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SIMULATED HERBICIDE APPLICATION BETWEEN ROWS OF BLACK PEPPER CROPS

PULVERIZAÇÃO SIMULADA DE HERBICIDA NAS ENTRELINHAS DA CULTURA DA PIMENTA-DO-REINO

APLICACIÓN SIMULADA DE HERBICIDAS ENTRE HILERAS DE CULTIVOS DE PIMIENTA NEGRA

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ABSTRACT

The efficiency of applications through spraying is connected to the capacity to minimize losses by endo-drift and exo-drift while ensuring adequate coverage and deposition on the target surface; the spray nozzles is the main factor connected to application quality. However, few researches focus on technology of application in black pepper crops. The objective of this work was to evaluate the coverage of droplets of simulated herbicide applications using different spray nozzles. The experiment was conducted in a commercial crop area of black pepper of the variety Bragantina, in a randomized block with a 2×2+1 factorial arrangement with four replications per treatment. The nozzles used were XR11002 VP, AI11002 VS, with and without protector (Chapéu de Napoleão) and an additional treatment using the manual backpack sprayer standard nozzle without protector. The results showed that, under these conditions, the nozzle AI11002 VS with protector resulted in adequate coverage and deposition of droplets between rows decreasing the risk of phytotoxicity to black pepper plants. The nozzle XR11002 VP presented higher coverage of droplets in the lower third of black pepper plants. The backpack sprayer standard nozzle resulted in the lowest coverage of droplets between rows.

RESUMO

A eficiência das aplicações por meio da pulverização está intimamente relacionada a capacidade de minimizar as perdas por endoderiva e exoderiva, garantindo ao mesmo tempo, cobertura e deposição adequadas na superfície-avo, sendo as pontas de pulverização o principal fator relacionado a qualidade da aplicação. Entretanto, há carência de pesquisas relacionadas à tecnologia de aplicação na cultura da pimenta-do-reino. O objetivo deste trabalho foi avaliar a cobertura de gotas na pulverização por simulação de herbicida utilizando diferentes pontas de pulverização. A área experimental utilizada foi em uma lavoura comercial de pimenta-do-reino da variedade Bragantina. O experimento foi conduzido em blocos casualizados em esquema fatorial 2 x 2 + 1 com quatro repetições por tratamento, sendo utilizado as pontas XR11002 VP, AI11002 VS com e sem chapéu-de-napoleão e um tratamento adicional utilizando a ponta padrão do pulverizador costal manual sem o chapéu-de-napoleão. Os resultados apresentaram que nessas condições, a ponta AI11002 VS com o chapéu-de-napoleão proporcionou cobertura e deposição de gotas adequadas nas entrelinhas diminuindo o risco de fitotoxidez nas plantas de pimenta-do-reino. A ponta XR11002 VP apresentou maior cobertura de gotas na camada inferior das plantas de pimenta-do-reino. A ponta padrão do pulverizador costal manual proporcionou menor cobertura nas entrelinhas.

RESUMEN

La eficiencia de las aplicaciones por aspersión está estrechamente relacionada con la capacidad de minimizar las pérdidas por endoderiva y exoderiva, asegurando al mismo tiempo una adecuada cobertura y deposición sobre la superficie objetivo, siendo las boquillas de aspersión el principal factor relacionado con la calidad de la aplicación. Sin embargo, falta investigación relacionada con la tecnología de aplicación en el cultivo de pimienta negra. El objetivo de este trabajo fue evaluar la cobertura de gotas en la simulación de aspersión de herbicidas utilizando diferentes boquillas aspersoras. El área experimental utilizada fue en un cultivo comercial de pimienta negra variedad Bragantina. El experimento se realizó en bloques al azar en un esquema factorial 2 x 2 + 1 con cuatro repeticiones por tratamiento, utilizando las boquillas XR11002 VP, AI11002 VS con y sin sombrero Napoleón y un tratamiento adicional utilizando la boquilla estándar del pulverizador manual de mochila sin el Sombrero de Napoleón. Los resultados mostraron que, en estas condiciones, la punta AI11002 VS con el sombrero de Napoleón proporcionó una cobertura adecuada y la deposición de gotas entre las líneas, lo que redujo el riesgo de fitotoxicidad en las plantas de pimienta negra. La punta XR11002 VP mostró una mayor cobertura de caída en la capa inferior de las plantas de pimienta negra. La boquilla estándar del rociador manual de mochila brindó menos cobertura entre hileras.

1. INTRODUCTION

Black pepper (*Piper Nigrum L.*) is a bindweed perennial plant native to India that belongs to the family Piperaceae (Costa & Medeiros, 2011). It is the world's most valued spice, due to its high economic and social importance to growers. Black pepper crops are concentrated in tropical climate regions, as India, Indonesia, Vietnã, Brazil, and China (Dalazen *et al.*, 2020).

