

Article

Optimization and Evaluation of Electrostatic Spraying Systems and Their Effects on Pesticide Deposition and Coverage Inside Dense Canopy Plants

Matthew Herkins ¹, Lingying Zhao ^{1,*}, Heping Zhu ², Hongyoung Jeon ²  and Jose Castilho-Theodoro ¹ 

¹ Department of Food, Agricultural, and Biological Engineering, The Ohio State University, Columbus, OH 43201, USA; herkins.4@osu.edu (M.H.); castilhotheodoro.1@osu.edu (J.C.-T.)

² Application Technology Research Unit, Agricultural Research Service, United States Department of Agriculture, Wooster, OH 44691, USA; heping.zhu@usda.gov (H.Z.); hongyoung.jeon@usda.gov (H.J.)

* Correspondence: zhao.119@osu.edu

Abstract: Electrostatic spraying systems can improve the pesticide application efficiency by enhancing droplet deposition and coverage within crop canopies. This study evaluated the droplet size spectra and charge-to-mass ratio (CMR) of five electrostatically charged hollow-cone nozzles and one flat-fan nozzle paired with an electrode. Each nozzle was mounted on a moving boom in a wind tunnel and operated with the electrode and voltage that produced the highest CMR. Their effects on the spray coverage and deposition inside boxwood shrubs at wind speeds of 0 and 2.24 m s^{−1} were assessed. The nozzles operated with the optimized electrode had average improvements in the canopy deposition and canopy coverage of 1.33 μg cm^{−2} and 4.4% at a wind speed of 0 m s^{−1} and 0.26 μg cm^{−2} and 0.9% at a wind speed of 2.24 m s^{−1}. The airborne drift measurements at various heights above the wind tunnel floor showed an average 0.50 μg cm^{−2} reduction in the drift at 0.1 m, variable results at 0.35 m, and minimal changes at heights of 0.7 m and above at a downwind distance of 2 m. These findings highlighted the potential of optimized electrostatic spraying systems to enhance pesticide deposition inside the crop canopy under various wind speeds while reducing the spray drift potential.

Keywords: electrostatic sprayers; pesticides; charge-to-mass ratio; boom sprayers



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1. Introduction

Excessive pesticide usage and drift into the environment have proven to be a challenge for agricultural spray applications, especially in specialty crops. The canopies in specialty crop orchards and vineyards have high amounts of variation between their respective shape, depth, and height, which makes targeted application difficult. In specialty crop orchards, sprays are typically delivered via air-assisted sprayers that generate a spray capable of penetrating dense foliage and provides adequate canopy coverage at the expense of resulting in excessive chemical waste [1,2]. Greenhouse systems often either employ handheld sprayers or boom sprayers for pesticide application. Handheld sprayers offer precise spraying, enabling operators to target individual plants or canopy zones with minimal equipment investment, though they can be labor-intensive and may result in operator fatigue, operator exposure, and inconsistent coverage [3]. Boom sprayers provide uniform, high-throughput coverage across large bench areas and can be automated for timing and volume control, but they require greater capital investment and can increase

the risk of off-target drift if the nozzle selection and operating parameters are not carefully managed [4,5]. Drift reduction is a critical need in both environments, as off-target deposition can damage sensitive adjacent crops or lead to regulatory noncompliance for both orchards and controlled environment settings [6,7]. To address the issues associated with these conventional sprayers, electrostatic sprayers have been investigated for use in agricultural pesticide applications due to their ability to reduce both pesticide usage and drift to the surrounding environment [8–11].

There are three primary methods by which an electrostatic spraying system can charge spray droplets: corona charging, conduction charging, and induction charging [12]. In corona charging, sharp points on an electrode generate corona ions that bombard the spray droplets, which impart electrical charge upon them. Corona charging can be unreliable and typically provides a weaker charge than other spray-charging methods. Conduction charging operates by having the electrode in direct contact with the water being sprayed. This can potentially cause safety issues due to direct electrical contact, including potential short-circuits and higher operating currents. Induction charging functions by producing a strong electric field that charges the spray droplets at a relatively low current. This suggests that induction charging is the safest and most reliable method to charge spray droplets [13,14]. The amount of charge is measured in terms of the charge-to-mass ratio (CMR), which is defined as the amount of imparted electrostatic charge in millicoulombs per kilogram of sprayed droplets. Key design parameters that impact the CMR include the applied voltage, liquid conductivity, mass flow rate, and spray pattern [15].

