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ORIGINAL ARTICLE

Application rate and nozzles associated with droplet electrification affect the spraying quality in common bean[1]

Taxa de aplicação e pontas associados à eletrificação de gotas afetam a qualidade da pulverização em feijoeiro

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HIGHLIGHTS:

The electrostatic technology increases the spray solution when using an empty conical tip in bean plants.
The leaf coverage of the abaxial and adaxial faces of common bean plants is not influenced by simple fan spray nozzles.
The application rate is a more relevant component than the spray tip when it comes to foliar coverage.

ABSTRACT: The objective of this work was to evaluate the application efficiency of different nozzle tips associated with increasing application rates. A field experiment was conducted in a factorial 3 × 4 randomized block design with four replicates. The first factor consisted of three types of nozzle tips (simple flat fan, hollow cone, and hollow cone with the electrification of the drops), and the second factor constituted the four application rates (50, 100, 200, and 250 L ha^{-1}). Electrostatic technology and a hollow cone tip increased the deposited volume on leaves on the upper and medium strata of the common bean plant, regardless of the application rate used. The increase in the application rate increased the volume of spray solution captured in the upper, medium, and lower strata, the drop density, the volumetric median diameter (VMD), and the percentage of foliar coverage, regardless of the spray tip evaluated. The percentage of leaf coverage on the adaxial and abaxial leaf was not influenced by the simple fan or hollow cone spray tips, with or without the association of electrostatic technology.

Key words: *Phaseolus vulgaris*, application technology, drift potential, spraying efficiency

RESUMO: O objetivo deste trabalho foi avaliar a eficiência de aplicação de diferentes pontas de bicos associada a taxas crescentes de aplicação. Foi conduzido um experimento de campo no delineamento em blocos ao acaso, em esquema fatorial 3 x 4, com quatro repetições. O primeiro fator consistiu em três tipos de bicos: leque plano simples, cone oco e cone oco com eletrificação das gotas; e o segundo fator por quatro taxas de aplicação (50, 100, 200 e 250 L ha^{-1}). A tecnologia eletrostática e o cone oco aumentaram o volume depositado nas folhas dos estratos superior e médio do feijoeiro, independentemente da dose de aplicação utilizada. O aumento da taxa de aplicação aumentou o volume de calda captado nos estratos superior, médio e inferior do feijoeiro, a densidade de gotas, o diâmetro médio volumétrico (DMV) e a porcentagem de cobertura foliar, independente da ponta de pulverização avaliada. A porcentagem de cobertura foliar na face adaxial e abaxial não foi influenciada pelas pontas de pulverização em leque simples e cone oco com ou sem a associação da tecnologia eletrostática.

Palavras-chave: *Phaseolus vulgaris*, tecnologia de aplicação, potencial de deriva, eficiência de pulverização

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Introduction

Brazil is among the world's largest producers of common bean (Leal et al., 2019). The common bean plant is of great socioeconomic importance and is cultivated in business systems, mainly by producers in family farming, in the most varied production environments in practically the entire national territory (Antolin et al., 2021).

According to the precepts of integrated management, chemical control should be the last technique used in farming. However, its importance and applicability are notorious, as it is a strategy with a high operational yield and high efficiency (Antolin et al., 2021). In this sense, landing spraying is one of the most commonly used forms of applying pesticides (Moraes et al., 2019). In most cases, much attention is paid to the product to be used in the application, neglecting the spraying technique (Contiero et al., 2016).

Drift in applications is considered one of the biggest problems in agriculture, both on the economic side and in the exposure of workers to pesticides, and environmental impacts must also be considered (Oliveira et al., 2019; Bish et al., 2021). Given the need for agricultural spraying, it is essential to use adapted technology to minimize these losses and optimize the deposition of the product on the biological target. Studies have already investigated the effect of nozzle selection and spraying rates (Mello et al., 2021; Li et al., 2021; Virk et al., 2022), but few have considered the effect of droplet electrification on these parameters. Since charged droplets behave differently from uncharged droplets, the definitions for efficient application can differ, changing the decisions made during spraying.

Therefore, the objective of this study was to evaluate the application efficiency of different nozzle tips associated with increasing application rates by electrostatic spraying technology.

Material and Methods

The work was carried out in the field in an area belonging to the Universidade de Rio Verde (UniRV), located in Rio Verde (Goiás State), Brazil, at the geographic coordinates of 17°47'14.11" S and longitude 50°57'53.81" W, at an altitude of 730 m. The experiment was carried out with common bean cultivated in the summer season in 2018/2019 (Figure 1). The climate is of the Aw type, according to Köppen's classification, identified as a tropical climate with a dry season, which is characterized by more intense rainfall in summer than winter.

The experimental design was randomized blocks with four replicates in a 3 × 4 factorial scheme. The first factor was composed of three variations of nozzle tips: simple fan (AXI11002 – 275.79 kPa), hollow cone (TXA80015 – 489.52 kPa), and hollow cone (TXA80015 – 489.52 kPa) with droplet electrification. The second involved four application rates (spray volume): 50, 100, 150, and 200 L ha^{-1}. The criterion for choosing the evaluated nozzle tips is that they are widely used in agricultural applications, and we aimed to compare them using droplet electrification technology. The dimensions of the experimental units were 6 m long and 2.5 m wide (5 rows of common beans). To compose the useful area of the plot, 4 m of the three central lines of the experimental units were considered, totaling 6 m^2.