Black pepper is an agricultural commodity in the world market; Brazil stands out as the second largest black pepper producing country in the world, after Vietnã. According to the Brazilian Institute of Geography and Statistics (IBGE, 2021), Brazil produced approximately 118,057 Mg of black pepper on an area of 37,994 hectares. Black pepper production in Brazil is concentrated in the states of Espirito Santo (61.0%), Para (30.0%), and Bahia (7.6%).

Black pepper production is challenging, since pepper crops are susceptible to attack of pests, diseases, and weeds. Weeds are the main cause of decreases in yield of agricultural crops, by resulting in competition for resources of the medium, including CO_2, water, light, mineral nutrients, and space (Agostinetto *et al.*, 2008; Pêssoa *et al.*, 2017). Weeds are alternative hosts for pests, diseases, nematodes, and parasites. Thus, adopting an efficient crop system to maintain the plant health is essential for simultaneously increasing yield and sustainability (Meng *et al.*, 2020).

Information on technology of application is important in modern agriculture to maximize weed control efficiency through a higher efficiency of application of agrochemicals. Contiero *et al.* (2018) reported that technology of application consists in a set of scientific information focused on a correct application of a product on the target surface, in an economic way, minimizing losses by drift and promoting sustainability.

Several factors, as regulation and calibration of devices, analysis of uniformity of solution, sizes of droplets (Sijs & Bonn, 2020), volume of application (Kharim *et al.*, 2019), and weather conditions (air temperature, relative air humidity, and wind speed) (Richardson et al., 2020) can interfere with the efficiency of spraying on a target surface.

The study of spectrum of droplets is the most common method to evaluate agrochemical application quality (Medauar *et al.*, 2018). According to Vitória & Campanharo (2016), the main parameters to determine the droplet population are the volumetric median diameter, relative amplitude, and percentage of droplets with diameters smaller than 100µm.

Regarding the emission of spray droplets, the spray nozzle is the most important component of a sprayer device (Bauer & Raetano, 2004). It determines the quality application by the flow, uniformity of distribution of the liquid, and droplet size, as the risk of drift is often connected to the spray droplet size (Hilz & Vermeer, 2013).

The selection of spray nozzles is determinant for the efficiency of herbicide applications regarding coverage and deposition of droplets on weeds and decrease of primary drift, which can cause phytotoxicity and affect the crop development and yield. However, little technical and scientific information are found for basing the technology of application for black pepper crops regarding the spray droplet coverage.

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The objective of this work was to evaluate the quality of coverage of droplets by simulating herbicide drift for assessing which spray nozzle, with or without protector (Chapéu de Napoleão), results in higher coverage of droplets for control of weeds between rows of black pepper crops.

2. MATERIAL AND METHODS

The experiment was conducted in a commercial crop area in the Corrego das Palmeiras Farm, in the municipality of Conceição da Barra, state of Espirito Santo, Brazil. The geographic coordinates of the experiment area are 18°20'1"S and 39°54'47"W. The region presents an Af climate, tropical wet, without a dry season, according to the Köppen classification (Alvares *et al*., 2013) and flat topography.

The experimental area was grown with black pepper of the variety Bragantina, planted with spacing of 3.0×1.80 m, totaling 1852 plants ha^{-1}. The crop age was 1 year and 2 months and the mean plant height was 1.55 m at the time of the experiment. *Commelina benghalensis L.*, known in Brazil as Trapoeraba, was the predominant weed species between rows in the area where the experimental units were installed.

The applications were carried out using a manual backpack sprayer (Jacto, model XP12) with capacity for 12 L, previously set and calibrated for an application rate of 200 L ha^{-1}. A solution with water mixed with a bright blue tracer was prepared at the rate of 400 g ha^{-1} for all treatments. All applications were carried out with operational speed of approximately 1 m s^{-1} with the spray boom at 0.5 m from the weeds to uniformize the application quality. A pressure and flow valve (Jacto) were used during the applications to keep a constant pressure and flow at 300 kPa.

The experiment was conducted in a randomized block design, with treatments arranged in a 2×2+1 factorial arrangement consisted of two spray nozzles (simple flat jet and flat jet with air induction), with and without protector (Chapéu de Napoleão), and an additional treatment with backpack sprayer standard nozzle without protector. Each treatment was repeated four times, totaling 20 plots. The area of each block was 30 m² (10×3 m) between plant rows (Table 1).

Table 1. Experimental treatments; droplet size classification, according to the manufacturer (TeeJet); and treatment with a backpack sprayer standard nozzle.

Treatment	Spray nozzle	Description	Protector	Droplet size classification
1	XR11002 VP	Simple flat jet	Without	Fine and medium
2	XR11002 VP	simple flat jet	With	Fine and medium
3	AI11002 VS	Flat jet with air induction	Without	Coarse to extremely coarse
4	AI11002 VS	Flat jet with air induction	With	Coarse to extremely coarse
5	Standard nozzle	Hollow cone jet	Without	Fine

The applications were carried out in the morning period. Data of air humidity, temperature, and wind speed during the applications were collected (Table 2) to monitor climate conditions; an anemometer (Thal-300 Digital) and a thermo-hydroanemometer (AKROM, model KR825) were used.

