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Design and evaluation of a nebulization system for pesticide application in greenhouses

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ABSTRACT

The aim of this study was to design and evaluate a pesticide application system that is run from outside the greenhouse, reducing the operator's exposure to pesticides. The system included a network of pipes with fixed nebulizers distributed above the crop and equipment that injects the pesticide into the network. Seven nebulizers, three operating methods, two diameters, and four pipe lengths were evaluated using Christiansen's uniformity coefficient (CUC). The deposition of the system was evaluated, on the floor of a greenhouse without cultivation and on a tomato crop (*Solanum lycopersicum*), comparing it with a spray gun. The three-stage operation method, filling of pipes, application and surplus collection on return (LLA) was the most homogeneous. It was observed that a nebulization system composed of hydraulic nebulizers with a properly sized pipe network achieved similar deposition to gun applications. With the nebulization system the deposition at the top is greater than at the bottom of the plant.

KEYWORDS

spraying, deposition, fixed nebulizers, pipe network, pesticide application equipment

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INTRODUCTION

The application of pesticides in greenhouses is mainly conducted using hydraulic spraying equipment with manual guns or vertical bars with nozzles, attached to a fixed external tank or a manual cart, with which the operator enters the greenhouse at the time of application (Cerruto et al., 2009; Sánchez-Hermosilla et al., 2021). This equipment is generally inefficient due to significant product losses on the ground, while it requires significant labor effort, and exposes the operator to high risks (Wang et al., 2022a).

The pesticide can reach the operator through contact with the cloud of droplets generated by the application equipment, friction with the treated crop, or equipment leaks when not properly maintained (Mercier et al., 2018; Rincón et al., 2018). Avoiding the sharing of the same environment between the operator and the application equipment is crucial to reducing such exposure (Li et al., 2020). Operating application equipment from outside the greenhouse, and setting appropriate re-entry times, are strategies to reduce operator exposure (Giles et al., 1995).

In a review, Sánchez-Molina et al. (2024) observed that pesticide application in greenhouses is one of the areas with the most research on task robotization or automation, explained by the high demand for labor and the significant health risks pesticides pose to human health.

Externally operated equipment can be self-propelled ground equipment (robots), or fixed or mobile units installed above the crop. González et al. (2009) studied the behavior of self-propelled ground application equipment with a width of 0.7 m and observed that it can be adapted to autonomous navigation between crop rows in typical greenhouses in southeastern Spain.

Rincón et al. (2020) compared a spray gun with a robotic unit equipped with vertical bar nozzles and noted that the robotic unit showed improvements in product deposition on tomato plants, especially on the inner parts.

This self-propelled equipment is difficult to implement in high-density greenhouse crops such as tomatoes (*Solanum lycopersicum*) or peppers (*Capsicum annuum*), due to the lack of space for free movement between crop rows (Lin et al., 2020). In addition, operator training is required to handle them and the cost often makes the investment unfeasible (Sánchez-Hermosilla et al., 2013).

Lin et al. (2020) designed an autonomous equipment unit guided by a hanging rail and found that the equipment could perform autonomous spraying with high efficiency, but there is still room for improvement in crop deposition uniformity.

Austerweil and Grinstein (1997) evaluated three cold foggers in tomato greenhouses that perform automatic application. This equipment was placed at one point and applied the product to the entire greenhouse. The authors noted that the application was not uniform, requiring the installation of auxiliary fans to improve distribution.

Olivet et al. (2011) evaluated a cold nebulizer, positioned near one end of the greenhouse programmed for automatic application at night. The unit was equipped with a fan to distribute the pesticides throughout the greenhouse. They observed that the deposition was very heterogeneous, decreasing with increasing distance from the equipment.

According to Wang et al. (2022b), micro-sprinkler irrigation systems in vineyards can be used for pesticide application as they spray the crop leaves with water, but pesticide application requirements differ from irrigation in terms of required uniformity and droplet size. These authors designed a micro-sprinkler, which, when evaluated in the laboratory at high pressures, achieved good performance for pesticide application and, at low pressures, good performance for irrigation.

Studies have been reported evaluating nebulization systems formed by a network of dual-fluid pipes (liquid and air) mounted with fixed nebulizers where a mist is formed when the liquid comes into contact with the air current.

Sánchez Hermosilla et al. (2013) conducted pesticide applications with a dual-fluid nebulization system used to control the climate inside greenhouses and compared it to traditional hydraulic application techniques. These systems produced a mist with very fine droplets which evaporated into the air. For pesticide application, these authors saturated the environment before application to reduce evaporation. However, they observed that deposition on the crop was higher with traditional manual application techniques.

According to Li et al. (2020), a dual-fluid spraying system with fixed nozzles, 2.5 m above the crop, obtained a uniform distribution of pesticides at different heights of a pepper crop, and, it also had the advantage that the operator can perform the application from outside the greenhouse.

Wang et al. (2023) evaluated a dual-fluid spray system with fixed nozzles and noted that the system was promising, but improvements were needed to obtain a more uniform product distribution.

These works (Wang et al., 2023; Li et al., 2020; Sánchez Hermosilla et al., 2013) do not detail the method of operation nor how the liquid present in the pipes is retired once the application is finished.

This study aimed to design a pesticide application system in greenhouses by means of a network of fixed hydraulic nebulizers to prevent the operator from entering the greenhouse during the application, to evaluate its components to determine the best configuration, the best method of system operation, and the quality of applications with the chosen configuration.

MATERIAL AND METHODS

In this study, a system was designed for pesticide application in greenhouses from the outside. The system consisted of a pesticide injection equipment and a network of pipes with fixed nebulizers distributed above the crop.

For the system design, a nebulizer was selected and tests were conducted to evaluate different pipes to obtain an optimal design in terms of diameter and length, ideal distances between pipes and nebulizers, and the most suitable operating methods.

Once the system was designed, its performance was evaluated in a greenhouse prior to the installation of a tomato crop, and then with a tomato crop installed.

Spraying equipment design

This equipment must be able to inject the pesticide into the pipes as well as inject air to push out the pesticide and clean the pipes after the application is complete. That is why a device with a hydraulic circuit and an air circuit was designed (Fig. 1A). Commercially there is equipment that fulfills this function (Special Serre 400, DSM, Italy). In this work we sought to design a similar equipment adapting a hydraulic atomizer (Vigneron 600, DSM, Italy), with a 600 L capacity tank and a pump (APS 145, Comet, Italy) driven by the tractor's power take-off, with a flow rate of 142 L min^{-1}–540 rpm sufficient to supply the network of nebulizers (Fig. 1B).