Similar to the study carried out by Mello et al. (2021), to accomplish the droplet electrification process, an adaptation of the electrostatic equipment was performed in a coupled sprayer, using a charging system with indirect induction manufactured by TSBJet® (TSBJet, Santa Maria, Brazil). The equipment works with voltage ranging from 3000 to 7000 volts using the maximum voltage supplied in the experiment. To obtain the expected application rate for each treatment, the working pressure of the spraying system was not altered, proceeding with the adjustment according to the speed of the equipment at the time of application. In this sense, speeds of 18, 9, 6, and 4.5 km h^{-1} were used to provide application rates of 50, 100, 150, and 200 L ha^{-1}, respectively.

The common bean cultivar used in the experiment was BRS Estilo, developed by Embrapa Arroz e Feijão, Santo Antônio de Goiás (Goiás), Brazil. This cultivar belongs to the *Carioca* commercial group and is characterized by a type II

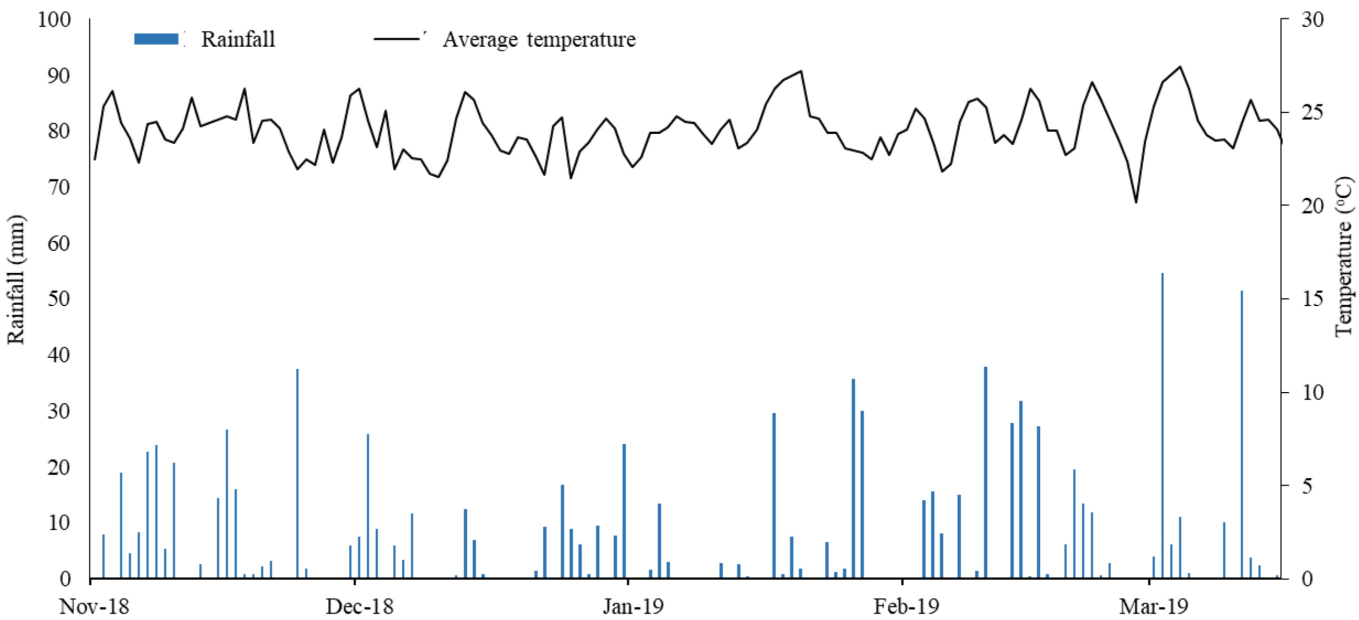


Figure 1. Data on average air temperature and rainfall during the experimental period

indeterminate growth habit, upright plant architecture, and high yield potential (Zanella et al., 2020). For mechanized sowing, seed density was adopted to obtain a final population of 180,000 plants ha^{-1}, using 0.5 m spacing between rows. All crop management regarding fertilization practices and control of weeds, pests, and diseases was executed by the technical recommendations for common bean.

The experiment contained a central transition corridor 3 m wide along its entire length since the applications were carried out using a coupled sprayer. A sprayer model Jacto Condor 600 AM12 was connected to an Agrale 5050 tractor (TDA) in the application. For the evaluation of the treatments, only a single application was carried out, and no phytosanitary product was used in the preparation of the spray solution. At the time of application, the common bean plants were at the R7 phenological stage of development (pod formation). The treatments were applied in the morning, between 8:00 and 12:00 hours, and in the afternoon/evening, between 16:00 and 19:30 hours. During the application, the average meteorological conditions were as follows: relative humidity of 47.5%, wind speed equivalent to 4.4 km h^{-1}, and air temperature of 31°C. The climatic conditions were measured using the portable thermo-hygro-anemometer device (Kestrel® 3000, Boothwyn, USA), positioned at a vertical distance of 0.5 m above the crop canopy.

Two methodologies were used to evaluate the characteristics related to spraying. The first aimed to quantify the volume of spray captured in the different strata of the common bean plant (upper, medium, and lower) and consisted of the application of spray containing water, adjuvant (Wide LIM; 50 mL 100 L^{-1} of water), and tracer (bright blue food dye FDC 1 at a concentration of 3 g L^{-1} of water) carried out with the application bar positioned 0.5 m above the canopy of the crop.