While the CMR is important, there are several other key parameters that significantly impact the effectiveness of electrostatic spraying systems when delivering pesticides to targeted crop canopies. The spray droplets must be large enough to resist evaporation and drift, but also small enough that the charge can alter the trajectory when they approach the target. Therefore, careful consideration must be given to the distance between the spray nozzle and the canopy to ensure that the droplets can be adequately charged while not being lost due to drift. Additionally, the droplet must reach the target, with previous works finding that the droplet generally has to pass within approximately four centimeters of the target for electrostatic charging to be impactful [16]. This can be problematic when spraying dense canopies since the spray will likely deposit on the first grounded object that it encounters. Additionally, the outer surface of the canopy could prevent spray from penetrating deeper into the canopy. Another factor to consider would be the space cloud effect. Since all the spray droplets would have the same charge, according to Coulomb's law, they would repel each other. This would help the plume expand into the canopy, potentially giving the system more uniform coverage [17]. However, it could also cause the droplets to excessively expand upwards and miss the target. The final major consideration is with regard to the shape, density, and spacing of a crop and its influence on the charged spray. Sharp points, such as the tips of leaves, can distort and concentrate the electric field generated by a charged particle. This can potentially result in an exchange of charges between the leaf tip and the spray, which could potentially neutralize or repel droplets [18].

Canopy deposition and spray drift associated with the use of electrostatic pesticide sprayers are also strongly influenced by the distance between the spray boom and the crop canopy [19]. As the spray distance increases, the electric field strength at the droplet's location diminishes, reducing the effectiveness of electrostatic forces at influencing droplet motion [20]. Furthermore, an increased travel distance allows more time for external forces, such as gravity and wind-induced drag, to alter the droplet trajectories, potentially decreasing deposition. This makes electrostatic spraying most effective at relatively short boom heights, though the spray height must still be sufficient to ensure full canopy coverage. This operational constraint makes electrostatic systems particularly well-suited to orchard

sprayers, greenhouse applications, and small- to medium-scale field operations where the spray can be discharged near the canopy. The efficiency of these systems can also vary based on the chemical composition of the spray solution, including the type of pesticide and adjuvants used. Certain adjuvants, especially those with high ionic strength or surfactant properties that alter droplet conductivity, may interfere with the charge retention or modify droplet formation, thereby influencing the deposition patterns [15,21]. While many electrostatic systems demonstrate broad compatibility, optimizing the performance for specific pesticides or adjuvants may be necessary to achieve the maximum deposition efficiency.

Previous studies on electrostatic pesticide spraying systems have primarily focused on handheld applications, though they have also been employed with pneumatic, air-blast, and boom sprayers [9,22,23]. Handheld electrostatic sprayers, while inexpensive, can suffer from limitations such as inconsistent spray coverage, operator fatigue, and difficulty in reaching higher or denser canopy areas, compromising the uniformity and effectiveness of pesticide application [3]. The use of electrostatic pneumatic sprayers has had mixed results in field conditions and can have problems with excessive drift, making their use tenuous [8,24]. However, these systems have found success in controlled environment conditions to increase the droplet deposition onto roots in aeroponic systems or canopy deposition in controlled environment settings [18,25,26]. Electrostatic boom sprayers can be utilized in many of the same applications as these other sprayers, such as in greenhouses, while offering the advantage of covering large areas more quickly and uniformly [3]. However, the challenge with electrostatic boom sprayers lies in maintaining consistent electrostatic charge across extended spray widths and ensuring effective coverage in varying canopy densities and structures [24,27]. Much of the inconsistent performance reported in previous studies may stem from suboptimal configurations of the electrode size, voltage, and nozzle type, which directly affect the charge-to-mass ratio and droplet behavior. Therefore, identifying and implementing optimal electrostatic settings is essential to improve the spray performance, which would enable better deposition, more uniform coverage, and reduced drift potential under a variety of operating conditions.

The objective of this study was to develop an optimized electrostatic pesticide nozzle for boom sprayers to enhance the spray canopy deposition and minimize the spray drift potential. The specific goals were to (1) determine the effects of the applied voltage, electrode geometry, and nozzle selection on the CMRs of spray droplets; (2) optimize the design and operation conditions of an electrostatic spraying system; and (3) evaluate the performance of the electrostatic spraying system with the optimal electrostatic settings on the spray deposition, coverage, and drift potential under wind tunnel conditions.