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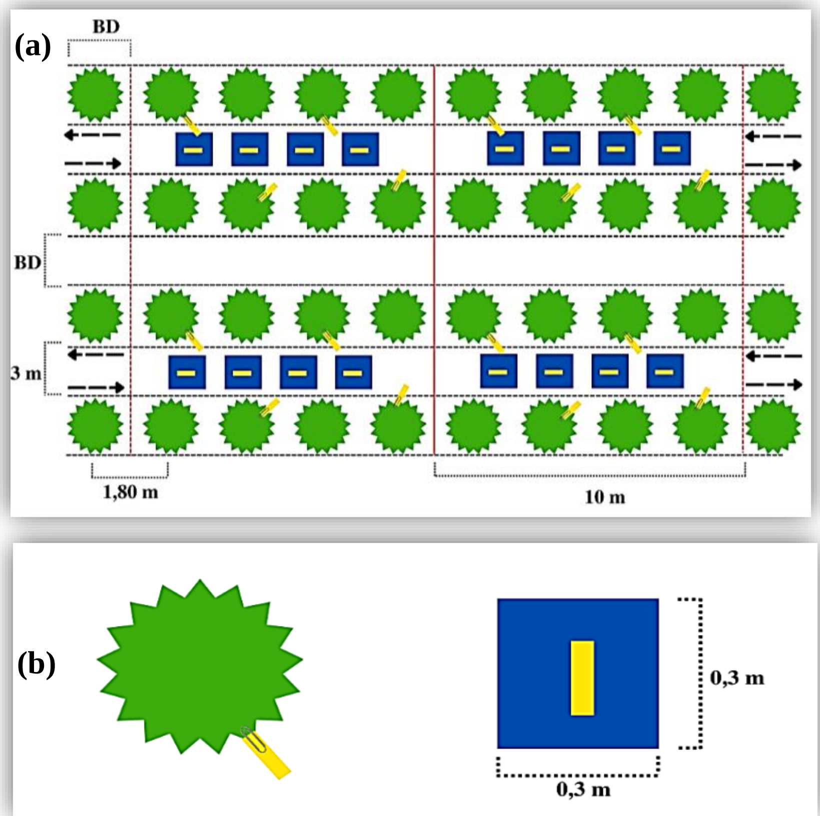
Table 2. Climate conditions at the time of the experiment.

Relative air humidity (%)		Air temperature (°C)		Wind speed (m s^{-1})	
Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
71.0	82.0	25.2	28.0	2.2	3.0
66.0	75.0	25.1	29.0	2.7	4.0
66.1	76.0	26.0	28.4	2.2	4.5
82.0	86.0	25.7	27.1	2.3	3.5

Water sensitive paper tags, with dimensions of 76×26 mm, were used to characterize the spectrum of droplets applied. Eight tags were distributed per replication, four tags between rows, placed in PVC plates and four tags in the lower third of black pepper plants, these latter were used to analyze the drift of the sprayed solution, totaling 32 tags per treatment. The quantification and characterization of impacts on the water sensitive paper tags were carried out immediately after the application of each treatment. Figure 1 shows the experimental arrangement used in the experiment.

Figure 1. (a) Experimental arrangement, considering the border (BD); (b) upper view of black pepper plant with water sensitive paper tag in lower third (left) and PVC plate with the tag placed in the center (right).



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The methodology described by Vitória *et al*. (2022) was used to obtaining the data and study the spectrum of droplets. Thus, after spraying, the water sensitive paper tags were scanned using a wireless DropletScope® system (SprayX Company, São Carlos, Brazil), which is composed by programs and a wireless digital microscope with a digital sensor for images of more than

2500 dpi. This system estimates partially overlapping droplets from approximately 35 μm onwards.

The following parameters were evaluated: volumetric median diameter (μm); density of droplets (droplets cm^{-2}); coverage of droplets (%); deposition of droplets (μL cm^{-2}); D_{v01} (μm): diameter of droplets in which 10% of the liquid volume applied consists of droplets with diameters lower than this value; D_{v09}: diameter of droplets in which 90% of the liquid volume applied consists of droplets with diameters lower than this value; and relative amplitude: coefficient that determines the droplet population homogeneity.

The Shapiro Wilk test was applied to evaluate the homogeneity and normality of residues. The results obtained for the parameters were subjected to analysis of variance. The means of the factors or the interactions between treatments were compared by the Tukey's test, for the results between rows and in the lower third, to analyze the effect of the factors on the respective locations of collection. All tests were carried out using the software Rbio (Bhering, 2017), considering a significance level of 5%.

3. RESULTS

The use of protector (Chapéu de Napoleão) in the spray nozzles showed no significant effect on the application efficiency variables (Table 3).