Immediately after the application of each treatment, a trifoliate leaf was collected from each stratum of five plants per experimental unit, which were randomly separated, packed, and identified in plastic bags (30 cm × 15 cm). Subsequently, the collected material was sent to the laboratory, where each trifoliate leaf was washed with 50 mL of distilled water to remove the dye (tracer). The absorbance of the solution obtained after washing each sample was read in a spectrophotometer with a wavelength of 630 nm. With the solution collected directly from the spraying equipment, a calibration curve with different concentrations (0.0, 0.2, 0.4, 0.6, 0.8, and 1.0 µL) was drawn to create a standard curve for comparing the analyzed samples.

The absorbance values for the different concentrations of the brilliant blue dye allowed the establishment of a linear equation ($y = -0.0327 + 0.1194x$; $R^2 = 99.55$), which was used to determine the dye concentration (mg L^{-1}) captured by the target during application (Scudeler & Raetano, 2006). By correlating the dye concentration in the sample washing solution with that obtained in the spray solution, the volume of spray captured by the target was established using the following equation:

$$Vi = \frac{(Cf \times Vf)}{CI}$$

where:

Vi - volume captured by the target (mL);

Cf - dye concentration in the sample, detected by the spectrophotometer in absorbance and transformed into mg L^{-1};

Vf - sample dilution volume (50 mL), and,

Ci - dye concentration in the sample (3000 mg L^{-1}).

Using a laser measuring scanner (Cl-202 Portable Laser Leaf Area Meter), the leaf area of the trifoliate collected from each treatment was obtained. The deposited volume was divided by the leaf area, thus obtaining the amount of spray solution in µL cm^{-2}.

At the time of application, the second methodology was performed concomitantly to evaluate droplet density cm^{-2}, volumetric median diameter (VMD) (µm), and coverage (%). At this stage, four pre-identified units of water-sensitive cards were fixed in each stratum of the plant in four plants per plot, which were randomly chosen in the useful area. After 30 seconds of application, the cards were collected and packed in absorbent paper, separated by the upper (adaxial face), medium (adaxial and abaxial face), and inferior (adaxial face) strata so that they could be later digitized and evaluated by the program Gotas 2.2, developed by Embrapa.

All statistical analyses were carried out using Sisvar software (Ferreira, 2019). The data were tested for normality using the Shapiro-Wilk test and for homogeneity of variance using the Bartlett test. As the droplet density and percentage of coverage data did not present a normal distribution or variance homogeneity, the square root transformation (x + 0.5) was used. Analysis of variance was followed by regression analysis for application rates and the Tukey test at $p \leq 0.05$ to compare the averages for the nozzle tips.

Results and Discussion

According to the results of the analysis of variance, for the upper and medium strata of common bean plants, there was a significant effect for nozzle tips and application rates on the volume of the spray captured but without interaction between these factors, which was verified only for the lower stratum. With the obtained results, for the upper stratum of the plants (Table 1), regardless of the application rate used, the hollow cone tip with the use of electrostatic technology provided a greater increase in the captured spray volume compared to the hollow cone applied without the addition of droplet electrification technology, with an increasing in this characteristic of 13.63%. In contrast to the present work, Assunção et al. (2019) did not find an increase in spray deposition due to droplet electrification, with the benefit of increasing application rates being more evident for these authors.

This result verified in the upper stratum was also observed in the medium stratum of common bean plants since the use of electrification of the drops promoted an increase of 38.96% in the volume of the sprayed solution compared to the use of the hollow cone tip without electrostatic technology (Table 1). Differences regarding the retention of the sprayed solution between the nozzle tips in the lower stratum of common bean plants were only verified at an application rate of 150 L ha^{-1}, where it was found that hollow cone-type nozzles with electrification

Table 1. Volume of spray captured (μL cm^{-2}) in leaves of the upper, medium, and lower strata of bean plants with variations in nozzle tips and application rates in the spraying process

Nozzle tips	Application rate (L ha^{-1})				
	50	100	150	200	Mean
			Upper strata		
Simple fan	0.2939	0.5973	0.8247	1.1311	0.7117 ab
Hollow cone	0.2777	0.6447	0.7123	1.1467	0.6953 b
Hollow cone with electrification	0.3471	0.7221	1.0448	1.0464	0.7901 a
Mean	0.3062	0.6547	0.8606	1.1081	
CV (%)			20.40		
			Medium strata		
Simple fan	0.1957	0.3792	0.3821	0.9932	0.4875 ab
Hollow cone	0.2071	0.3943	0.3624	0.6381	0.4004 b
Hollow cone with electrification	0.1736	0.5727	0.4947	0.9847	0.5564 a
Mean	0.1921	0.4487	0.4131	0.8721	
CV (%)			34.60		
			Lower strata		
Simple fan	0.1781 a	0.2344 a	0.2553 ab	0.4095 a	0.2693
Hollow cone	0.1862 a	0.2228 a	0.2012 b	0.3528 a	0.2475
Hollow cone with electrification	0.1045 a	0.3557 a	0.4114 a	0.3341 a	0.3014
Mean	0.1562	0.2709	0.2893	0.3654	
CV (%)			24.50		

Means followed by the same letter in the column do not differ by Tukey's test at p ≤ 0.05

provided a 104.47% increase in the volume of spray captured (compared to the hollow cone), demonstrating a positive result higher than that seen in the strata above (medium and superior).

