than 100 µm, with a median of 15.68% on the upper part and an average of 15.23% on the lower part. Thus, the application with the AirMix 11001 nozzle shows a lower drift potential, less than 2%. Jomantas et al. (2023) observed that spray solutions applied with the air induction flat fan nozzle (Lechler IDK 12004) reduced drift risk. Applications using the standard flat nozzle (Lechler ST 11004) showed a deviation approximately twice as large. This is to be expected, as coarse droplets are less susceptible to air currents. Thus, if efficacy is not reduced, nozzles that form larger droplets should be used in applications (Brankov et al., 2023).

For efficient spraying, the correct choice and adjustment of the application is necessary, ensuring it aligns with environmental conditions and target characteristics. The correct choices will be based on the highest efficiency of the plant protection treatment and the reduction of drift (L. R. do Amaral et al., 2021). Furthermore, the parameters of RPA application are multivariate, where equipment model, flight heights and direction, displacement speed, and spray nozzles are relevant to the application quality. Different authors (Hou et al., 2019; Liao et al., 2019; Martinez-Guanter et al., 2020) have found specific responses to the studied situations. In light of the results obtained from this research, the use of RPA with the AirMix 11001 nozzle could be recommended for spraying. However, it should be noted that the application via RPA has a higher potential for drift and low coverage.

4. Conclusions

Using RPA, the spray deposition on the target was greater, but this deposition showed more variation across the plot points as observed in the control charts. Despite this variation, no non-random behavior was detected. The AirMix 11001 nozzle showed the most significant deposition.

The highest application rate, via backpack sprayer, demonstrated the best target coverage, approximately 10 times greater on the upper part of the crop, and a higher droplet density. This same application method using the AirMix 11001 nozzle showed better performance in coverage on the lower part of the crop. The XR 11001 nozzle showed a higher droplet density regardless of the part of the plant studied.

Applications using the AirMix 11001 nozzle showed a higher VMD and lower drift potential. The RPA application indicated a lower VMD on the upper part of the crop than that observed through the ground application.

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Authors contributions

LLL and JPARC were responsible for study design, data collection and revising. LLL was responsible for drafted the manuscript. QSSN was responsible for the statistical analysis. All authors read and approved the final manuscript.

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