Table 3. Effect of different nozzles, with and without protector (Chapéu de Napoleão), on the coverage (%), density (droplets cm^{-2}) and deposition (μL cm^{-2}) of spray droplets between rows of black pepper crops.

Variables	Ponta	Protector	
		Without	With
Coverage of droplets (%)	XR11002 VP	24.10 aA	17.36 aA
	AI11002 VS	11.38 bA	11.24 aA
	Standard nozzle	10.29	
CV= 34.93 %	W= 0.548^{ns}		
Density of droplets (droplets cm^{-2})	XR11002 VP	256.17 aA	225.26 aA
	AI11002 VS	75.81 bA	92.18 bA
	Standard nozzle	312.9	
CV= 43.81%	W=0.254^{ns}		
Deposition of droplets (μL cm^{-2})	XR11002 VP	0.980 aA	0.842 aA
	AI11002 VS	0.710 aA	0.852 aA
	Standard nozzle	0.300	
CV= 39.22%	W=0.676^{ns}		

Means followed by different lowercase letters in the columns, or uppercase letters in the rows, are significantly different from each other by the Tukey's test (p> 0.05); CV = Coefficient of variation of ANOVA; W = Shapiro-Wilk test.

Source: authors

The spray nozzles presented a significant difference in coverage of droplets. The nozzle XR11002 VP without protector resulted in higher coverage on the weeds, representing an increase of 52.78% in coverage when compared to the nozzle AI11002 VS without protector. Despite not statistically different, the spray nozzles (XR11002 VP and AI11002 VS) resulted in 1.61% and 1.23% higher coverage of droplets, respectively, without protector, when compared to that with protector. The backpack sprayer standard nozzle presented the lowest coverage of droplets on weeds.

The spray nozzles presented a significant difference in density of droplets. The nozzle XR11002 VP presented, in general, higher density of droplets on the weeds than the nozzle AI11002 VS.

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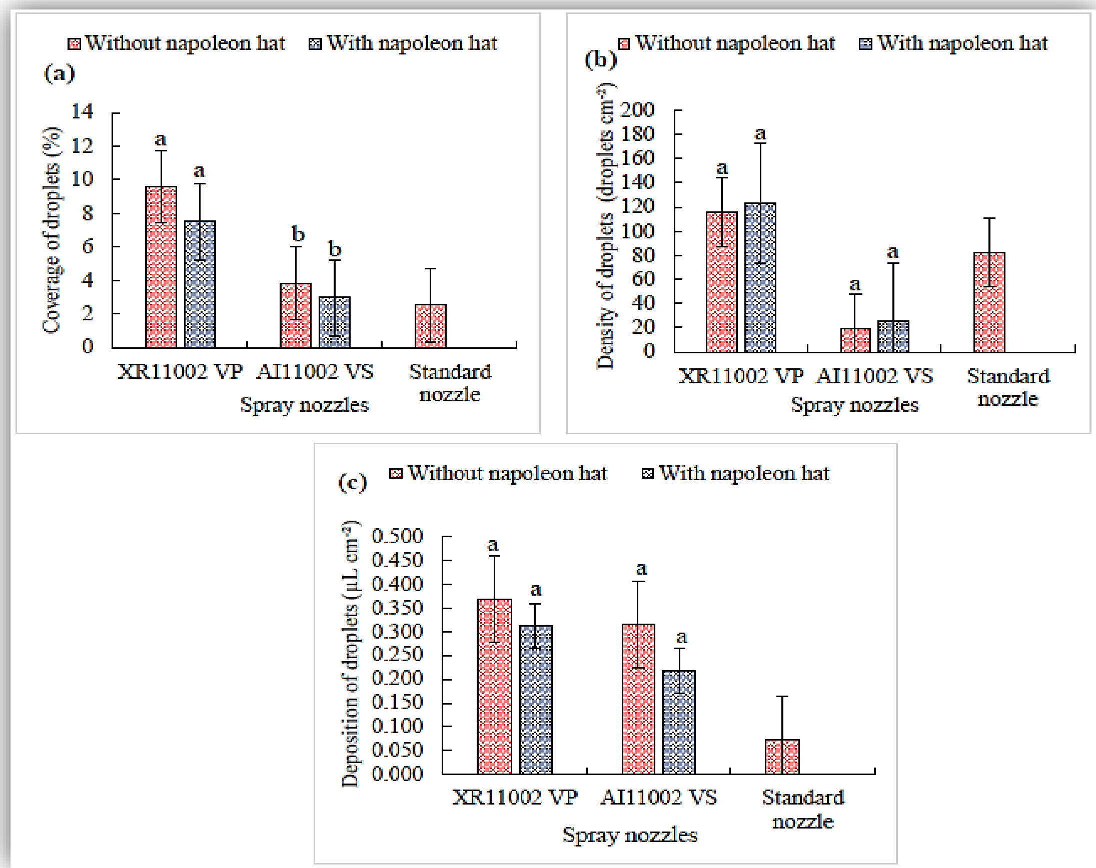
The spray nozzles presented statistical equal results with and without protector. The nozzle XR11002 VP presented increases of 180.36 and 133.08 droplets cm^{-2} when compared to the nozzle AI11002 VS without and with protector, respectively. However, the backpack sprayer standard nozzle presented higher density of droplets on the weeds, contrasting with the nozzles XR11002 VP and AI11002 VS.