A compressor with an airflow of 500 L min^{-1} (CSL 30BR/250 Schulz, Brazil) and a 250 L air tank were installed at the back of the equipment, enough to extract the excess liquid supply from

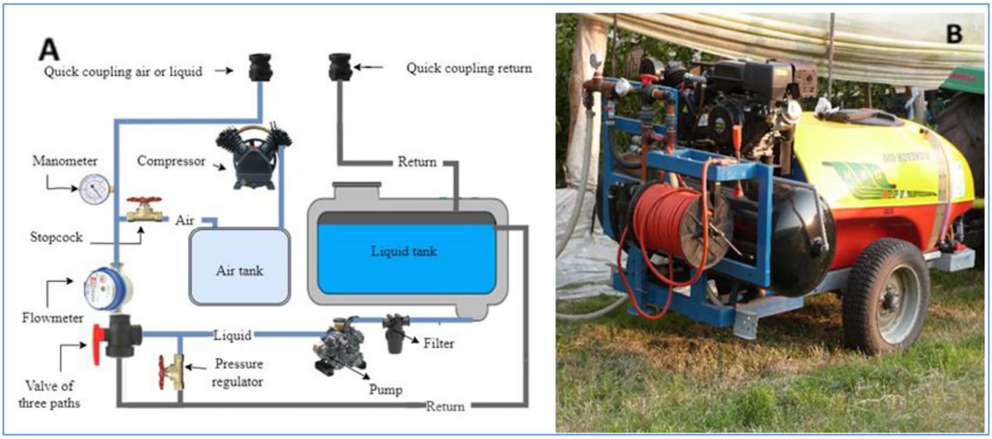

Fig. 1. Equipment designed for pesticide injection. A: Diagram of the liquid and air circuit. B: Equipment. Own creation

the application of the entire network of pipes and final cleaning of the system. This compressor is powered by an internal combustion engine, which was installed at the back of the sprayer, where the equipment commands were also situated.

The main difference between the designed equipment and the commercially available equipment is the incorporation of a return pipe that connects to the pipe network and allows all the liquid present in the system to be removed.

Nebulizer selection

Since no specific pesticide application nebulizers were found commercially, available nebulizers for irrigation and/or humidity and temperature control were evaluated. Seven nebulizers of different configurations and/or flow rates were assessed (Table 1). Tavlit nebulizers consist of a module, the same for all, with different nozzles, with a nominal flow rate at 200 kPa pressure of 12, 20 and 35 $L\,h^{-1}$ for Tavlit 12, Tavlit 20 and Tavlit 35, respectively. The X-fogger and the T-fogger consisted of a T-shaped module and a cross-shaped module with two and four nozzles respectively, arranged horizontally. Each nozzle had a nominal flow rate of 7 $L\,h^{-1}$ at 400 kPa.

Table 1. Evaluated nebulizers

Model (manufacturer)	Nominal flow rate ($L\,min^{-1}$) at 300 kPa	Treatment ID
Ein-dor 4191 (TAVLIT)	0.240	Tavlit 12
Ein-dor 4191 (TAVLIT)	0.398	Tavlit 20
Ein-dor 4191 (TAVLIT)	0.710	Tavlit 35
X-fogger (Naandanjain)	0.404	X-fogger
T-fogger (Naandanjain)	0.202	T-fogger
Superfogger (Naandanjain)	0.188	Superfogger
Hadar 7110 (Naandanjain)	0.696	Mister

Superfogger consisted of a complete nebulizer, with two horizontal outlets, each outlet with a nominal flow rate of 6.5 L h^{-1} at 400 kPa. Mister consists of a module, with a nozzle, with a nominal flow rate of 34 L h^{-1} at 200 kPa.

In order to avoid air currents, a structure with polyethylene walls and roof, measuring 64 m^2 and 2.5 m high, was built inside a warehouse. The nebulizer was located in the center, and a grid of collectors spaced 0.25 m apart was placed below it to collect the water emitted by the nebulizer (Fig. 2A). The cylindrical collectors had an area of 95 cm^2 at the top and a capacity of 1.2 L.

In each evaluation, the nebulizer continued spraying for 90 min and three repetitions of each evaluation were performed.

All nebulizers were evaluated at a height of 2 m and operating at 300 kPa. The protocol outlined in the ISO 15886-3 standard for the evaluation of micro-sprinklers (ISO, 2012) was strictly followed. Once the data were obtained, they were entered into an electronic spreadsheet and different distances between sprinklers were simulated. The distance between pipes was considered to be 1.5 m since this is the expected distance between crop lines in greenhouses. The quality of the application was estimated using Christiansen's uniformity coefficient (CUC) (Christiansen, 1942). The following formula was used for this purpose:

$$CUC = 100 * \left(1 - \sum_{y}^{n} \frac{|Xi - M|}{M * n}\right)$$

Where:

CUC: Christiansen's uniformity coefficient
n: number of collectors
Xi: volume obtained in each collector
M: mean value of all collectors

For each distance between nebulizers, the time needed to perform an application with a rate of 1,000 L ha^{-1} at 300 kPa was also calculated. This application rate was taken as a reference because it is the most widely used by producers in Uruguay (Olivet, 2009).

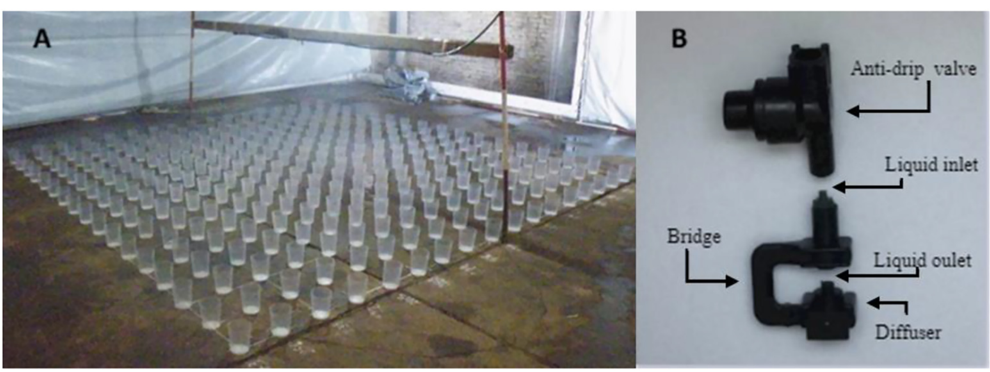

Fig. 2. A: Collectors distributed under the nebulizer for distribution evaluation. B: Tavlit 20 nebulizer. Own creation

Based on these results, the nebulizer with the best characteristics was chosen to be included in a pesticide application system in greenhouses. For the selection, the most uniform spatial distribution was considered, as well as the greatest possible time of application rate.

