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ORIGINAL ARTICLE

Coverage of corn plants using different hydraulic nozzles and application volume rates

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Abstract

An efficient application of phytosanitary products depends, among other factors, on a good selection of nozzles and the application volume rate of the solution used. Thus, the objective of this work was to evaluate the efficiency of different models of hydraulic tips and application volume rates on spray coverage on targets positioned in the upper, middle and lower thirds of corn plants. The application volume rates evaluated were: 50 l · ha^{-1}; 100 l · ha^{-1}; 150 l · ha^{-1}; 200 l · ha^{-1}; 300 l · ha^{-1} and 400 l · ha^{-1}. The following nozzles were used: TT 11001, TTJ60 11002, TXA 8003, 30HCX 12, GRD120 02 and GAT11002. Applications were carried out in phenological stages V6–V7 of corn plants. There was a directly proportional relationship between an increase in application volume rate and the levels of spray coverage and droplet density in the three thirds of corn plants. The application volume rate evaluated, except for 50 l · ha^{-1} in the lower third, provided a number of droplets compatible with the literature recommendations for the application of systemic fungicides. All tips evaluated provided a number of droplets compatible with the recommendations in the literature for the application of systemic fungicides, therefore, they can be recommended for use in spraying on corn crops.

Keywords: application technology, droplet density, spray coverage, *Zea mays*

Introduction

The cultivation of corn (*Zea mays*) is an agricultural activity of great importance to Brazil, due to the wide use of this grain in human and animal food and as a raw material for industry. Brazilian corn production is the third largest in the world, and the country is the largest corn exporter (Conab 2020). However, the entire productive potential of this crop may suffer damage due to the incidence of foliar diseases. Pathogens colonize leaf tissue causing a decrease in the photosynthetic capacity of plants, which leads to early necrosis and senescence and, as a consequence, reduced yield (Eastburn *et al.* 2011; Faria *et al.* 2015).

The increase in the incidence and severity of foliar diseases in corn is related to the increase in irrigated areas, to consecutive corn plantations and the use of susceptible hybrids (Tomazela *et al.* 2006). The most efficient management to control diseases in corn is based on the use of resistant varieties, cultural measures and chemical control. In recent years, chemical control has become essential to prevent corn yield losses due to disease occurrence (Costa *et al.* 2009). However, although there are efficient phytosanitary products for disease control, their effectiveness depends on the application technology adopted (Nascimento 2020).

The application technology of phytosanitary products must promote efficient deposition of the phytosanitary product on the desired target, while avoiding losses to the environment (Van Zyl *et al.* 2013). Efficient application depends on good tip selection, which is influenced by application volume rate, operating parameters, favorable environmental conditions and correct application timing, taking into account the recommendations of each product (Balsari *et al.* 2019). Understanding the biology and behavior of the biological target to be achieved is of paramount importance for the control to be efficient (Balan *et al.* 2012).

With regard to the spray nozzles, the diameter of the droplets produced is also an important factor for efficiency in the spraying process. Larger diameter droplets promote less coverage on the target surface, however they present less risk of being lost by drift. Smaller diameter droplets, in general, promote greater surface coverage, however under unfavorable environmental conditions they are easily lost by drift (Hilz and Vermeer 2013). For efficient deposition of the spray on the target the tips should distribute the sprayed droplets as homogeneously as possible with adequate numbers and size (Nuyttens *et al.* 2007; Cunha and Silva 2010a).

For the application volume rate, the sprayed mixture should provide maximum droplet coverage with minimum run-off losses. However, the application volume rate is not responsible for controlling the pest, pathogen or weed, Rather, it is controlled by the uniform distribution of the spray on the desired target, since excessive wetting causes runoff losses (Van Zyl *et al.* 2014). The use of smaller application volume rates can provide an increase in the operational capacity of sprayers, since the time spent for refueling slows down the operational pace, and reduces production costs due to the reduction in the number of stops for refueling with water, which is the transport vehicle of phytosanitary products in spraying (Souza *et al.* 2012).

The coverage provided by spraying can also be affected by plant size and architecture. Therefore, in the lower and internal parts of the crop canopy, spray deposition is lower, due to barriers created by the highest parts of the plants (Gossen *et al.* 2008; Silva *et al.* 2014). Thus, it is important to know the penetration profile of the droplets produced by the hydraulic tips and the application volume rate in the canopy of the crop, in order to overcome this barrier and deposit the spray satisfactorily on the lower parts of the plants.