The results found for deposition of droplets confirmed those of density of droplets; the nozzle XR11002 VP without protector presented higher deposition of droplets on the weeds. However, the spray nozzles presented statistical equal results, i.e., both XR11002 VP and AI11002 VS nozzle resulted in statistically equal quantities of droplets on the weeds, denoting no significant effect of spray nozzles or use of protector on deposition of droplets. The backpack sprayer standard nozzle showed an inversion in deposition of droplets in relation to coverage, i.e., despite providing higher coverage of droplets, the number of µL cm^{-2} was lower.

The normality of data was confirmed by the Shapiro Wilk test, since it was between the probabilities of 0.10 and 0.50 and, thus, the hypothesis of normality of errors is not rejected at 5% significance level. In the lower third of black pepper plants, the use of protector presented no effect within spray nozzles for the application efficiency variables (Figure 2).

Figure 2. Effect of different nozzles, with and without protector (Chapéu de Napoleão), on (a) coverage (%), (b) density (droplets cm^{-2}), and (c) deposition (µL cm^{-2}) of spray droplets in the lower third of black pepper plants. Bars with different letters comparing spray nozzles are significantly different from each other by the Tukey's test (p> 0.05).



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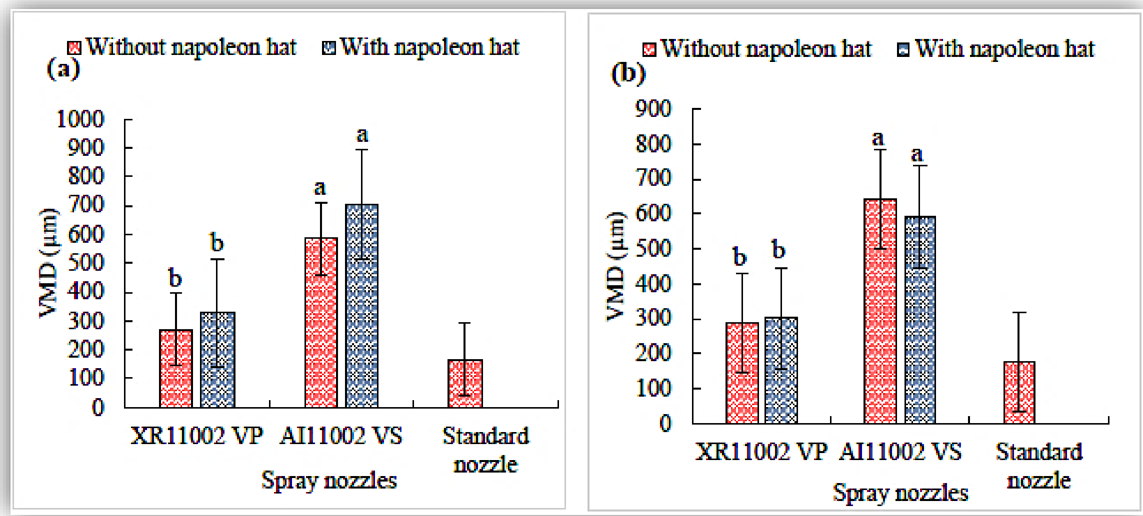
Regarding droplet coverage, the nozzle XR11002 VP without protector presented higher percentage of area of leaves in the lower third of black pepper plants covered by droplets (9.58%) when compared to the nozzle AI11002 VS and the backpack sprayer standard nozzle. It represented increases of 15.73% and 20.48% when compared to the nozzle AI11002 VS without and with protector, respectively. This result is confirmed by the significant difference between the nozzles XR11002 VP and AI11002 VS, which presented equal results, with or without protector. The backpack sprayer standard nozzle presented lower (2.53%) coverage of droplets on the lower third of black pepper plants.

The density and deposition of droplets in the treatments presented statistically equal results. However, the density of droplets for the nozzle XR11002 VP with protector resulted in higher quantity of droplets (123.23 droplets cm^{-2}), whereas the nozzle AI11002 VS presented lower quantity of droplets, 19.68 and 25.09 droplets cm^{-2} without and with protector, respectively. The backpack sprayer standard nozzle presented higher density of droplets (82.41 droplets cm^{-2}), compared to the nozzle AI11002 VS.

The deposition of droplets by the spray nozzles XR11002 VP and AI11002 VS without protector were higher, representing increases of 0.055 and 0.090 µL cm^{-2}, when compared to that using protector. The backpack sprayer standard nozzle presented lower deposition of droplets (0.072 µL cm^{-2}) when compared to the other spray nozzles.

The spray nozzles presented a significant difference in volumetric median diameter (VMD); however, they presented no difference regarding the use of protector (Figure 3).