2. Materials and Methods

2.1. Measurement of Droplet Size Distribution

The droplet size distribution across the entire spray pattern discharged from each nozzle was measured using a particle/droplet image analysis (PDIA) system (VisiSize N60, Oxford Lasers Inc., Didcot, UK) by following the procedures documented in [28]. A brief description of the procedure is given here. A nozzle was mounted on a stepping motor rail system (VELMEX Inc., Bloomfield, NY, USA) to move it back and forth to measure the droplet sizes of nozzles across the spray pattern while operating the system at 276 kPa. The nozzle was approximately 0.35 m above the droplet size measurement area of the PDIA system. The rail system was set to move at a rate of 2 mm s^{-1} across a 0.35 m range along the centerline of the PDIA system until the sizes of 10,000 droplets were measured. The uniformity of the droplet size distribution was evaluated by examining its relative span,

which was calculated using Equation (1). The schematic and the experimental setup of the spray droplet size measurement are shown in Figure 1.

$$RS = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \quad (1)$$

where RS is the relative span; $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ are the droplet diameters where 10%, 50%, and 90% of the droplet volumes are smaller than this size.

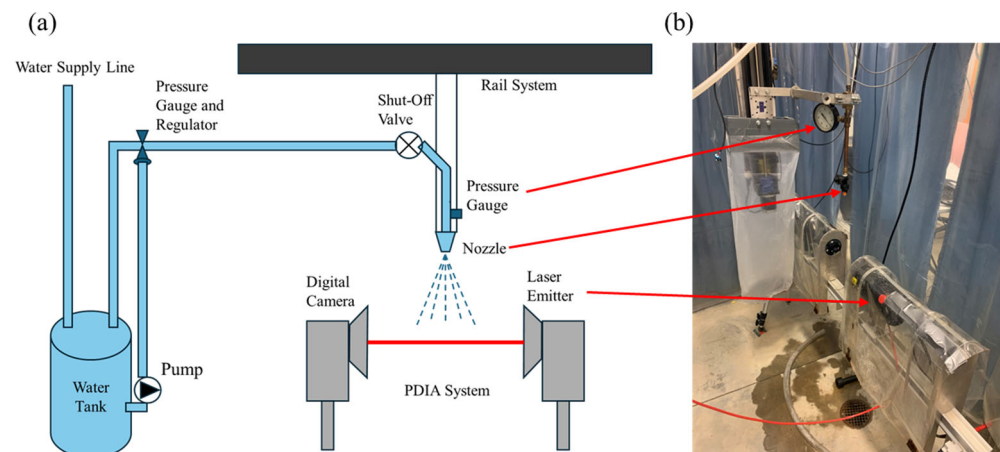


Figure 1. The (a) schematic and (b) experimental setup of the droplet size measurement experiment using a PDIA system.

2.2. Charge-to-Mass Ratio

The electrostatic spraying system used a similar setup to the one that was used to measure the droplet size without the PDIA system. Additional components were also used, including a mounting clamp (Tough-Claw, RAM Mounts, Seattle, WA, USA), 304L stainless steel electrode, high-voltage wire (392050 WH005, AlphaWire, Elizabeth, NJ, USA), high-voltage power supply (AU-60R5-LC, Matsusada Precision, Kusatsu, Japan), electrometer (Model 6514, Keithley Instruments, Solon, OH, USA), and a custom-built 304L stainless steel Faraday pail (Figure 2).