The selected nebulizer was Tavlit 20. This nebulizer is static and has a bridge (Fig. 2B), so the wetting area is not a complete circle but covers a 320° area, and the droplet size produced is 150 µm at 300 kPa (manufacturer information). Once selected, it was evaluated at different heights and pressure to determine the optimal working height and pressure in greenhouses. Again, the CUC was estimated as an indicator of application uniformity. The heights evaluated were 0.5, 1, 1.5 and 2 m, and the pressures evaluated were 300 and 400 kPa.

Pipeline evaluation and operating method

Considering that greenhouses vary in dimension, it was decided to evaluate pipes of different lengths and diameters. The lengths evaluated were 24, 48, 60 and 72 m and the diameters evaluated were 16 and 20 mm. To this end, a structure was built with wooden posts and steel wire where the pipes to evaluate were mounted and leveled so that there were no pressure variations due to height differences (Fig. 3).

A non-drip valve (530 X, Tavlit, Yavne, Israel) was placed at the inlet of each nebulizer, which opens and allows the passage of liquid or air when the pressure is above 250 kPa (Fig. 2B).

The volume of water emitted by the nebulizers and the pressure losses along the pipes were evaluated for each treatment.

To assess the volume of water emitted by each nebulizer, polypropylene bags with a capacity of 1.9 L were installed to collect the liquid emitted when an application was made at a rate of 1,000 L ha^{-1}. Since CUC is an indicator of uniformity that can be used for both the uniformity of sprayer distribution as well as flow rates of drip irrigation systems (Santos et al., 2022; Lopes et al., 2021), this coefficient was calculated for the volume data emitted by the nebulizers to determine uniformity across the nebulizer line.

To measure pressure drops, a pressure sensor (NP 600, NOVUS, Canoas, Brazil) was installed in the first nebulizer of the line and another in the last nebulizer, both previously calibrated by an accredited laboratory. Three repetitions were performed for each treatment. An Arduino Uno board (Ivrea, Italy) was used for the configuration of each sensor. A program was created for the Arduino software, in which the signal generated by the sensor is translated into a decimal value. An AAMS pressure gauge tester (Maldegem, Belgium) was used to verify the readings made by the sensor and generate the signal transformation model.

The time the nebulizer spent on the application was also measured with each method of operation. This measurement was taken at the two nebulizers at the ends and the nebulizer in the center of the line. To do this, three stopwatches were synchronized, and a person was present at each nebulizer with a stopwatch and recorded the moment the nebulizer started and stopped emitting.

Treatments. A total of 24 treatments were evaluated in a three-factor arrangement: two-level pipe diameter (16 and 20 mm), four-level pipe length (24, 48, 60 and 72 m), and three-level method of operation.

Evaluated operating methods. Considering that it is necessary to introduce the pesticide into the pipe, distribute it homogeneously throughout the greenhouse, and extract the remaining liquid in the pipe, three operating methods were evaluated.

Fig. 3. Structure for nebulizers flow rates evaluation. Own source

Liquid-Air ***(LA):*** With this method, the liquid shut-off valve is first opened and the intended amount is injected. Then, the liquid valve is closed, and the air valve is opened to force the liquid through the nebulizers. With this method, the liquid enters the system and fills the pipes, but until the pressure rises to a value above 250 kPa, the non-drip valves do not open, so the liquid takes a few seconds to come out through the nebulizers.

Air – Liquid – Air ***(ALA):*** With this method, air is injected first, then the application liquid, and then the air again. The first injection of air aims to increase the pressure inside the system so that when the liquid enters, the non-drip valves are open, and the liquid is applied from the beginning.

Liquid-Liquid-Air ***(LLA):*** This method involves the installation of a return system to the spraying equipment's tank. First, the return is opened and low-pressure liquid is injected into the system, filling the pipes without opening the non-drip valves; in this way, all the air in the system exits into the tank and the pipes are filled with liquid (Fig. 4C). When the system is full, the return closes (Fig. 4B) and the pressure increases (up to 400 kPa), thus opening the non-drip valves and starting the application. The duration depends on the desired application rate and the

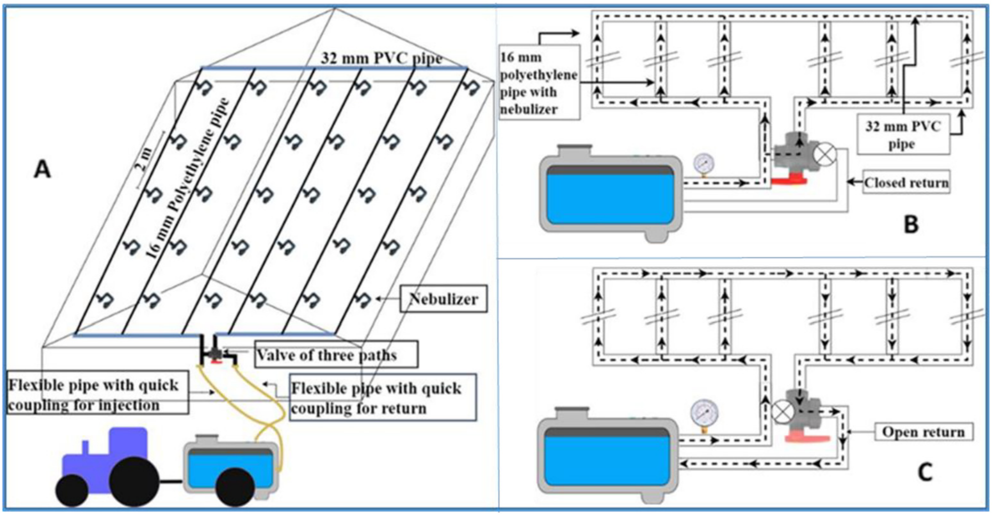

Fig. 4. Illustrative diagram of the system installed in a greenhouse. A: Greenhouse. B: System with closed return during application. C: System with open return for filling or emptying the system. Own creation

flow rate of the nebulizers. After the application is completed, the system is full of liquid, so the liquid in the system must return to the tank. For this, the return is opened and low-pressure air is injected into the pipes so that the non-drip valves remain closed and the liquid returns. At the end, a small volume of liquid is kept in the system, so the air pressure is increased to open the non-drip valves and remove the remaining liquid through the nebulizers, leaving the system clean.