Figure 3. Effect of different nozzles, with and without protector (Chapéu de Napoleão), on volumetric median diameter (VMD) (a) between rows and (b) in the lower third of black pepper plants. Bars with different letters comparing spray nozzles are significantly different from each other by the Tukey's test (p> 0.05).



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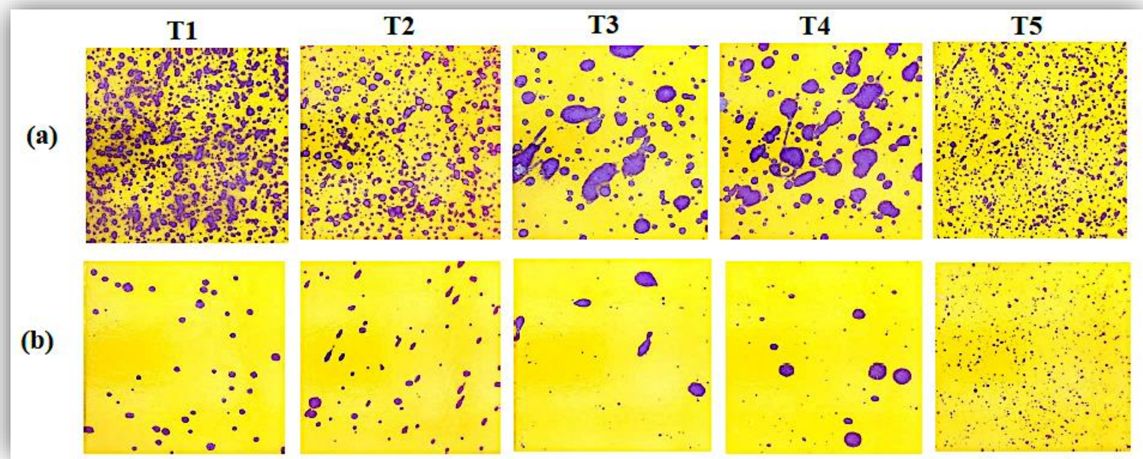
The nozzles with protector resulted in higher VMD between rows, where weeds usually grow. The nozzle AI11002 VS resulted in VMD of 585.66µm and 706.10µm, without and with protector, respectively. These values were higher than those found for the nozzle XR11002 VP, which presented mean VMD of 269.63µm and 326.65µm, without and with protector, respectively.

The VMD in the lower third of black pepper plants followed the same trend, confirming the significant difference in VMD between rows. The nozzle AI11002 VS resulted, in general, in higher VMD; the highest value was found for nozzles without protector (641.15µm), however, it was statistically equal to that found for nozzles with protector (591.17µm). The nozzle XR11002 VP presented VMD of 288.37µm and 302.60µm on leaves in the lower third of black pepper plants.

The backpack sprayer standard nozzle presented lower VMD between rows and in the lower third than the nozzles XR11002 VP and AI11002 VS. This nozzle resulted in VMD of 166.96µm between rows and 176.33µm in the lower third of black pepper plants.

Figure 4 shows the distribution and deposition of droplets on the water sensitive paper tags. The values of variables connected to efficiency of application tend to be lower as the VMD is increased (Figure 4 T3 ab and T4 ab). The nozzle XR11002 VP present higher coverage of droplets between rows (24.1 %) (Figure 4 T1a), where weeds usually grow, and resulted in higher coverage of droplets in the lower third of black pepper plants, with 9.58% and 7.52% with and without protector, respectively (Figure 4 T1b). These coverages of droplets are approximately 2.51- and 2.54-fold higher than those found for the nozzle AI11002 VS without (3.82%) and with (2.96%) protector.

Figure 4. Effect of spray nozzles, with and without protector (Chapéu de Napoleão), and a backpack sprayer standard nozzle on coverage and density of droplets (a) between rows and (b) in the lower third of black pepper plants.



Source: authors

Contrastingly, the results showed that the lower the VMD, the higher the number of droplets cm^{-2} (Figure 4 T5 ab). This characteristic was observed in the backpack sprayer standard nozzle. However, the backpack sprayer standard nozzle resulted in higher density of droplets (82.41 droplets cm^{-2}) in the lower third of black pepper plants, which was approximately 4.18- and 3.28-fold higher than those found for the nozzle AI11002 VS without (19.68 droplets cm^{-2}) and with (25.09 droplets cm^{-2}) protector.

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The volumetric distribution per size class and relative amplitude presented significant differences between spray nozzles (Table 4); however, the spray nozzles presented no differences for the use of protector, with results statistical equal for all variables between rows and in the lower third of black pepper plants.