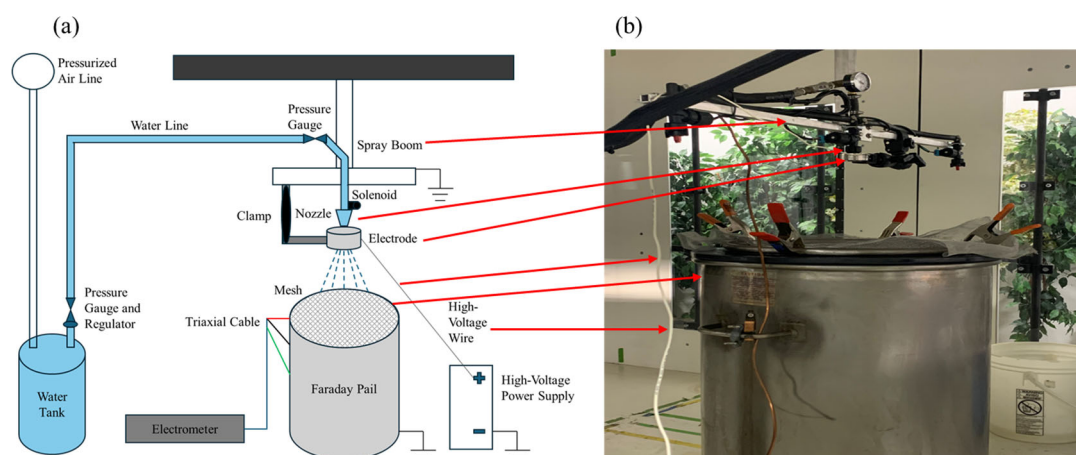


Figure 2. The (a) schematic and (b) experimental setup of the spray charging measurement experiment.

Two 304L stainless steel electrode rings were used in this experiment. The inner diameters of the rings were 50 mm (height of 20 mm, hereafter referred to as an electrode 1) and 100 mm (height of 40 mm, hereafter referred to as an electrode 2). A spray nozzle was positioned to spray at 4 mm below the top of electrode ring 1's center and 8 mm below

the top of electrode ring 2's center while spraying at a pressure of 276 kPa. These spraying heights maximized the droplet residence time within the electrode field without causing significant electrode wetting, which would have otherwise reduced the charging efficiency.

The electrode ring was connected to the high-voltage power supply to electrically isolate it from the rest of the system. The droplets were sprayed downward through the center of the electrode into an aluminum mesh screen that was placed 200 mm below the bottom of the electrode. The aluminum mesh was attached to the top of the Faraday pail using metal clamps to help collect the droplets and reduce the drift. The Faraday pail was placed inside a larger grounded 304L stainless steel vat. Electrical isolation of the pail was maintained between these vats using a PVC spacer. An electrometer was connected to the Faraday pail with a low-noise triaxial cable that connected the inner vat of the pail, the outer vat of the pail, and the ground. When the charged droplets impacted onto the inner vat, they imparted their charge to the inner vat. This caused a current to flow between the inner and outer vats, which was measured and recorded by the electrometer every second for 5 s. The CMR for each electrostatic spray setting was calculated with Equation (2):

$$CMR = \frac{I}{\rho Q} \quad (2)$$

where CMR is the charge-to-mass ratio (mC kg^{-1}); I is the average electric current (A); ρ is the density of water (kg m^{-3}); and Q is the average volumetric flow rate of the nozzle ($\text{m}^3 \text{s}^{-1}$).

Table 1 shows the values of the varied parameters to determine the CMRs for this experiment. Each spray nozzle was operated at a pressure of 276 kPa to ensure that the droplets would be classified as “fine” according to ASABE standard S572.1 [29]. All of the spray nozzles used ceramic spray tips due to their high durability and decreased wear [13]. All the selected nozzles delivered an 80° hollow-cone spray pattern. The only exception was the TP11001VK nozzle, which delivered a 110° flat-fan spray pattern, which was also tested due to its high CMR in a previous study [15]. Positive DC voltages between 4 and 20 kV were tested to ensure that a strong electric field would develop without excessive amounts of corona forming [30].

Table 1. Tested values of the voltage and electrode diameter to determine the maximum charge-to-mass ratio from 5 hollow-cone nozzles and 1 flat-fan nozzle.

Factors	Parameters
Nozzle	TXVK-6, TXVK-12, TXVK-18, TXA8001VK, ALBUZ ATR 80, TP11001VK
Applied Voltage (kV)	4, 8, 10, 12, 14, 16, 18, 20
Electrode Diameter (mm)	50, 100