Measurement of the spray deposition

To assess the performance of the designed system, two evaluations were carried out in a commercial greenhouse 10 m wide, 70 m long and 4 m high in the central part and 2.1 m at the ends. One evaluation was carried out on the greenhouse soil without crops, and the other, on a tomato crop. A nebulization system was installed, consisting of pipes 36 m long, 16 mm in diameter, spaced 1.5 m apart, with nebulizers every 2 m, at 2.5 m high and using the LLA application method.

Deposition on the greenhouse soil without crops

To characterize the spatial distribution, a representative area of 86.4 m^2 (9 m * 9.6 m) was selected in the center of the greenhouse, and 247 collectors were placed at a distance of 0.8 x 0.5 m. The cylindrical collectors had 54 cm^2 at the top and a capacity of 0.22 L. An application was made at a rate of 1,000 L ha^{-1} by adding the bright blue dye (FD&A N°1) to the water at a rate of 0.6 kg ha^{-1}. After the application, and once the samples were dry, the collectors were covered and taken to the laboratory to quantify the tracer amount. A volume of 0.02 L of distilled water was added to each collector and stirred for approximately 10 s, and the absorbance was determined with a spectrophotometer model 1200 (Unico NJ, USA) at 630 nm wavelength. The concentration was estimated through a calibration curve, with a correlation coefficient $R^2 = 0.9985$ between 1 and 17 ppm of bright blue, determined immediately before, with solutions of known concentration. The uniformity and amount deposited in the line under the nebulizers (this line corresponds to the line where the crop would later be installed) and the line between the nebulizers (corresponding to the path between crop rows) were analyzed from the obtained data.

Spray deposition on a tomato crop

To evaluate the spray deposition on a crop, a tomato crop was installed in the same greenhouse (Fig. 5). The crop was grown in double rows on beds 1.5 m apart. The resulting density was 3.1 plants m^{-2}, and the cultivar used was Elpida (Enza Zaden, Spain). When the crop was 2 m tall, a trial was conducted to evaluate the deposition of the liquid on different parts of the crop canopy; at three heights, (top, middle and bottom) and two positions in the bed (inner and outer). Two treatments were performed: nebulization system application, and manual hydraulic application. The hydraulic application was taken as a reference because it is the main technology used for pesticide application in greenhouses (Olivet, 2009; Sánchez-Hermosilla et al., 2021). The manual equipment presented a gun with a hollow cone nozzle, made of ceramic, with a hole of 1.5 mm in diameter (model 8282003, Geoline, Italy), with a flow rate of 3.4 L min^{-1} at 600 kPa. The application rate was 1,000 L ha^{-1} in both treatments, with the bright blue dye at a rate of 0.6 kg ha^{-1}.

The application was carried out in the early evening. During the spray gun application, the temperature was 27.1 °C and the relative humidity was 53%. During the nebulizer application, the temperature was 26.3 °C and the humidity was 59%. This information was obtained through a hobo sensor (HOBO H8 Pro Temp/RH Data Logger (H08-032-08) Onset Computer Corporation, Bourne, England) installed in the greenhouse.

The greenhouse was divided into 6 plots to 105 m^2, 23.5 m long by 4.5 m wide, so samples were randomly taken from three plots of each treatment. In each plot, leaflets were taken from three heights (top, middle and bottom) and two positions (outer and inner foliage), six leaflets were extracted from each position per plot. The amounts of bright blue were determined by the

Fig. 5. Application of tracer with a spray gun and nebulizer in tomato crops for deposition evaluation. Own source

same method that was used for floor deposition. Each leaflet was scanned using an MFC-J200 scanner (Brother Industries, Ltd., Japan), with a resolution of 1200 DPI. The images were analyzed using the ImageJ program (NIH. MD, USA) to determine the leaf area and express the results in μg cm^{-2}.

Statistical analysis

A statistical analysis of the data obtained in the nebulizer selection, pipe evaluation, operation method, and greenhouse deposition trials was performed.

In all cases, the analyses were performed using Infostat software, version 2008 (Di Rienzo et al., 2008). Assumptions of homoscedasticity and normality were tested using Levene's test and Shapiro-Wilks tests, respectively. In cases where these assumptions were met, analysis of variance and mean comparison using Tukey's test was performed, with a significance level set at $P < 0.05$.

In the nebulizer selection test, the assumptions of normality and homoscedasticity were not verified for the CUC variable, so non-parametric analysis was performed using Kruskal–Wallis's test.

In the evaluation of different heights and pressures, an analysis of variance was performed for the CUC variable.

For the test evaluating different operation methods with varying pipe lengths and diameters, an analysis of variance was performed for the CUC variable of the volumes emitted by the nebulizers.

In the greenhouse deposition tests, an analysis of variance was performed for the CUC and deposition variables in the soil test. For the variable leaf deposition, the analysis of variance and Tukey's test was performed considering two treatments, two positions and three heights.

RESULTS

Nebulizer selection

Table 2 shows that with the Tavlit 35 nebulizer, greater uniformity is achieved at all evaluated distances. The Tavlit 20 nebulizer did not differ statistically from Tavlit 35 when nebulizers were used every 1.75 and 2 m. At all distances, no differences were observed between the Tavlit 20, X-fogger, mister and Tavlit 12. The T-fogger and superfogger obtained very low uniformity values at all evaluated distances between nebulizers.

Based on the information provided in Table 2, a new evaluation was decided with different pressures and heights for the Tavlit 20 nebulizer. It is noted that using a pressure of 400 kPa, there were no significant differences between the different working heights (Table 3). It is also observed that the nebulizer located at a height of 2 m working at 400 kPa differed from the nebulizer working at 3 kPa at 0.5, 1, and 1.5 m high.

Pressure losses in pipelines

Table 4 shows, as expected, that the longer the length of the pipe, the greater the pressure drop.

Regarding the pipe diameter, it is observed that the pressure loss is greater in the pipe of 16 mm, and the longer the length of the pipe, the greater the difference between the losses obtained between the two diameters.

Figure 6 shows the same effect, where the difference between the first and last nebulizer is greater when the pipe is longer and when the pipe diameter is smaller.