Despite not statistically different, the nozzles with protector resulted, in general, in higher $D_{v0.1}$ and $D_{v0.9}$ between rows. The nozzle AI11002 VS resulted in higher values for these variables than the nozzle XR11002 VP. The nozzle AI11002 VS presented $D_{v0.1}$ between rows of 301.24 µm and 333.83µm without and with protector, respectively, denoting that 10% of the liquid applied had droplets below these values. However, the nozzle XR11002 VP presented 10% droplets of the sprayed liquid with diameters smaller than 168.42µm and 181.64µm, denoting a potential drift to the lower third of black pepper plants.

The results found for $D_{v0.9}$ (which denotes that 90% of the liquid volume applied consists of droplets with diameters lower than this value) between rows confirmed those found for $D_{v0.1}$. The nozzle AI11002 VS presented larger diameter droplets when compared to the nozzle XR11002 VP, denoting a probable lower risk of spray drift.

The volumetric distribution $D_{v0.1}$ and $D_{v0.9}$ were significantly different between spray nozzles in the lower third of black pepper plants. The $D_{v0.1}$ found showed a trend of larger diameters for the nozzle AI11002 VS; however, there was an inversion in values between rows regarding the use of protector. The nozzles XR11002 VP and AI11002 VS without protector presented higher values for this variable. The highest $D_{v0.9}$ in the nozzles XR11002 VP and AI11002 VS was found with and without the use of protector, respectively.

Considering the $D_{v0.1}$ and $D_{v0.9}$ found between rows for the backpack sprayer standard nozzle, the diameters of the droplets were smaller than those found for the nozzles XR11002 VP and AI11002 VS without and with protector, respectively. However, in the lower third of plants, the $D_{v0.1}$ was significantly higher and the $D_{v0.9}$ was lower.

The nozzle AI11002 VS presented lower relative amplitude between rows, however, with no significant differences when compared to the nozzle XR11002 VP. The relative amplitude in the lower third of black pepper plants followed the same trend; however, with a significant difference, presenting the lowest values for the nozzle AI11002 VS.

The coefficients of variation of the analysis of variance of $D_{v0.1}$, $D_{v0.9}$ (µm) and the relative amplitude varied from 9.88% to 23.93% between rows and from 19.24% to 25.67% in the lower third of black pepper plants. These values denote a possible effect of the operational conditions of the sprayer, directly connected to environmental factors, but did not make the statistical analyses unviable.

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Table 4. Effect of nozzles on volumetric distribution per size class ($D_{v0.1}$ and $D_{v0.9}$) and relative amplitude (RA) of spray droplets between rows of black pepper crops.

Variables	Ponta	Between rows		Lower third	
		Protector			
		Without	With	Without	With
$D_{v0.1}$ (µm)	XR11002 VP	168.42 bA	181.64 bA	194.44 bA	191.12 bA
	AI11002 VS	301.24 aA	333.83 aA	411.06 aA	345.97 aA
	Standard nozzle	99.58		126.15	
	CV= 9.88%	W=0.867^{ns}		CV=25.67%	W=0.320^{ns}
$D_{v0.9}$ (µm)	XR11002 VP	435.63 bA	619.47 bA	431.96 bA	467.01 bA
	AI11002 VS	829.47 aA	959.46 aA	743.49 aA	685.65 aA
	Standard nozzle	283.41		250.99	
	CV= 21.88%	W=0.811^{ns}		CV=19.24%	W=0.170^{ns}
RA	XR11002 VP	0.98 aA	1.18 aA	0.83 aA	1.08 aA
	AI11002 VS	0.93 aA	0.89 aA	0.50 bA	0.56 bA
	Standard nozzle	1.05		0.70	
	CV= 23.93%	W=0.934^{ns}		CV=22.52%	W=0.188^{ns}

Means followed by different lowercase letters in the columns, or uppercase letters in the rows, are significantly different from each other by the Tukey's test (p> 0.05); CV = Coefficient of variation of ANOVA; W = Shapiro-Wilk test.

Source: authors

4. DISCUSSION

The results found denote that the spray nozzles have significant effect on distribution of droplets between rows and in the lower third of black pepper plants; however, none of the variables analyzed were significantly affected by the use of protector (Chapéu de Napoleão).

The nozzle XR11002 VP resulted in higher coverage, density, and deposition of droplets between rows, since this nozzle produces medium size droplets, decreasing the drift at low pressures. The higher density of droplets was found for the nozzle XR11002 VP, since the smaller the diameter of droplets, the greater the coverage of droplets on the target. According to Chen *et al*. (2020), density of droplets is highly connected with the type of spray nozzle and directly affects the control of the target.

Contrastingly, the nozzle AI11002 VS presented lower coverage, density, and deposition of droplets between rows; however, the values were statistically equal to those of the nozzle XR11002 VP. In the lower third of black pepper plants, the nozzle AI11002 VS with protector presented lower deposition of droplets, i.e., lower risk of phytotoxicity to the black pepper plants, denoting that, despite the lower values found for the application efficiency variables, the risk of drift was decreased.

The lower coverage and deposition of droplets between rows and the higher density of droplets between rows and in the lower third of the plants promoted by using the backpack sprayer standard nozzle were due to the drift of droplets. Despite the increases of droplets cm^{-2}, the deposition of droplets was significantly lower due to the smaller diameters of droplets by using this nozzle.