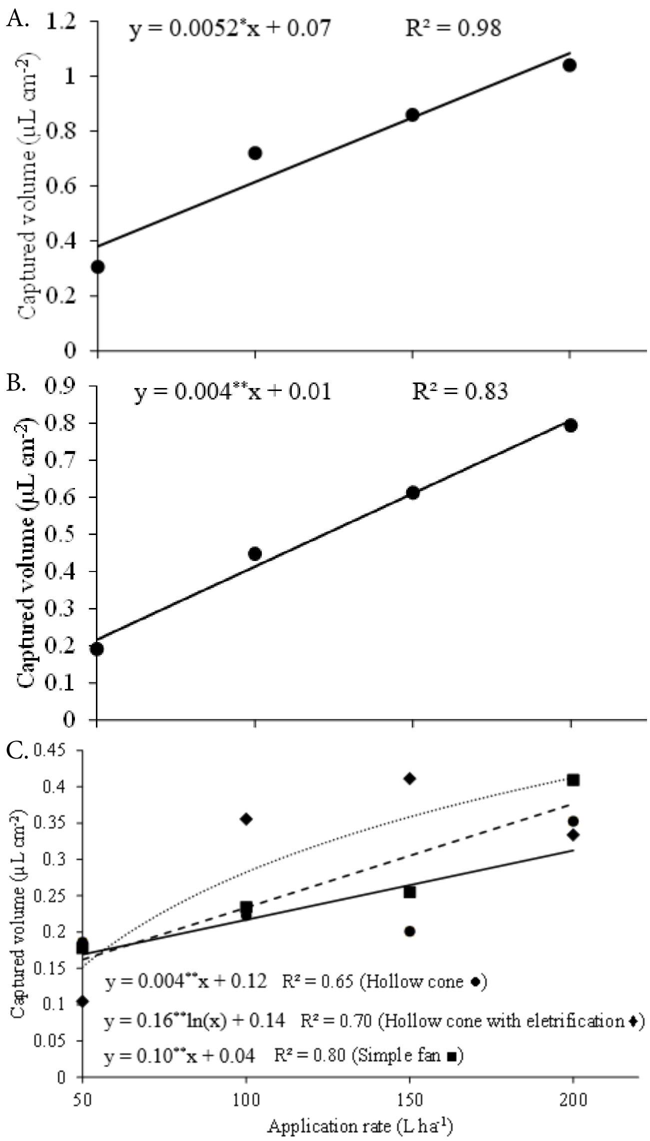
In the three strata of the evaluated common bean plants, the simple fan nozzle tip showed intermediate behavior regarding the volume of spray captured, not differing much from the hollow cone with electrification as from the hollow cone without additional technology.

The increase in the volume of spray captured in the upper stratum when the electrostatic system was activated can be explained by the fact that there was an attraction between the drops energized with a negative charge by the electrostatic equipment and the foliage of the common bean plants. Working with electrostatic spraying on coffee crops, Sasaki et al. (2013) reported a 37% increase in the deposition of the spray solution on the leaves of the crop when the electrostatic system was turned off.

This behavior also occurred in the middle stratum of plants since due to higher working pressure, hollow cone tips generate fine droplets and are therefore more subject to losses by drift and evaporation (Costa et al., 2018). Therefore, the electrification of the drops may have reduced such losses given the increase in the volume captured with the use of this technology.

Regarding the increasing application rates in the upper and medium strata of common bean plants, an ascending linear behavior was observed in the volume of spray captured, regardless of the nozzle tip used (Figures 2A and 2B). For the lower common bean stratum, the spray volume showed a linear increase with an increase in the application rate when the simple fan and hollow cone spray nozzles were used without the addition of electrostatic technology (Figure 2C).

However, when using the hollow cone spray tip with electrification, the volume of spray captured increased only with an increase in the application rate from 50 to 100 L ha^{-1} (Figure 2C). No interaction was observed between the factors nozzle tips and application rates for the droplet density,



* and ** - significant at p ≤ 0.05 and p ≤ 0.01 by F test, respectively

Figure 2. Spray volume captured in the leaves of upper (A), medium (B), and lower (C) strata of common bean plants as a function of application rate

VMD, or coverage carried out in the upper stratum on the adaxial face of typical bean leaves. In this stratum, there was a significant effect only for the application rates of the VMD and the coverage parameters. For droplet density, in addition to application rates, there was also a considerable effect for variations in nozzle tips.

In the lower strata (Figure 2C), when using the hollow cone spray tip with electrification, the captured spray volume remained very close above an application rate of 100 L ha^{-1}, even with the use of the 200 L ha^{-1} application rate, which demonstrates the capacity of this droplet electrification technology in promoting the reduction of spray volume without altering the quality of the coverage of the lower stratum of the common bean canopy.

Regarding droplet density on the adaxial face of the leaves present in the upper stratum of common bean, even though the hollow cone, with or without droplet electrification, showed an increase in this characteristic when compared to the simple fan nozzle tip, this difference was not enough to provide better coverage in the upper stratum. This result differs from that found by Fergusson et al. (2016), who found better foliar coverage of soybean with the use of hollow cone tips compared to double fan tips. These differences may be related to the distinct morphological characteristics that exist between soybean and common bean plants.

The hollow cone nozzle tip, with or without electrification, promoted a higher density of droplets on the adaxial face of the leaves present in the upper stratum of common bean plants compared to the simple fan nozzle (Table 2). The VMD of the sprayed drops and the percentage of foliar cover of the adaxial face of the leaves did not differ between nozzle tips in the evaluation of the upper stratum of common bean plants.

These results demonstrate that, in the upper stratum of the plants, the region most exposed to spraying, the differences between the nozzle tips are not as evident in comparison to the more protected parts of the canopy, such as the leaves located in the lower regions of the plant. The increase in VMD likely occurred due to the overlap of the drops since the higher the application rate used, the greater the volume of sprayed solution per area, which increases the chances of overlapping drops on the water-sensitive card. This behavior corroborates the results obtained by Debortoli et al. (2012), in which the highest application rate provided the largest VMD of the drops. Furthermore, the authors concluded that this could be related to the more significant overlap and coalescence of droplets on the water-sensitive card.