There is no consensus on the recommendations of specific spray nozzles or application volume rates for application of fungicides in corn crops. Some authors have used the following models of spray nozzles: flat jet – API 110-02, double flat jet with air induction – ADIA 110-02D, flat deflector jet – TT 110-02, conical empty jet – MAG 02, and jet double plane – AD/D 110-02 (Cunha and Pereira 2009; Juliatti *et al.* 2010; Silva *et al.* 2014). As for the application volume rate, some authors used application volume rates ranging from 70 to 200 $l \cdot ha^{-1}$ (Cunha and Pereira 2009; Juliatti *et al.* 2010). Therefore, there is no specific recommendation in the literature indicating the best spray nozzles and application volume rates for application of fungicides for disease control in corn crops.

Different types of nozzles and application volume rates can provide different spray coverage on plant parts depending on their architecture. The selection of nozzles and application volume rates that provide the greatest droplet deposition on corn plants can contribute to improving pesticide efficiency. Given the above, the aim of this study was to evaluate the influence of different models of hydraulic nozzles and application volume rates on spray coverage on targets positioned in the upper, middle and lower thirds of corn plants.

Materials and Methods

Two experiments were carried out at the Diogo Alves de Melo experimental unit at the Federal University of Viçosa – UFV, Viçosa, MG, located under the coordinates 20°45'14", latitude S, 42°52'54", longitude W and altitude of 649 m. The corn cultivar used was BM 709, a conventional double hybrid of early cycle, sown in a no-tillage system, with a spacing of 50 cm between rows and a stand of 60,000 plants per hectare. Planting, fertilization, as well as cultural treatments and herbicide applications were carried out in accordance with the recommendations indicated for the corn crop.

In the first experiment, the treatments consisted of evaluating different application volume rates: 50 $l \cdot ha^{-1}$, 100 $l \cdot ha^{-1}$, 150 $l \cdot ha^{-1}$, 200 $l \cdot ha^{-1}$, 300 $l \cdot ha^{-1}$ and 400 $l \cdot ha^{-1}$. The applications were carried out with a CO_2-pressurized backpack sprayer, equipped with a bar with four spray nozzles 0.5 m apart, a bar height of 0.5 m in relation to the crop, with a flat jet type fan tip, model TT 11001 from Teejet®. The working pressure used was 500 kPa (5 bar) for all application volume rates, changing, in this case, the displacement speeds to reach the different application volume rates.

In the second experiment, the following six nozzles were also evaluated: flat deflector jet (TT 11001), double deflector flat jet (TTJ60 11002), empty cone jet (TXA 8003), empty cone jet (30HCX 12), single fan jet (GRD120 02) and double fan jet with air induction (GAT11002). The applications were carried out with a CO_2-pressurized backpack sprayer, equipped with a bar with four nozzles 0.5 m apart, and a bar height of

0.5 m in relation to the crop. All the nozzles evaluated worked with a pressure of 500 kPa (5 bar) and an application volume rate of 200 l · ha^{-1}. In the application volume rate and spray nozzle evaluations, only water was used to evaluate the sprays.

A completely randomized design was used, with 10 replications, and in a split-plot scheme, with the application volume rate and nozzles being the plots, and the subplots the parts of the corn plants (upper, middle and lower third). Data were subjected to analysis of variance and means were compared using the Tukey test, adopting the level of 5% probability, with the aid of the statistical program SISVAR® (Ferreira 2011). Regression analysis was performed for the variable percentage covered area and droplet density for the application volume rate.

Applications were carried out in phenological stages V6–V7 of corn plants. During the application of the treatments, referring to the nozzles and the application volume rate, the average temperature was 25.9 and 27.1°C, the average relative humidity was 35 and 34%, and the wind speed 8.0 and 6.9 km · h^{-1}, respectively. Wind speed, temperature and relative humidity data were collected with the aid of a thermohygrometer and a portable digital anemometer.

The evaluation of spray leaf coverage was carried out on 10 plants per treatment using hydrosensitive paper (76 × 26 mm), positioned horizontally on the adaxial surface, in the upper, middle and lower thirds of the plant. Each paper was considered to be a repetition. The papers were fixed directly on the corn leaves and were removed immediately when the applied spray had dried. Analysis of the hydrosensitive papers was performed using the DropScope® scanner model, which, together with the software, made it possible to obtain the relative amplitude (Span), volumetric median diameter (*VMD*), covered area (%) and droplet density (droplets · cm^{-2}).