The volumetric flow rate of the nozzle, which is shown in Table 2, was measured three times before each series of tests by capturing the nozzle output in a SpotOn sprayer calibrator (SC-2, Innoquest, Woodstock, IL, USA). The application rate for a chemical using a particular nozzle with the parameters laid out in this experiment was calculated using Equation (3):

$$AR = \frac{600Q}{R \times TS} \quad (3)$$

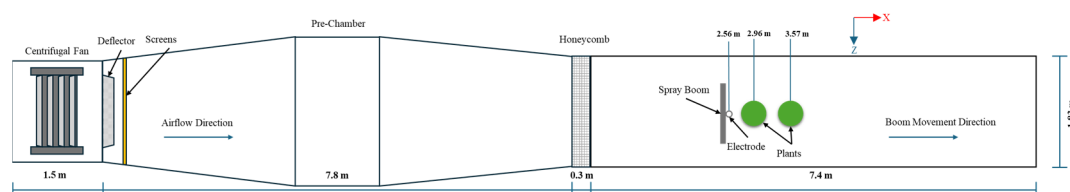
where AR is the chemical application rate (g ha^{-1}); Q is the flow rate (L min^{-1}); RS is the crop row spacing (m); and TS is the travel speed (km h^{-1}).

Table 2. Measured flow and chemical application rates from 5 hollow-cone nozzles and 1 flat-fan nozzle (L min^{-1}).

Nozzle	Flow Rate (L min^{-1})	Chemical Application Rate (g ha^{-1})
TXVK-6	0.38	233.31
TXVK-12	0.76	466.63
TXVK-18	1.15	706.08
TXA8001VK	0.37	227.18
ALBUZ ATR 80	0.34	208.76
TP11001VK	0.39	239.45

2.3. Wind Tunnel Tests

Experiments were performed in a low-speed wind tunnel to evaluate the effectiveness of using an electrostatic spraying system with the highest CMR setup (Figure 3). Each nozzle was mounted at the center of a spray boom 0.35 m above the top of a grounded boxwood plant (*Buxus* “Green Mountain”) and was set to move at a speed of 0.89 m s^{-1} for three seconds using a motion controller (PMC-2TU, Autonics, Mundelein, IL, USA) and a nozzle timer. Boxwood evergreen shrubs were used as target plants during this experiment due to their hardiness, slow rate of growth, and ability to maintain their shape. A total of two shrubs were used for testing and were placed in the center of the wind tunnel directly below the nozzle at a distance of 0.61 m apart. The same two shrubs were used for all of the tests throughout the experiment to minimize the measurement variability.

**Figure 3.** Top-down schematic of the wind tunnel.

The environmental conditions in the wind tunnel were measured using a VelociCalc (9545-A, TSI Inc., Shoreview, MN, USA). The average temperature throughout testing was measured as $15.6 \text{ }^{\circ}\text{C} \pm 2.3 \text{ }^{\circ}\text{C}$. During the droplet diameter, CMR, and canopy coverage and deposition tests conducted at a wind speed of 0 m s^{-1} , the air velocity was consistently measured at $0.0 \pm 0.0 \text{ m s}^{-1}$. When the wind tunnel was operated at a frequency of 12.5 Hz, the resulting wind speed was recorded as $2.24 \pm 0.13 \text{ m s}^{-1}$. The leaf area index (LAI) of the boxwood canopy was measured with five replications using a LI-COR Plant Canopy Analyzer (LAI-2200C, LI-COR Environmental, Lincoln, NE, USA). The LAI and measurements of important canopy characteristics are in Table 3.

Table 4 shows the values of the parameters that were varied for this experiment to determine the canopy deposition and spray drift. The canopy deposition and drift that resulted from the use of all the selected nozzles were evaluated under the condition in the CMR testing, which resulted in the overall highest CMR, which was at 20 kV using electrode 1. Three replications were performed for each spraying configuration at wind speeds of 0 and 2.24 m s^{-1} , which are representative of typical spray conditions in a greenhouse or field.

Table 3. Canopy characteristics of boxwood plants.

	Plant 1	Plant 2
Pot Height (m)	0.23	0.23
Pot Width (m)	0.25	0.25
Trunk Height (m)	0.06	0.05
Trunk Width (m)	0.04	0.04
Canopy Height (m)	0.45	0.48
Canopy Width (m)	0.28	0.35
Canopy Depth (m)	0.30	0.32
Leaf Area Index	2.74	3.84
Leaf Length (m)	0.02	0.02
Leaf Width (m)	0.01	0.01

Table 4. Tested nozzles, voltages, and wind speeds used to evaluate canopy deposition and drift in boxwood plants.