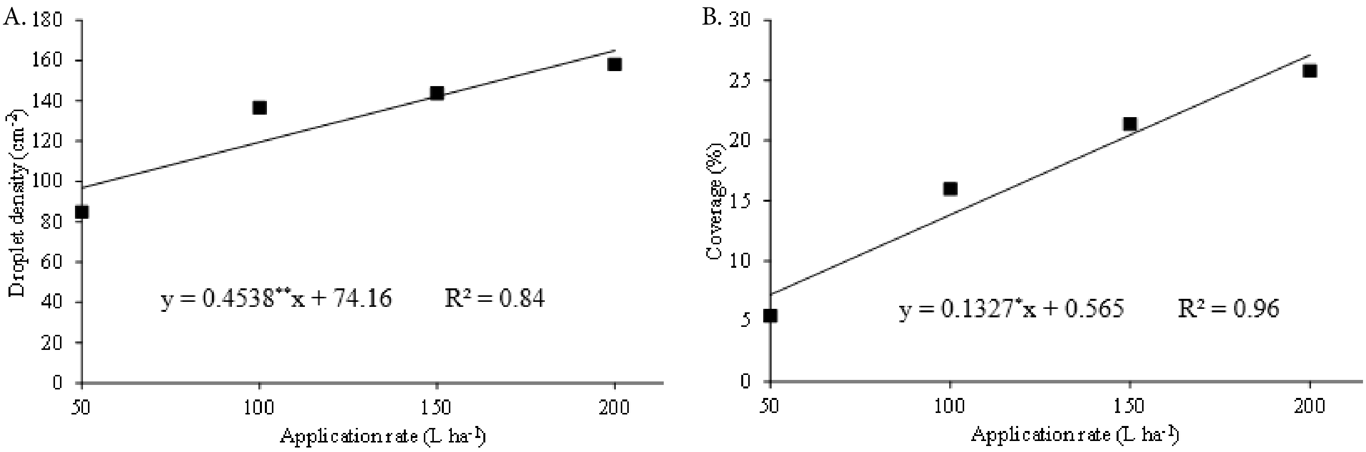
The increase in application rates influenced all spray characteristics evaluated in the upper stratum, where an increasing linear behavior was observed for droplet density (Figure 3A) and coverage (Figure 3B). For VDM, there was not a sufficient adjustment of data for the linear model ($y = 0.26^{*}x + 242.66$, $R^2 = 0.33$). Therefore, regardless of the nozzle tip used, the increase in the volume applied can improve the quality of the application since the increase from 50 to 200 L ha^{-1} increased the droplet density and foliar coverage on the adaxial face of the leaves by 86 and 371%, respectively. The VMD showed an increase of 21% using an application rate of 200 L ha^{-1} compared to the lowest spray volume evaluated (50 L ha^{-1}), and this value was much lower than what was verified for droplet density and leaf coverage.

Concerning the medium stratum of common bean, for the number of droplets, the increase promoted by the hollow cone tip with the use of electrostatic technology may be due to the higher working pressure of the simple fan tip associated with the more significant attraction of electrified drops to the typical bean foliage (Figure 4A). Thus, the interaction between the energized drops and the foliage of the plants increased the droplet density, as there may have been finer drops since there was a significant difference between the nozzle tips and the diameter of the droplets in this location of the plant. Assunção et al. (2020) also observed an increase in coverage in the lower canopy of maize under electrified droplet applications, resulting in lower spray losses to non-target locations such as the ground. This behavior reinforces the fact that electrostatic technology can enhance this characteristic.

Table 2. Droplet density, volumetric median diameter, and percentage of coverage observed on the adaxial surface of leaves from the upper stratum of the common bean after application with variations in spray rates and nozzle tips

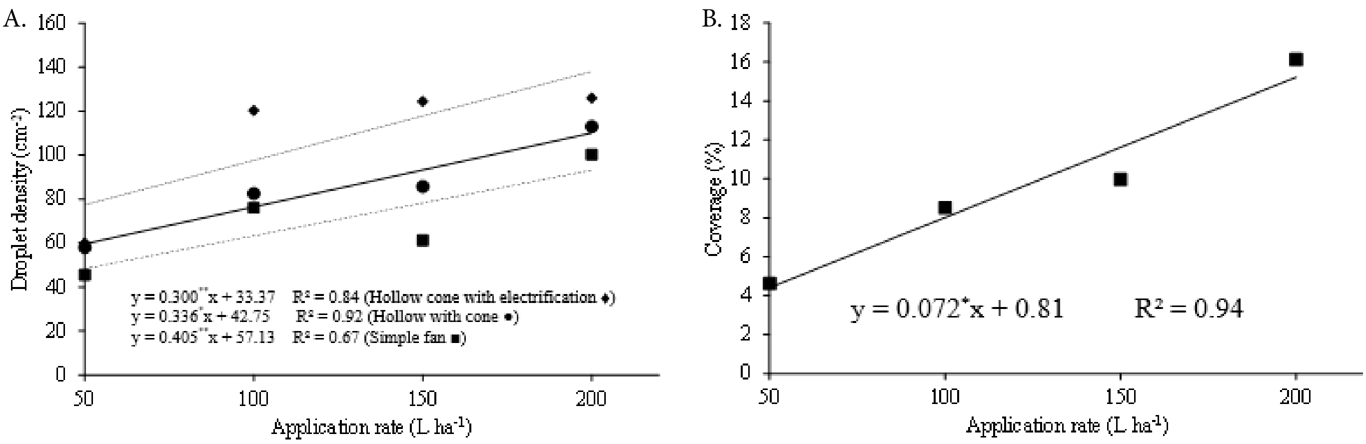
Nozzle tips	Application rate (L ha^{-1})				
	50	100	150	200	Mean
			Droplet density (cm^{-2})		
Simple fan	71.00	104.75	120.00	139.25	108.75 b
Hollow cone	93.50	137.25	138.50	168.00	134.31 a
Hollow cone with electrification	90.25	168.00	173.00	167.25	149.62 a
Mean	84.91	136.66	143.83	158.16	
CV (%)			14.30		
			Volumetric median diameter (µm)		
Simple fan	294.84	301.48	273.02	304.92	293.56a
Hollow cone	239.06	279.24	221.23	334.64	268.54a
Hollow cone with electrification	238.22	270.52	246.80	299.97	263.87a
Mean	257.37	283.74	247.01	313.17	
CV (%)			14.00		
			Coverage (%)		
Simple fan	5.18	15.90	23.59	25.98	17.66 a
Hollow cone	5.21	14.90	18.44	27.71	16.56 a
Hollow cone with electrification	6.02	17.15	22.07	23.73	17.24 a
Mean	5.47	15.99	21.37	25.80	
CV (%)			16.20		