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The control of weeds between rows of agricultural crops should avoid drift of herbicides to the plants of commercial interest. Nozzles without protector resulted in higher coverage and deposition of droplets in the lower third of plants, denoting possible drift of droplets. This drift results in a possible herbicide phytotoxicity to black pepper plants; the damages can be significant, depending on the age of the plant, hindering the vegetative formation and, consequently, the production of fruits.

Contrastingly, the nozzle AI11002 VS with protector showed significantly lower coverage, density, and deposition of droplets in the lower third of black pepper plants. Similar results were found by Sossai et al. (2020), who found that the use of protector and air-induction flat jet nozzles in the backpack sprayer resulted in higher spray deposition on weeds in conilon coffee crops.

Volumetric median diameters (VMD) have direct impact on application efficiency variables. The nozzle XR11002 VP resulted in medium droplets between rows. Minguela and Cunha (2010) established criteria of droplet size for herbicides, considering a minimum droplet diameter of 150µm and a maximum of 500µm as preferable for pre-emergence, contact, and systemic herbicides.

The VMD found for the nozzle AI11002 VS are consistent with those reported by Doruchowski *et al*. (2017), Vitória *et al.* (2019), Hunter *et al.* (2020), and Lamare *et al.* (2022), who found that air-induction nozzles with can reduce the potential drift. This characteristic is common in air-induction nozzles, as droplets with air are carried to the target surface at high speed, and the air is compressed before leaving the nozzle, which decreases the risk of drift. This characteristic makes the VMD of air-induction nozzles to be higher than those of simple flat jet nozzles.

Butts *et al*. (2019) found that the droplet size of 395µm increased the mortality of weeds when using a mixture of dicamba and glyphosate, and that the droplet size can be increased to 620µm while maintaining a 90% mortality of weeds and mitigating the potential drift risk. These droplet sizes used for increasing weed control efficiency were also found in the present study when using the XR11002 VP and AI11002 VS nozzles.

Fine spray droplets (<150µm) have a wide range of application and promote a greater penetration of the solution into the target surface; however, smaller droplets are highly susceptible to drift and evaporation under inadequate weather conditions. Contrastingly, Ribeiro and Vitória (2022) found that medium droplets (200-400µm) present intermediate characteristics, being less susceptible to drift. However, the higher the VMD, the higher the chances of runoff of the product to non-target areas, causing serious environmental damages.

Regarding the volumetric distribution per size class, the nozzle AI11002 VS presented coarse to ultra-coarse droplets and the nozzle XR11002 VP presented medium droplets. The values described are consistent with the droplet classification described by the nozzle manufacturer. The backpack sprayer standard nozzle without protector resulted in extremely fine droplets in both $D_{v0.1}$ and $D_{v0.9}$, thus, the droplets had small diameters, which are susceptible to drift.

According to Viana *et al.* (2010), the lower the relative amplitude, the most homogeneous the spectrum of droplets. The most homogeneous values were found for the nozzle AI11002 VS with protector, due to the larger diameter of the spray droplets, since VMD and relative

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amplitude require joint evaluation to characterize the spraying (Vitória & Campanharo, 2016; Machado *et al*. 2019).

The results found in the present study are consistent with those of Costa et al. (2008), who evaluated burndown of *Brachiaria brizantha* plants and found higher deposition of spray solution for the nozzle AI 11002 VS when compared to the nozzle XR11002 VS; however, using the air-induction nozzle resulted in an uneven deposition. Similarly, Barros *et al.* (2014) evaluated the control of weeds with the herbicide glyphosate and found that the nozzle XR 11002 presented lower control of weeds until 21 days after application, compared to the nozzles AI11002 VS, TT 11002 VP, and TJ 60110 VS.

Thus, the use of spray nozzles that result in higher coverage of the target by the spray solution with a uniform distribution is essential for an efficient weed control in black pepper crops, ensuring that all weeds are reached by the spray droplets. The effects of spray nozzles on weed control found were consistent with results reported by Nieweglowski Filho *et al*. (2014), who evaluated chemical control of weeds using different spray nozzles. Other studies also found significant differences between spray nozzles regarding spray deposition and coverage, for onion (Amler *et al*., 2021) and conilon coffee (Soela *et al*., 2020) crops and for application of insecticides to soybean crops (Costa *et al*., 2017).

5. CONCLUSION

The nozzle XR11002 VP without protector (Chapéu de Napoleão) presented higher coverage, density, and deposition of droplets between rows of black pepper crops.

The nozzle AI11002 VS with protector resulted in an adequate coverage and deposition of droplets between rows and in lower coverage and deposition of droplets in the lower third of black pepper plants, thus avoiding the risk of spray drift.

The backpack sprayer standard nozzle generated lower coverage and deposition of droplets between rows, since fine droplets are easily dragged by wind, increasing the risk of drift.

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