Factors	Parameters
Nozzle	TXVK-6, TXVK-12, TXVK-18, TXA8001VK, ALBUZ ATR 80, TP11001VK
Applied Voltage (kV)	0, 20
Wind Speed (m s^{-1})	0, 2.24

Canopy Deposition and Coverage

A procedure similar to the one performed by previous studies was used to determine the deposition and coverage on these targets [31,32]. Brilliant Sulfaflavine (BSF) was mixed with water to achieve a 2 g L^{-1} concentration to measure the spray deposition on the spray targets. Acrylic plates (26 mm (height (H)) $\times$ 76 mm (width (W))) were used to collect the droplets at four locations within the canopy of each boxwood plant, while 38 mm diameter stainless steel meshes were used to collect airborne droplets at the outlet of the wind tunnel as an indicator for the potential airborne drift (Figure 4). The plates or meshes were placed side by side with the water-sensitive papers (203011N, 26 mm (H) $\times$ 76 mm (W), TeeJet Technologies, Glendale Heights, IL, USA) at each sampling location, which was used to determine the coverage. To prevent contamination, the plant was trimmed so that the samples would not come into contact with the plant prior to testing. Additionally, the clamps holding the samples were wiped down between the tests. Three replicates were performed for each spraying configuration during this experiment.

After spraying, all the samples were collected after approximately a five-minute drying period and were transferred to the laboratory for analysis. The collected meshes and acrylic plates were put in 120 mL glass bottles and washed using 20 mL distilled water. The bottles were then secured and placed on an open-air orbital shaker (Solaris SK4000, Thermo Scientific, Waltham, MA, USA) operated at 200 rpm for two minutes. After this, each rinsate was transferred to a cuvette to read the fluorescent intensity of each sample using a pre-calibrated fluorimeter (Trilogy Laboratory Fluorimeter, Turner Designs, San Jose, CA, USA). The water-sensitive papers were scanned using an HP Scanjet (G4050, HP Inc., Palo Alto, CA, USA) at 600 dpi and the coverage was analyzed using DepositScan version 1.2 [33].

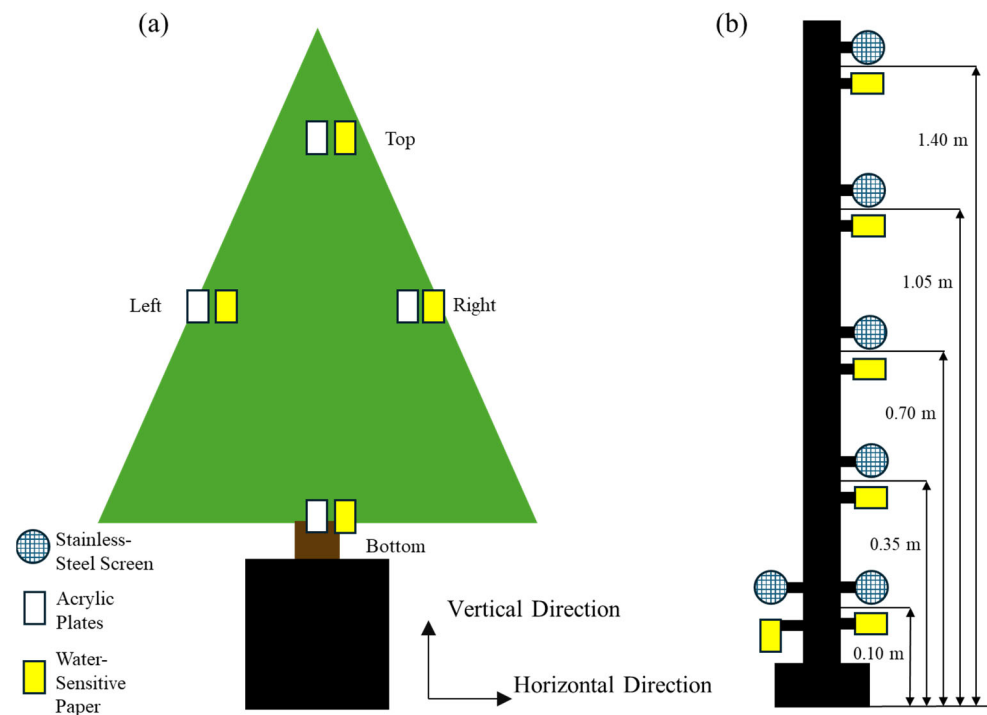


Figure 4. Schematic of target positions for (a) canopy and (b) potential airborne drift.