Table 2. CUC obtained by the nebulizers with different distances between nebulizers, and time required to apply 1,000 L ha^{-1}, working at a height of 2 m and 300 kPa

	1.5 m		1.75 m		2 m		2.25 m		2.5 m	
Nebulizer	CUC (%)	T(s)	CUC (%)	T(s)	CUC (%)	T(s)	CUC (%)	T(s)	CUC (%)	T(s)
Tavlit 35	64 a*	19	59 a	22	46 a	25	34 a	28	25 a	32
Tavlit 20	46 b	45	44 ab	52	42 ab	60	19 b	68	10 b	75
X-fogger	34 b	33	35 b	39	27 b	44	19 b	50	12 b	56
Mister	41 b	41	33 b	22	22 b	25	13 b	29	6 b	32
Tavlit 12	35 b	56	28 b	65	17 b	75	9 b	84	3 b	94
T-fogger	−36 bc	66	−29 c	78	−28 c	89	−30 c	100	−33 c	111
Superfogger	−39 c	71	−33 c	83	−34 c	96	−35 c	108	−34 c	118

* Treatment means identified with the same letter in the same column do not differ significantly from each other with $P < 0.05$ according to the nonparametric Kruskal–Wallis's test.

Table 3. CUC results with the Tavlit 20 nebulizer at different pressures and heights, taking 1.5 m as the distance between lines and 2 m between nebulizers

Pressure (kPa)	Height (m)	CUC (%)
400	2.0	57 a*
400	1.5	44 ab
400	1.0	37 ab
400	0.5	38 ab
300	2.0	42 ab
300	1.5	30 b
300	1.0	28 b
300	0.5	27 b

* Treatment means identified with the same letter do not differ significantly from each other with $P < 0.05$ according to Tukey's test.

Table 4. Pressure drop between the start and end of the pipe using different lengths and pipe diameters with nebulizers installed every 2 m using the LLA application method

Diameter (mm)	Length (m)	Start pressure (kPa)	End pressure (kPa)	Difference (%)	Expected flow difference (%)
20	24	373.0	366.1	1.8	0.9
20	48	354.9	347.1	2.2	1.1
20	60	387.0	368.1	4.9	2.5
20	72	401.0	370.2	7.7	3.9
16	24	338.0	331.6	1.9	1.0
16	48	356.3	347.1	2.6	1.3
16	60	365.1	330.2	9.6	4.9
16	72	365.2	307.7	15.7	8.2

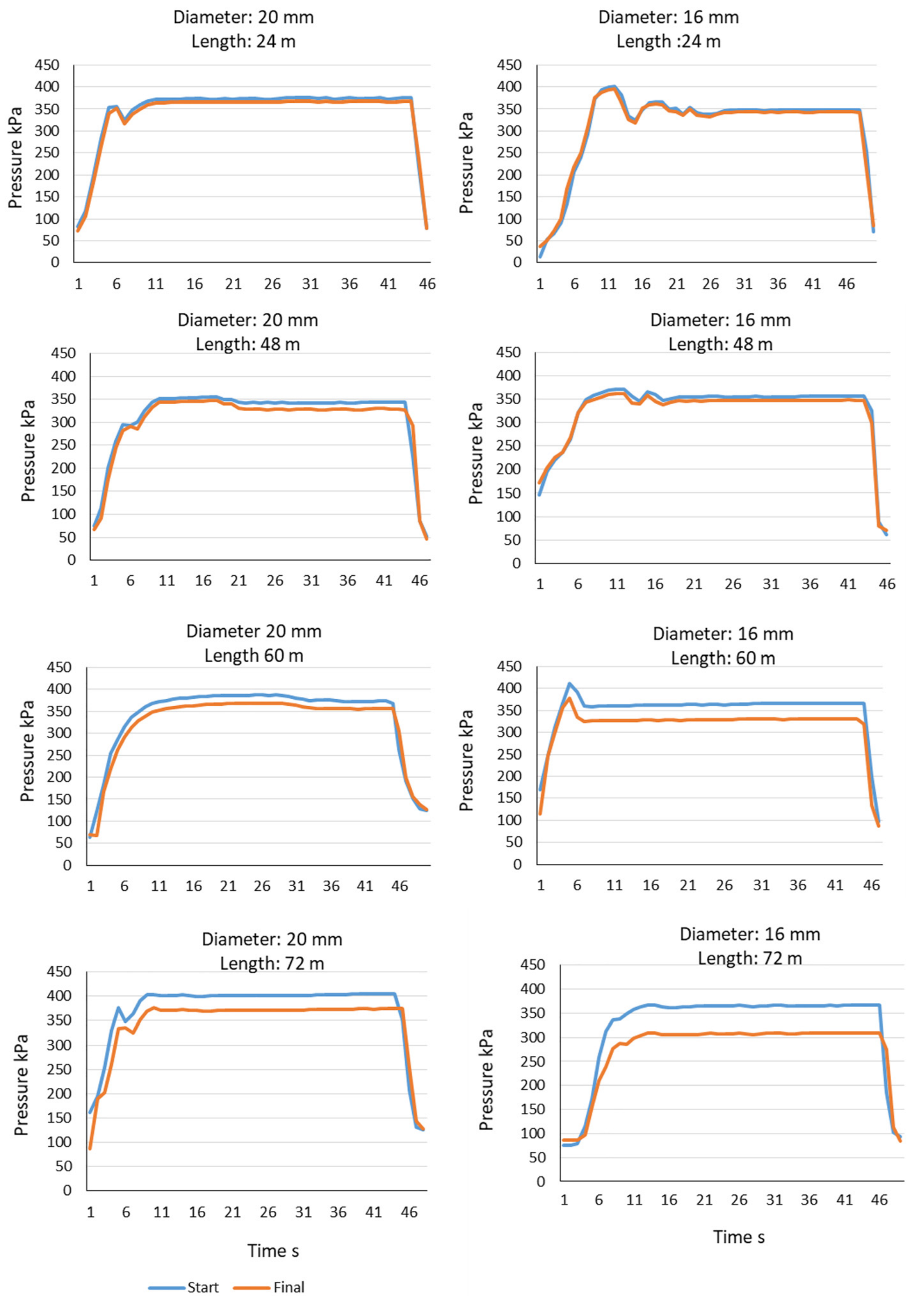

Fig. 6. Pressure variation at the beginning and end of the pipe when applied by the LLA method with pipes of different diameter and length, with nebulizers installed every 2 m. Own creation

Emission time of nebulizers

Figure 7 shows that when applied by the LLA method, the nebulizers at the beginning, middle, or end emit liquid simultaneously. On the other hand, with the LA and ALA methods, nebulizers emit at different times and the duration of the emission time varies.