Means followed by the same letter in the column do not differ by Tukey's test at probability ≤ 0.05



*and ** - significant at $p \le 0.05$ and $p \le 0.01$ by F test, respectively

Figure 3. Droplet density (A) and coverage (B) in the upper stratum of common bean plants as a function of application rate



*and ** - significant at $p \le 0.05$ and $p \le 0.01$ by F test, respectively

Figure 4. Droplet density (A) and coverage (B) in the medium stratum of common bean plants as a function of application rate

Droplet density is an important variable for evaluating application technology in crop management, as it presents the relationship between the translocation characteristics of the products. In general, products that present full translocation (systemic) need a density between 30 and 50 drops cm^{-2} to have no restrictions on their effectiveness, and products with restricted translocation (contact) have 70 or more drops cm^{-2}. Therefore, according to the results presented in Table 2, given the constant search to reduce the volume of solution used in terrestrial spraying, applications carried out at 50 L ha^{-1} with products of limited translocation (contact) may not present satisfactory control, even with the aid of electrostatic equipment.

In the medium stratum of common bean, there was an interaction between the factors of nozzle tips and application rates for the characteristic droplet density. Leaf coverage on the adaxial face was significantly altered only by variations in the application rate. At the same time, the VMD was influenced by both the application rate and the nozzle tip. However, there was no interaction between these factors. For the characteristic droplet density, the nozzle tips provided different results in the medium stratum of common bean for the applications carried out with 100 and 150 L ha^{-1}, highlighting the result presented by the hollow cone tip with the use of electrostatic technology, which was superior compared to simple fan and hollow cone tips without electrification (Table 3).

The use of the simple fan nozzle tip resulted in a higher VMD of droplets sampled on the adaxial face of the leaves present in the medium stratum of the common bean canopy compared to hollow cone nozzles with or without electrification, regardless of the application rate (Table 3). The use of larger droplets can reduce the likelihood of drift, thereby decreasing the risk of toxicity to non-target organisms (Contiero et al., 2016). However, it can impair foliar coverage, although this did not occur in the medium stratum of common bean in the present study. No differences were found between the nozzle tips at all evaluated application rates.

Furthermore, even though the hollow cone tip with electrostatic technology provided an increase in droplet density, this was not enough to improve the coverage of the medium stratum of common bean plants (Table 3). Comparing double and conical fan nozzles, Román et al. (2009) observed a result similar to that of the present study when evaluating the percentage of coverage in the medium stratum in soybean. In this sense, the present results demonstrate that the increase in this characteristic for this location of the plants is also due to other factors, not only the choice of nozzle tip or even the addition of droplet-energizing technology.

The increase in the application rate associated with using the simple fan and hollow cone spray nozzles without electrification resulted in a linear increase in the droplet density recorded on the adaxial face of leaves in the medium

Table 3. Droplet density, volumetric median diameter, and percentage of coverage observed on the adaxial surface of leaves in the medium stratum of the common bean after application with variations in spray rates and nozzles tips

Nozzle tips	Application rate (L ha^{-1})				
	50	100	150	200	Mean
			Droplet density (cm^{-2})		
Simple fan	45.50 a	76.00 b	61.25 b	100.25 a	70.75
Hollow cone	58.00 a	82.50 b	85.75 b	113.00 a	85.31
Hollow cone with electrification	60.00 a	120.25 a	124.50 a	126.00 a	107.18
Mean	54.50	92.91	90.50	103.08	
CV (%)			17.50		
			Volumetric median diameter (μm)		
Simple fan	257.96	289.70	245.96	296.60	272.55 a
Hollow cone	200.76	232.80	209.11	215.67	214.58 b
Hollow cone with electrification	219.19	219.80	209.39	273.11	230.37 b
Mean	225.97	243.43	221.49	261.79	
CV (%)			14.20		
			Coverage (%)		
Simple fan	4.69	8.85	9.60	17.80	10.23a
Hollow cone	4.34	7.74	9.32	13.32	8.68a
Hollow cone with electrification	4.84	8.96	11.00	17.31	10.52a
Mean	4.62	8.52	9.97	16.14	
CV (%)			27.00		

Means followed by the same letter in the column do not differ by Tukey's test at $p \leq 0.05$

stratum of common bean plants (Figure 4A). However, when the application was performed with the hollow cone tip with electrostatic technology, an increase in droplet density was observed only at application rates below 100 L ha^{-1}. From this application rate, the droplet density no longer increased with the increase in the application volume (Figure 3A), demonstrating once again that with the use of electrification, it is possible to reduce the spary volume without losing quality in certain situations.