Results

Through data analysis, significant differences ($p \leq 0.05$) were observed in the covered area and droplet density evaluations for the application volume rate, and in the covered area, droplet density and relative amplitude evaluations for the spray nozzles.

Table 1 shows a summary of the analysis of variance. There was significant interaction between plant thirds and application volume rate factors for the covered area and droplet density variables.

Figures 1 and 2 show an increase in the coverage levels and droplet density of the hydrosensitive papers with an increase in the application volume rate in the three thirds of the corn plant. Therefore, the results indicate that there was a directly proportional relationship between the application volume rate and the coverage and droplet density of hydrosensitive papers.

With regard to the covered area and droplet density in the different thirds, there was greater coverage of hydrosensitive papers located in the upper third of the corn plants, than in the middle and lower thirds for all application volume rates (Table 2). For the middle and lower thirds, there was no difference in the percentage of covered area for the evaluated application volume rate, except for the application volume rate of 200 and 400 l · ha^{-1}, where there was greater coverage in the middle third. However, the sprayed droplet density by all the application volume rates differed between the middle and lower thirds for the application volume rate, except for the application volume rate of 100 l · ha^{-1}.

Table 3 shows the summary of the analysis of variance for area covered, droplet density, volumetric median diameter (*VMD*) and relative amplitude (Span), according to the sprays with the different nozzles. There was significant interaction between the plant thirds and application volume rate factors for the covered

Table 1. Summary of analysis of variance for covered area (%) and droplet density (droplets · cm^{-2}), after application of different application volume rates

Source of variation	*df*	Covered area mean square	Droplet density mean square
Repetition	9	36.73 ns	2,043.09 ns
Application volume rate	5	2,275.95**	234,545.41**
Residue (a)	45	23.84	1387.35
Thirds	2	10,865.82**	1,414,353.38**
Thirds × Application volume rate	10	266.59**	26,861.64**
Residue (b)	108	22.01	1,155.02
CV (%) of the plot	–	27.52	19.14
CV (%) of the subplot	–	26.44	17.46

df – degree of freedom; ** significant *F* at 1% probability; ns – not significant; CV (%) – coefficient of variation

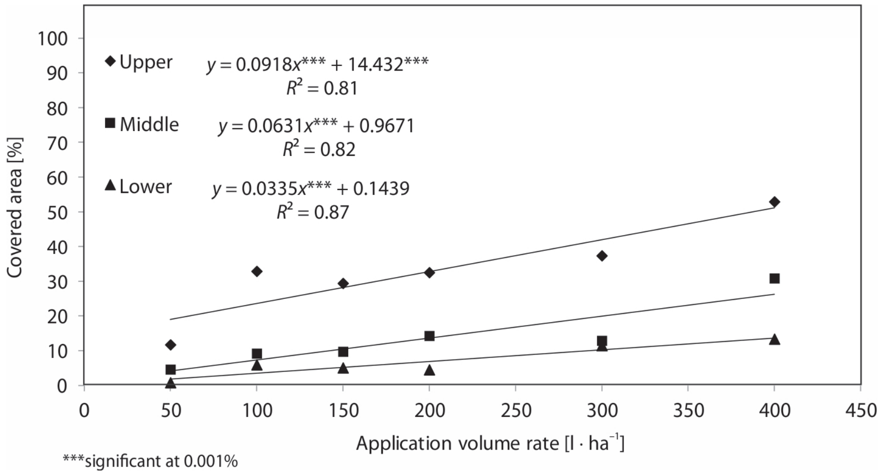

Fig. 1. Mean values of the percentage of covered area according to the upper, middle and lower thirds of corn plants

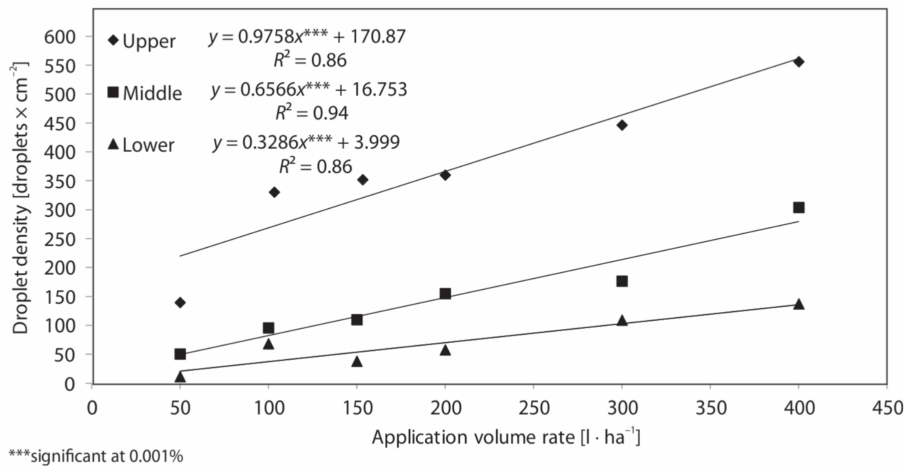

Fig. 2. Mean values of droplet density according to the upper, middle and lower thirds of corn plants