Volume collected in nebulizers

Figure 8 shows that the collected volume is similar in all nebulizers when applied with the LLA method. When applied with the ALA and LA methods, there are notable differences between nebulizers; the first discharges a smaller amount of liquid, and the last discharges a larger amount. It is also observed that with the ALA and LA methods, the volume of liquid collected in the last nebulizers was greater when 20 mm pipes were used.

Table 5 shows that regardless of the pipe diameter or length, the uniformity obtained with the LLA method of operation was greater than that obtained with the other methods. It is also noted that the uniformity obtained with this method of operation was greater than 90% in all cases.

As for the diameter of the pipe, when the LLA operating method was applied, there was no difference in the uniformity obtained, but when the other operating methods were used, the uniformity obtained with 16 mm pipes was greater.

When the diameter was 16 mm, no difference was observed between the ALA and LA methods; when the diameter was 20 mm, the ALA method was more uniform at the length of 72 m.

Measurement of the spray deposition

In a greenhouse without cultivation it is observed that the spray deposition was higher in the collectors that were in the line under the pipes (Fig. 8) and that the CUC was also higher in those

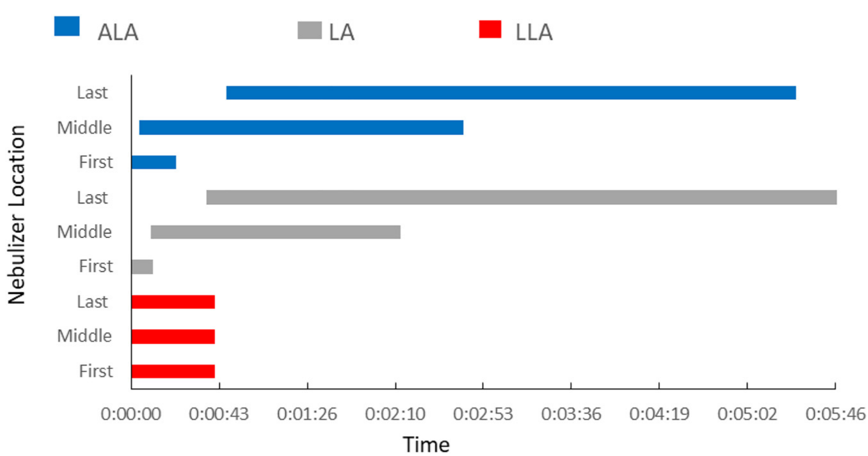

Fig. 7. Emission time of three nebulizers (first middle and last) with three application methods (ALA; LA; LLA) when using a pipe with a diameter of 20 mm and a length of 72 m. Own creation

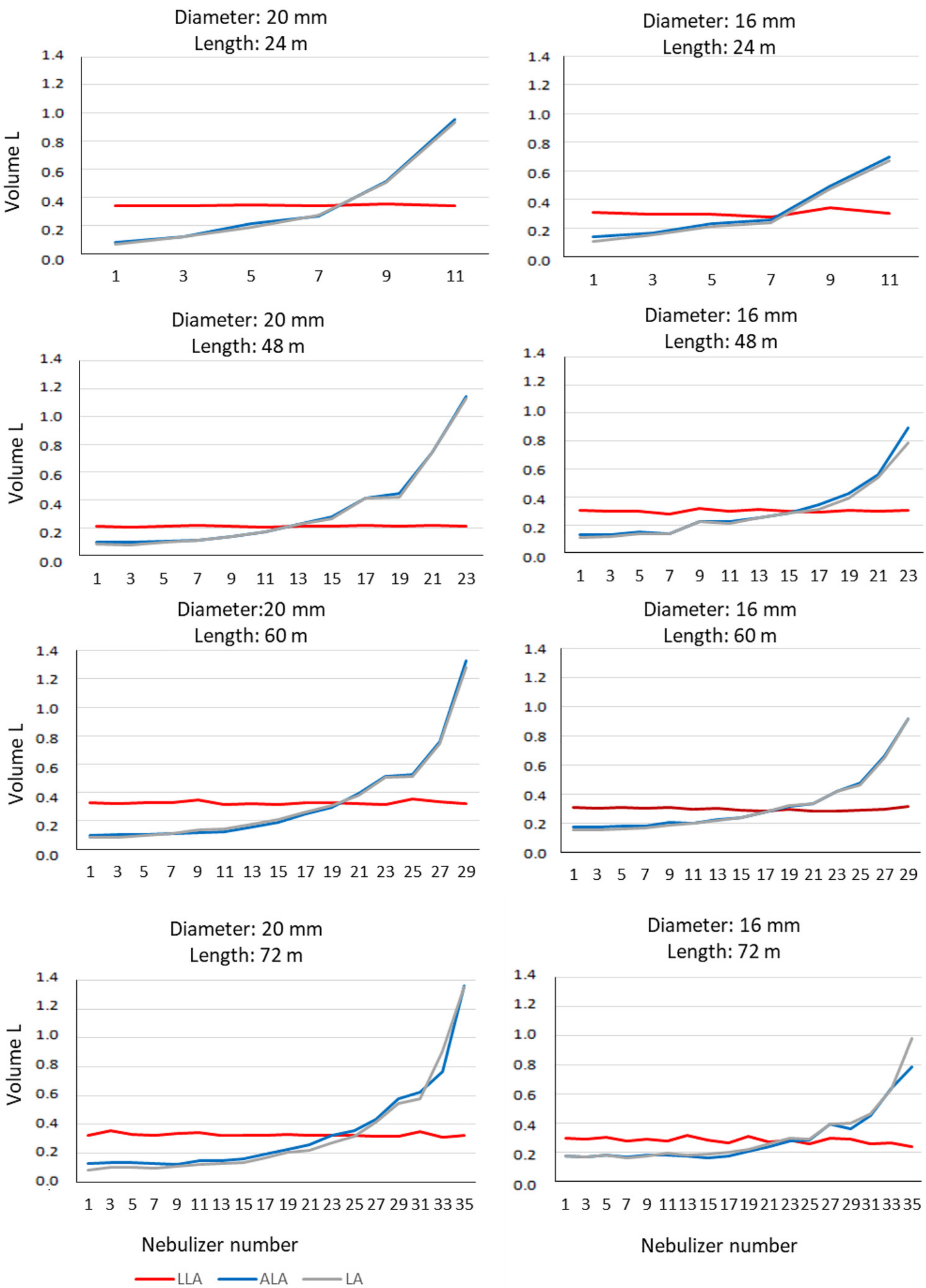

Fig. 8. Volume emitted by each nebulizer according to operation method. Own creation

Table 5. CUC obtained with three application methods, two diameters and 4 pipe lengths

Method	Length	CUC (%)	
		16 mm	20 mm
LLA	24	94 a*	98 a
LLA	48	97 a	97 a
LLA	60	96 a	96 a
LLA	72	92 a	95 a
ALA	24	41 b	28 c
ALA	48	39 b	23 cd
ALA	60	44 b	22 cd
ALA	72	44 b	27 cd
LA	24	38 b	27 cd
LA	48	42 b	22 cd
LA	60	42 b	25 cd
LA	72	45 b	19 d

* Means of all treatments identified with the same letter do not differ significantly from each other with $P < 0.05$ according to Tukey's test.