The increase in the application rate did not elevate the droplet VMD for any nozzle type; for this variable, there was not a sufficient adjustment of data in the linear model ($y = 0.16^{*}x + 218.79$, $R^2 = 0.31$). However, the percentage of foliar coverage of the medium stratum of common bean plants increased linearly with the increment in the application rate, regardless of the nozzle tip used (Figure 4B). Regarding the evaluation of the common bean lower stratum, there was no interaction between the nozzle tip and application rate factors for any application quality characteristics evaluated on the adaxial face of the leaves. The variation in nozzle tips significantly influenced droplet density and VMD, regardless of the application rate used. However, the nozzle tips did not differ in the percentage of foliar coverage.

The use of the hollow cone tip associated with electrostatic technology promoted the highest density of droplets sprayed on the adaxial surface of the common bean leaves arranged in the lower stratum (Table 4). The simple fan nozzle showed the worst performance in this regard among the evaluated nozzle tips, providing 37.25 drops cm^{-2}, on average, on the adaxial surface of leaves positioned in the lower stratum of common bean. The VMD of the drops produced by the simple fan tips was significantly higher when compared to the other tips (Table 4).

As verified for the other strata of common bean (medium and upper), the percentage of leaf cover of the adaxial face

Table 4. Droplet density, volumetric median diameter, and percentage of coverage observed on the adaxial surface of leaves from the lower stratum of common bean plants after application with variations in spray rates and nozzle tips

Nozzle tips	Application rate (L ha^{-1})				
	50	100	150	200	Mean
			Droplet density (cm^{-2})		
Simple fan	29.00	30.25	38.00	51.75	37.25 c
Hollow cone	35.50	45.25	54.00	76.75	52.87 b
Hollow cone with electrification	38.00	67.25	75.00	77.50	64.46 a
Mean	34.16	47.58	55.66	68.66	
CV (%)			23.10		
			Volumetric median diameter (μm)		
Simple fan	204.45	262.37	214.41	246.60	231.96 a
Hollow cone	182.87	197.59	200.79	214.86	199.03 b
Hollow cone with electrification	193.55	200.32	198.21	232.36	206.11 b
Mean	193.62	220.09	204.47	231.27	
CV (%)			11.60		
			Coverage (%)		
Simple fan	1.97	3.81	3.48	5.87	3.78a
Hollow cone	2.55	3.76	4.39	6.37	4.27a
Hollow cone with electrification	2.12	4.20	6.11	8.09	5.13a
Mean	2.21	3.92	4.66	6.78	
CV (%)			33.30		

Means followed by the same letter in the column do not differ by Tukey's test at $p \leq 0.05$

evaluated in the lower stratum of the plants was not influenced by the nozzle tip type (Table 4). Coverage of the lower strata of the canopy, especially in phases of greater phenological development of the crop, is a challenge during agricultural spraying due to the high interception of drops by the upper strata of the canopy. Reducing the size of the droplets can aid in their penetration into the canopy and greater coverage in the lower region (Farias et al., 2020; Santos-Júnior et al., 2022).

However, even for the empty cone tip, a condition that provided a smaller droplet size compared to the other tips, it was not possible to observe an increase in the lower coverage of the canopy. This result evidences the effect of droplet interception by the upper canopy in the tested conditions. The increase in droplet VMD and the percentage of foliar coverage of the medium stratum of common bean plants with the increment of the application demonstrates the importance of working with an adequate application rate to satisfactorily reach leaves positioned in the lower portions of the plants.

The highest droplet density on the adaxial surface of the leaves in the lower stratum of the plants after the use of the hollow cone tip associated with electrostatic technology is a result of great relevance, as there is a suspicion in the technical/scientific community that the drops under energization would be retained, in almost their entirety, in the upper stratum of the plants, due to the force of attraction present in the most exposed leaves of the canopy, which could cause a loss of pesticide efficiency and consequently a phytosanitary risk (Bish et al., 2021).

The VMD of the drops produced by the simple fan tips was higher when compared to the other tips, regardless of the application rate used. This could be associated with the fact that larger diameter drops have a lower chance of reaching the lower stratum of common bean in the reproductive stage. Changes in application rates significantly influenced droplet density (Figure 5A) and the percentage of coverage (Figure 5B). These two evaluated characteristics increased linearly with an increasing application rate, regardless of the nozzle tip or the associated technology. However, there was no difference for VMD due to an increase in the application rate; for this variable, there was not sufficient adjustment of data to the linear model ($y = 0.19^{*}x + 188.03$, $R^2 = 0.57$).