Table 2. Mean values of covered area and droplet density of the different application volume rates, according to the upper, middle and lower thirds of corn plants

Covered area [%]			
Application volume rate [l · ha^{-1}]	upper	middle	lower
50	11.71 A	4.59 B	0.79 B
100	32.87 A	9.19 B	5.94 B
150	29.40 A	9.72 B	5.06 B
200	32.50 A	14.27 B	4.51 C
300	37.35 A	12.88 B	11.47 B
400	52.90 A	30.83 B	13.35 C
Droplet density [droplets · cm^{-2}]			
Application volume rate [l · ha^{-1}]	upper	middle	lower
50	139 A	50 B	11 C
100	342 A	95 B	68 B
150	355 A	109 B	38 C
200	360 A	155 B	57 C
300	446 A	176 B	109 C
400	556 A	304 B	137 C

Means followed by the same capital letter in the line, do not differ significantly at 5% probability by the Tukey test ($p < 0.05$)

Table 3. Summary of analysis of variance for covered area (%), droplet density (droplets · cm^{-2}), VMD and relative amplitude (Span) after application with the different spray nozzles

Source of variation	*df*	Covered area (mean square)	Droplet density (mean square)
Repetition	9	34.55 ns	7,044.65 ns
Spray nozzles	5	415.21**	37,559.45**
Residue (a)	45	42.04	8,628.30
Spray nozzles	2	10,088.39**	148,9381.11**
Thirds × Spray nozzles	10	146.33**	31,021.56**
Residue (b)	108	37.74	7,750.61
CV (%) of the plot		34.58	41.50
CV (%) of the subplot		32.76	39.34
Source of variation	***df***	**VMD (mean square)**	**Relative amplitude (mean square)**
Repetition	9	2,850.68 ns	0.060 ns
Spray nozzles	5	6,703.0 ns	0.050 ns
Residue (a)	45	3665.47	0.040
Thirds	2	9,334.35 ns	0.398**
Thirds × Spray nozzles	10	5,285.25 ns	0.028 ns
Residue (b)	108	3,322.09	0.033
CV (%) of the plot	–	21.45	22.76
CV (%) of the subplot	–	20.42	20.62

df – degree of freedom; **significant *F* at 1% probability; ns – not significant; CV (%) – coefficient of variation

Table 4. Mean values of covered area, droplet density, volumetric median diameter (*VMD*) and relative amplitude (Span) of the different nozzles, according to the upper, middle and lower thirds of corn plants

Nozzles	Covered area [%]			
	upper	middle	lower	mean
TTJ60 11002	32.26 abA	18.14 abB	23.38 aB	21.60
GRD 12002	29.63 abA	21.92 aB	6.80 abC	19.45
30HCX 12	34.63 aA	24.91 aB	5.84 abC	21.79
GAT 11002	33.82 aA	13.29 bcB	4.71 bC	17.27
TXA 8003	37.69 aA	17.61 abB	6.07 abC	20.46
TT 11001	25.70 bA	6.91 cB	3.24 bB	11.95
Mean	32.45	17.13	6.67	–
Nozzles	**Droplet density [droplets · cm^{-2}]**			
	upper	middle	lower	mean
TTJ60 11002	405 abA	163 bB	146 aB	238
GRD12002	345 bcA	225 abB	73 aC	214
30HCX 12	417 abA	307 aB	87 aC	270
GAT 11002	472 aA	142 bB	51 aB	222
TXA 8003	441 abA	197 abB	68 aC	235
TT 11001	277 cA	153 bB	61 aB	163
Mean	393	198	81	–

Table 4. Mean values of covered area, droplet density, volumetric median diameter (*VMD*) and relative amplitude (Span) of the different nozzles, according to the upper, middle and lower thirds of corn plants – *continuation*