Table 6. Deposition on collectors located in the soil of the greenhouse without crops

Collector Location	Deposition $\mu g.cm^{-2}$	CUC (%)
Below the pipeline	4.45 a*	70.1 a
Between pipelines	3.41 b	49.9 b
The entire plot	4.08	51.9

* Treatment means identified with the same letter do not differ significantly from each other with $P < 0.05$ according to Tukey's test.

collectors (Table 6). In Fig. 9, greater deposition is also observed in the lines under the pipes with nebulizers.

Table 7 shows that there were no differences in deposition between the inner and outer leaves of the tomato crop.

Regarding the treatment, greater deposition is observed when applied with a nebulizer system. It is observed that the deposition obtained when applied with a spray gun was the same at all three heights, while when applied with a nebulizer system, the deposition at the top was greater. In the middle and lower part of the plant, there were no differences between treatments, but the deposition obtained with a nebulizer was greater at the top.

DISCUSSION

Nebulizer selection

When selecting a nebulizer suitable for this application system, it is essential to ensure that it generates the most uniform application possible and that the time to achieve the desired

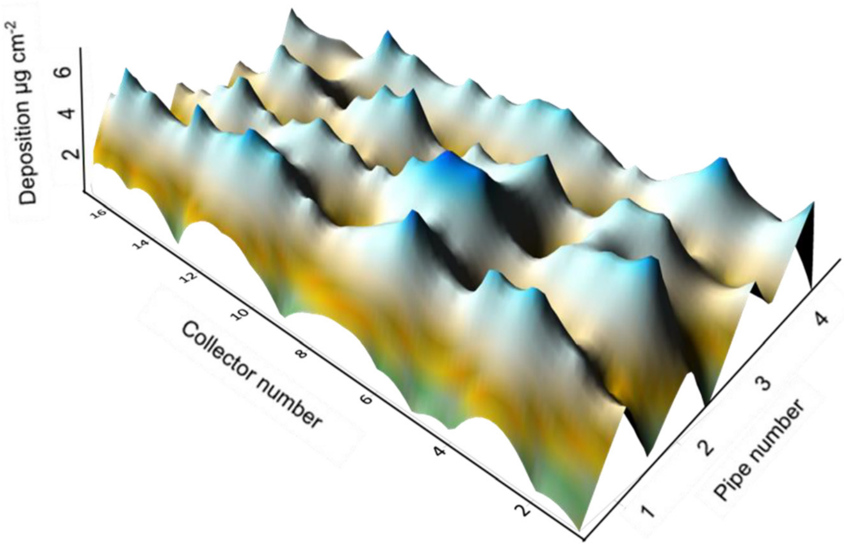

Fig. 9. Spatial distribution observed through deposition in collectors located on the greenhouse floor without crops. Own creation

Table 7. Deposition on foliage

Factor	Deposition (µg cm^{-2})
Treatment	
Nebulizer	1.44 a
Spray gun	1.13 b
Location	
Inner foliage	1.31 ^{ns}
Outer foliage	1.26
Treatment by Height	
Nebulizer. Top	2.02 a
Nebulizer. Middle	1.42 ab
Nebulizer. Bottom	0.88 b
Spray gun. Top	1.09 b
Spray gun. Medium	1.21 b
Spray gun. Bottom	1.10 b

a, b: Means of treatments in each factor identified with the same letter do not differ significantly from each other with $P < 0.05$ according to Tukey's test. ^{ns} Not significant.

application rate is not too short. If a short liquid emission time is required, small differences between the theoretical and actual application times can lead to significant differences between the desired and obtained volume application rates.

It is observed that the distance between nebulizers within the line should be 2 m, as greater distances result in loss of application uniformity, and shorter distances increase the number of nebulizers required. Thus, each nebulizer covers a smaller area, reducing the time required to apply a 1,000 L ha^{-1} application rate.

Based on the CUC results, it is observed that the Tavlit 20 nebulizer meets the requirements. The CUC obtained with this nebulizer does not statistically differ from that obtained with Tavlit 35 (Table 2) at two of the simulated distances. In addition, with nebulizers, every 2 m and pipes every 1.5 m, at 300 kPa, this nebulizer takes 60 s to apply an application rate of 1,000 L ha^{-1}, while with the Tavlit 35 nebulizer requires 25 s. Although the T-fogger and superfogger nebulizers require more time to apply the same rate, they are not advisable because of the low observed CUC.

Wang et al. (2023) observed that in a fixed mist application system, the product is distributed throughout the greenhouse, but the uniformity of the application in this system needs improvement. These authors used nebulizers with a horizontal output and observed that in the front area of the nebulizers there is greater deposition than in the back, with high variation coefficients in both areas. In this case, the nebulizer used ejects the liquid vertically, hits a static diffuser (Fig. 2B) and forms a 320° fan, resulting in a more homogeneous distribution.

According to Sánchez-Hermosilla et al. (2013), misting systems used for environmental modification in greenhouses experience product losses due to evaporation, even when the environment is previously saturated. In the tests carried out by these authors, the droplets had a VMD of less than 55 µm. The nebulizer chosen in this study is designed for irrigation use and produces a droplet size of 150 µm at 300 kPa. The equipment used as a reference in tomato application (spray gun, spray booms whit nozzles) technology evaluations generates droplets with VMD ranging between 100 and 170 µm (Llop et al., 2015; Rincón et al., 2020), so the selected nebulizer produces a droplet size suitable for the application of pesticides in tomato crops, and is also larger than the size produced in environmental modification systems, indicating that the droplets are less likely to evaporate as they do in those systems.

Regarding application height and pressure, it was observed that working at 400 kPa would be recommended, since at that pressure no difference was observed between the different application heights. Considering that crops get closer to the nebulizer as they grow, it is appropriate to use the pressure that ensures greater uniformity and maintains this uniformity as the crop grows.