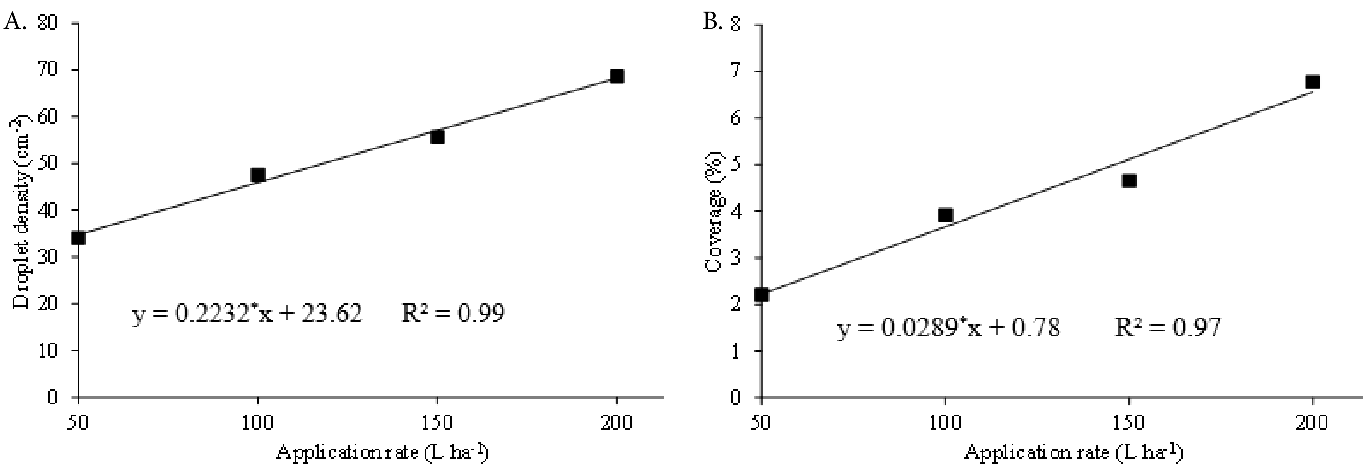
The increase in the application rate from 50 to 200 L ha^{-1} increased the leaf coverage of this location by 206%. Working with applications with different nozzle tips, Silva et al. (2014) reported that the highest droplet density in the lower stratum of soybean plants was observed in applications with nozzles that produced finer droplets. In this sense, to obtain a greater number of droplets in this location of the plant, it is necessary to use tips that generate fine droplets, which can be aided by the electrostatic resource, thus providing improvements in the use of the droplets that would likely be lost. Assunção et al. (2020) observed that the density of the lost droplets in soil showed a significant reduction with the use of electrostatic applications compared to conventional applications.

The highest VMD of the droplets produced by the simple fan tips can compensate for the lower density of droplets that reach the foliage of common bean plants, especially the trifoliates located in the lower region since the percentage of leaf cover of the adaxial face evaluated in this locality which the different nozzle tips did not influence it.

Concerning the increase in density and VMD of sprayed droplets with an increasing application rate, there was a more significant amount of sprayed solution per area at higher application rates, thus increasing the chances of droplets overlapping on the water-sensitive card. Debortoli et al. (2012) studied fungicide applications on soybean and found an increase in the spectrum of droplets deposited in the upper stratum, and there was a higher concentration and overlapping of droplets compared to the other strata.

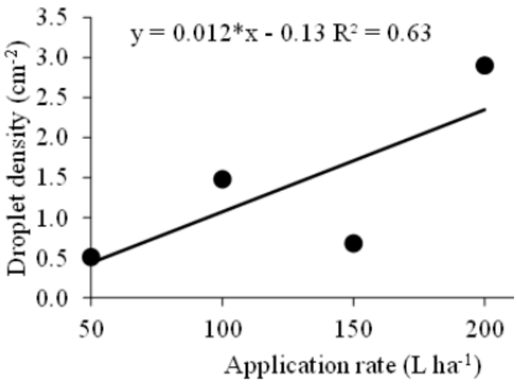
Regarding the abaxial face of the leaves of the medium stratum of common bean, no interaction was observed between the nozzle tip type and application rate for any of the characteristics evaluated (data not shown). Droplet density, VMD, and percentage of coverage were not influenced by nozzle tip type for this leaf face. The increasing application rates had a significant influence only on the droplet density since the increase from 50 to 200 L ha^{-1} increased the droplet density per cm^{-2} by 387%, regardless of the nozzle tip used (Figure 6).

Cunha et al. (2016) evaluated the deposition between the upper and lower strata of soybean plants, observing more uniformity with the highest volumes of spray applied, results that corroborate those found in the present study.



* - significant at $p \leq 0.05$ by F test

Figure 5. Droplet density (A) and coverage (B) in the lower stratum of common bean plants as a function of application rate



* - significant at $p \leq 0.05$ by F test

Figure 6. Droplet density on the abaxial face of the leaves of the medium stratum of common bean plants as a function of application rate

Regarding the abaxial face of the leaves of the medium stratum of common bean, the increasing application rates had an influence only on droplet density. Liu et al. (2020) evaluated applications with different types of nozzle tips without varying the application rate and found an inefficiency for all tips used to cover the abaxial surface of leaves of fruit tree species. The results obtained in this study agree with this information. Thus, the nozzle tip, even with the aid of electrostatic technology, should not be used as the sole factor when the target is present on the leaf of the plants.

However, at the highest application rate used, the average of this characteristic was only 2.83 drops per cm^{-2}, demonstrating that the increment in the application rate alone was not enough to obtain significant improvements in the coverage of the abaxial surface of the leaves. Studies have shown that air-assisted applications along the spray bar reported improvements in spray levels on the abaxial surface of the lower leaves (Baio et al., 2016; Godinho Júnior et al., 2018). This suggests that the distribution of the spray applied to the abaxial surface of the leaves requires optimization of the application technology, combining the result of a set of factors.

Conclusions

1. The electrostatic technology increased the volume of spray solution when using the hollow cone tip in the upper and medium strata of common bean plants, regardless of the application rate used.

2. The increase in the application rate increased the volume of spray captured in common bean's upper, medium, and lower strata when using the simple fan and hollow cone spray tips with or without electrification of the droplets.

3. The application rate was a more relevant factor than the nozzle tip concerning the leaf coverage of the typical common bean canopy.

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