Nozzles	Volumetric Median Diameter (*VMD*)			
	upper	middle	lower	mean
TTJ60 11002	265	275	294	278 a
GRD12002	308	271	274	284 a
30HCX 12	299	267	230	265 a
GAT 11002	290	320	315	308 a
TXA 8003	324	283	253	287 a
TT 11001	288	266	262	272 a
Mean	296 A	280 A	271 A	–
Nozzles	**Relative amplitude (Span)**			
	upper	middle	lower	mean
TTJ60 11002	1.03	0.89	0.93	0.95 a
GRD 12002	0.88	0.89	0.76	0.84 a
30HCX 12	0.99	0.91	0.82	0.91 a
GAT 11002	1.00	0.80	0.72	0.84 a
TXA 8003	1.00	0.86	0.77	0.88 a
TT 11001	0.91	0.90	0.83	0.88 a
Mean	0.97 A	0.88 AB	0.81 B	–

Means followed by the same capital letter, in the line, and lower case, in the column, do not differ significantly at 5% probability by the Tukey test ($p < 0.05$)

area and droplet density variables, and a simple effect for thirds for the relative amplitude variable.

According to Table 4, there was no difference in the percentage of coverage in hydrosensitive papers between the nozzles, in the upper and middle thirds, except for nozzle TT 11001 which promoted the lowest coverage for both thirds. In the lower third, nozzle TTJ60 11002 provided greater surface coverage of the hydrosensitive papers, however the other nozzles did not differ from each other. For droplet density, in the upper third, the lowest value was promoted by the TT 11001 nozzle, and for the middle third, the highest value was promoted by the 30HCX 12 nozzle, and for both thirds there was no difference between the other spray nozzles. In the lower third, the spray nozzles did not differ in terms of droplet density.

Regarding the evaluations between the thirds of the plant, there was a higher percentage of coverage by the sprayed solution and droplet density in the upper third, than the lower third, for all spray nozzles (Table 4).

For *VMD* there was no statistically significant difference between the tips or between the thirds of corn plants. However, for the relative amplitude there was a difference only between the thirds of the plants, although only the upper and lower thirds differed from each other (Table 4).

Discussion

There was an irregular distribution of the phytosanitary product in the thirds of the plant, with greater coverage in the upper third. As expected, this feature shows less penetration of the spray inside the canopy. Furthermore, the leaves present on the upper part of the plants are more exposed to spraying, which explains the increase in spray coverage and droplet density in this part of the plant. The lower values of spray solution coverage in the middle and lower parts of the plant can be explained as a function of the architecture and leaf area index that cause changes in the leaf surface coverage and in the penetration of droplets of the phytosanitary product along the crop canopy. According to Halley (2008) and Silva *et al.* (2014) there is a noticeable decline in the covered area and droplet density deposited in the lower thirds of corn plants.

The use of high application volume rates results in better coverage along the canopy of the crop. High volumes allow for a redistribution of the spray liquid by draining from the upper to the lower third, which causes greater coverage in the lower parts of the plants. However, such applications present a greater risk of soil contamination due to an insufficient capacity of retaining the phytosanitary product in the leaves at high application volume rates.

With regard to the spray coverage promoted by the nozzles, it is expected that, in general, tips that produce fine droplets promote greater coverage of the target (Silva *et al.* 2014; Chechi *et al.* 2020), especially under conditions of low wind speed. However they require more attention, since they are easily transported by the wind, and therefore, present a greater risk of drift and evaporation. According to De Oliveira and Antuniassi (2011), thin droplets are recommended when greater coverage and penetration into the plant canopy is required, and medium or thick droplets when application occurs under conditions of greater risk of drift. Despite the findings of Silva *et al.* (2014) and De Oliveira and Antuniassi (2011), in the present study, greater coverage and spray deposition was not observed on the leaf surfaces of plants when spraying with nozzles that produce a higher percentage of fine droplets, than those that produce more medium droplets.

According to Nascimento (2020), in a study with a real-time particle analyzer, which analyzes the droplets in transit, the volumetric median diameter (*VMD*), at a working pressure of 5 bar, of the droplets sprayed by the TXA 8003 nozzles, 30HCX 12, TT 11001, TTJ60 11002, GRD120 02 and GAT11002, is respectively, 100.41, 122.07, 163.48, 169.72, 202.40 and 200.88 μm. Therefore, droplets sprayed by TXA 8003 and 30HCX 12 nozzles are classified as very fine, while droplets sprayed by TT 11001 and TTJ60 11002 nozzles are classified as fine, and GRD120 02 and GAT11002 nozzles spray produce medium droplets. However, in general, the nozzles used, despite the differences in the classification of droplets, promoted similar target coverage within each third evaluated, with an application rate of 200 $l \cdot ha^{-1}$. In this case, the choice of nozzles should be based on the weather conditions at the time of application.