Pressure loss in pipelines

Although this system is still being studied and differs from traditional application methods, if we take into account the ISO 16122-2:2015 standard that applies to boom sprayers, the pressure drop between the start and the furthest point of the bar should not vary more than 10%, and the flow rate of the nozzles should not differ by more than 15% in nozzles whose nominal flow rate at the maximum pressure recommended by the manufacturer is less than 1 L min^{-1}. In this case, considering that the pipe with nebulizers meets the same function as a boom sprayer, and that the nominal flow rate of these nebulizers is 0.46 L min^{-1} at 400 kPa, the same criterion could be applied.

When the pipe diameter was 16 mm with 72 m pipes, the pressure had a difference of 15.7% (Table 4), but considering that the expected flow variation is 8.2%, it could be said that the pipes 16 mm can be used in all evaluated lengths.

When selecting a pipe, it should be considered that smaller-diameter pipes are less expensive, but have greater friction losses, while larger-diameter pipes are more expensive, but suffer less pressure loss. An appropriate balance would be to use a smaller-diameter pipe when pressure losses remain below acceptable values. In this system, it must also be taken into account that if the LLA operating method is used, a return is required for the liquid remaining in the pipe after the application is completed to return to the tank, resulting in surplus product. However, in general, horticulturists have several greenhouses in which the same pesticide is applied, and the surplus product can be given another use, such as application in another greenhouse, or field cultivation.

Emission time of nebulizers

When using the LLA method of operation, all nebulizers emit liquid simultaneously because the entire system is filled with liquid at the time increases the pressure. When applied by the other methods, the liquid enters the system and when all the liquid passes through, it is pushed with air. Thus, at the beginning of the application the system is filled with air, and as the liquid is injected into the system the nebulizers closest to the inlet emit liquid and the farthest emit air. When all the liquid is injected, it is pushed out with air, causing the liquid to move within the pipe, and nebulizers farthest from the inlet begin to emit liquid, while those closest emit air. For this reason, differences are observed in the application time of each nebulizer (Fig. 7). In order for all nebulizers to emit the same volume, they should emit for the same amount of time. However, this does not happen because when the pipe is empty, the liquid moves quickly toward the end, passing rapidly through the first nebulizers. In the end, the liquid that did not come out through the nebulizers closest to the inlet accumulates in the last nebulizers, and these emit for a longer time, resulting in a greater emitted volume (Fig. 8).

When applied using the ALA method, it is expected that the air entering before the liquid allows the valves to open, and when the liquid enters, it begins to come out, resulting in a longer emission time in the first nebulizers and, therefore, a smaller difference in emission time between the first and last nebulizers. Although nebulizers at the beginning and middle have a longer emission time with this method compared to the LA method, a significant difference in emission time is evaluated between nebulizers in different positions (Fig. 7).

Volume collected in nebulizers

The volume obtained when using the LLA method is quite homogeneous along the pipeline, whereas with the ALA and LA methods, there is a significant difference between the volume collected in the first and last nebulizers. This difference was expected since the observed behavior in emitted volume depends on the emission time, which had a similar behavior.

When applied by the LLA method, the flow rate of all nebulizers (Fig. 8) varied by less than 15% from the nominal flow rate at the pressures used, which is considered appropriate according to the criteria used by the ISO 16122-2:2015 standard. On the other hand, when applied by the ALA and LA methods, in all the evaluations performed, some nebulizers vary more than 15% of their nominal flow rate.

Taking the CUC into account, the difference between the LLA operating method and the other methods is explained by the fact that the LLA method emits a similar volume in all nebulizers while the other methods emit less liquid in the first nebulizers and more in the last ones (Fig. 8). This effect is due to the incorporation of the return, which allows the system to be previously filled and the application to be carried out in all the nebulizers at the same time.

Regarding pipe diameters, was observed that with the LLA method, there is no difference in CUC between the two diameters used.

When applied with the ALA or LA methods, the application is more uniform when using the 16 mm pipe (Table 5). It would be expected that the larger diameter pipe presents lower pressure losses, therefore the volume emitted should be more homogeneous. However, with a larger diameter, the volume of water passing per unit of time is higher, which means that the volume that does not enter the first nebulizers is greater and the volume that accumulates in the nebulizers at the end of the pipe is also greater. Figure 8 shows that the nebulizers at the end of the pipe discharge more volume when using the 20 mm pipe, which explains the lower uniformity obtained with this pipe.

Measurement of the spray deposition

Several authors have observed that with a fixed nebulization system a lot of produce is lost in the pathways (Sánchez Hermosilla et al., 2013; Wang et al., 2023). Although in this work the losses to the soil with the crop installed were not evaluated, observing deposition in uncultivated soil, the deposition on the crop would be expected to be greater than the deposition on the pathways, since the collectors under the nebulizers are located where the tomato plants will later be located (Table 6). The difference with the studies of other authors is that in this study, a pipeline with nebulizers is used for each crop line, concentrating the pesticide on the plants.

In this trial, greater uniformity between plant heights were observed in the application with a gun, but there were no differences between the two treatments in bottom and medium height. In the top of the plants, the amount deposited by the nebulization system was higher, due to the descending trajectories of the spray.

Wang et al. (2023) using a fixed spraying system with horizontally arranged nozzles, observed higher product concentration in the areas near the front of the nozzle. In this study, vertically positioned nebulizers were used, which emit a 320° range in which there is no marked difference between the front or back of the nebulizer, so the distribution is more homogeneous.

This study proposed to work with lines every 1.5 m, which implies having a line of nebulizers above each crop line, so that, as observed in Table 6, the highest concentration of product occurs on the crop line.

CONCLUSIONS

It was observed that among the nebulizers evaluated, a hydraulic nebulizer, designed for irrigation and/or humidity and temperature control, presented the best performance for pesticide application considering spatial distribution uniformity and operating time.

Considering the flow variations for the lengths evaluated, it is advisable to use 16 mm pipes.

The liquid return system designed allowed filling the system with liquid, applying, and then recover with air the content of the product in the pipes (LLA operating method). This method achieved the greatest uniformity of the volume emitted by the nebulizers along the pipes.

The evaluated nebulization system was not uniform in deposition on the plants, with greater deposits on the upper leaves, on the lower and middle leaves it presents a deposition similar to the sprayer gun. Future studies will require evaluation of the performance of this system in pest control and losses to the soil.

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