With regard to droplet density, the values observed in this work for both the application volume rates and the nozzles are suitable for the application of systemic fungicides, according to Christofoletti (1999) and Ugalde (2005), who recommended from 30 to 45 droplets $\cdot$ cm^{-2}, except for the application volume rate of 50 $l \cdot ha^{-1}$ in the lower third that only promoted the spraying of 11 droplets $\cdot$ cm^{-2}. As the application volume rate is reduced, droplet density is a factor that requires more attention, as it can become limiting (Boller *et al.* 2007). However, analyzing droplet density alone can appear as a higher application volume rate, especially when using systemic fungicides, which have a certain mobility in the plant. Thus, the droplet density must be analyzed by also taking into account that there is a difference in spray concentration (Cunha *et al.* 2010b). Nascimento *et al.* (2021), in a study with different application volume rates in the spraying of systemic fungicide to control Asian soybean rust, found that an increase in application volume rate resulted in an increase in spray coverage and droplet density in three thirds of the plants. An application volume rate of up to 50 $l \cdot ha^{-1}$ did not negatively affect Asian rust control and soybean plant grain yield.

However, it may be that if the TTJ60 11002 nozzles had been used to apply the application volume rate of 50 $l \cdot ha^{-1}$, instead of the TT 11001 nozzles, the spraying of droplet density would have been promoted in the lower third of the plants, recommended for application of systemic fungicide in corn crops. Cunha and Silva (2010a) in a study with air induction flat deflector jet nozzles (TTI 11002) and double flat deflector jet (TTJ 11002), with an application volume rate of 100 ha^{-1}, found that the land application with the jet deflector tip double plan provided greater droplet density in the lower third of corn plants. In a work carried out by Zhu *et al.* (2004), studying the spray penetration provided by different nozzles in peanut crops, the authors concluded that the double flat jet tips promoted greater target coverage than other nozzles. In these nozzles, the size of each of the two elliptical outlet holes is smaller than the orifice of a standard tip with the same nominal flow rate, which leads to more spraying of the jet.

To obtain applications with good leaf coverage indices, the *VMD* values must be below 365 μm, which, according to Sasaki *et al.* (2016), is limiting in the case of applications that require high coverage of the biological target. Thus, in this work, the mean *VMD* values of sprayed droplets from all evaluated tips were below 365 μm, so they can provide good coverage of the surface of the biological target. When comparing the *VMD* of the impacted droplets on hydrosensitive paper and the droplets in transit, an overestimation of the *VMD* of the impacted droplets was observed, since, as Nascimento (2020) noted, the characterization of the spectra of droplets in transit or *VMD* was much lower than that observed in hydrosensitive papers, thus, the device read a droplet with an overestimated *VMD*. The relative amplitude, on the other hand, shows the sprinkler quality of the spectrum, so that the lower the relative amplitude value, the more homogeneous the droplets are (Sasaki *et al.* 2013). All tips evaluated in the present study showed similar droplet homogeneity in the three thirds of the plants.

Finally, determination of the droplet spectrum helps in choosing the nozzles according to the size of the droplets, but the selection of the nozzles must be based, in addition to the spectrum, on the product formulation, application volume rate, environmental conditions, target type to be achieved, the agricultural crop to be sprayed and leaf area index, among others. The use of low application volume rates, on the other hand, must respect the limitations imposed by weather conditions and the biological target to be achieved.

This means that there is no general rule for indicating a certain droplet spectrum, but all factors must be evaluated to correctly define the choice of tip and the application volume rate to be used.

Conclusions

The application volume rates evaluated, except for 50 l · ha^{-1} in the lower third, provided the number of droplets (density) in the three thirds of the corn plant compatible with the literature recommendations for the application of systemic fungicides. Complementary studies regarding the biological effectiveness for fungicide application through the application volume rate of 50 l · ha^{-1} are needed.

All tips evaluated provided the number of droplets (density) in the three thirds of the corn plant compatible with the literature recommendations for the application of systemic fungicides. Therefore, all nozzles evaluated can be recommended to be used in the spraying of systemic fungicides on corn crops, when the spray application volume rate applied is 200 l · ha^{-1}.

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