2.4. Data Analysis

Statistical analyses were conducted using JMP 17.0 software (SAS Institute, Cary, NC, USA) with a significance level of 0.05. Analysis of Variance (ANOVA), Tukey–Kramer tests, and pairwise Student’s *t*-tests were performed to compare the charge-to-mass ratios across the tested voltages for each electrode and nozzle. These tests were also used to evaluate the differences in the canopy deposition, canopy coverage, and airborne drift between the selected nozzles, wind speeds, and charging conditions. Additionally, a standard least squares regression analysis was employed to develop a linear regression model for predicting the average deposition within a crop canopy using hollow cone nozzles. The predictor variables included the applied voltage, air velocity, CMR, volume median diameter, and flow rate, and incorporated full factorial interactions and second-order polynomial terms. To verify the assumptions of linear regression, a Shapiro–Wilk test and a Levene test were performed to ensure the data was normally distributed with equal variances. Additionally, the trend in the residual plots were examined to see whether the data exhibited homoscedasticity, which indicated that there was equal variance in the residuals. Multicollinearity between independent variables was evaluated using variance inflation factors, while the independence of residuals was assessed using the Durbin–Watson test. The model performance was further evaluated based on goodness-of-fit metrics and the root mean squared error. The Shapiro–Wilk and Levene’s tests yielded *p*-values of 0.061 and 0.19, respectively, indicating that the data did not significantly deviate from normality and exhibit homogeneity of variance across groups. All variance inflation factors ranged between 1 and 5, suggesting no concerning multicollinearity between the predictors.

3. Results and Discussions

3.1. Droplet Size Distribution

Figure 5 presents the cumulative spray volume distributions over the spray droplet sizes of the nozzles evaluated in this study. The TP11001VK nozzle did not conform to the expected cumulative volume pattern observed for hollow-cone nozzles with comparable

flow rates. Instead, its distribution closely aligned with that of the TXVK-18 nozzle, despite the latter having a flow rate nearly three times greater than the TP11001VK. Additionally, it appears that the TP11001VK flat-fan nozzle produced a lower volume of droplets between 125 and 275 μm compared with the hollow-cone nozzles with similar flow rates. This potentially suggests that the difference in droplet size distribution might impact the deposition in an electrostatic system by reducing the concentration of smaller droplets that are optimal for charging.

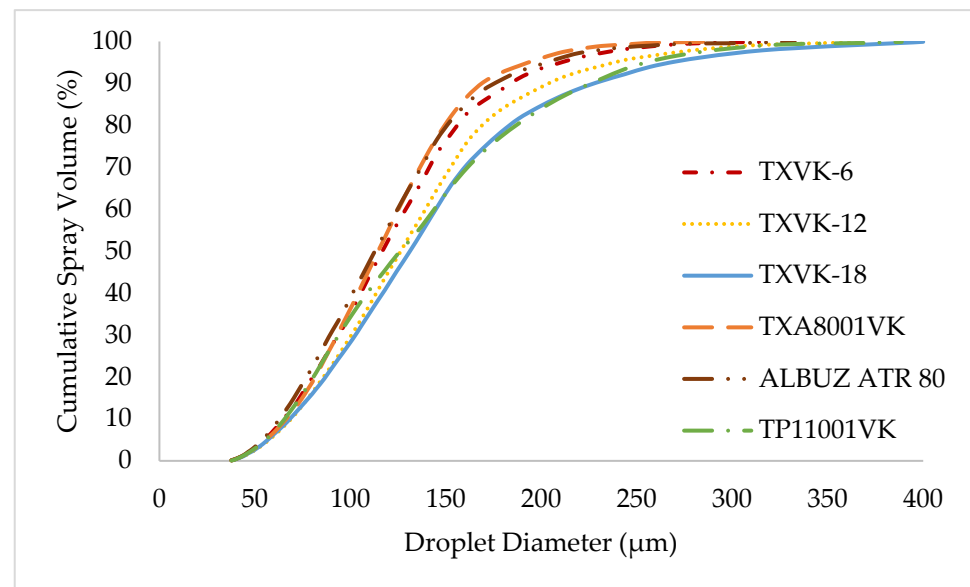


Figure 5. Cumulative spray volume distributions and droplet diameters discharged from 5 hollow-cone nozzles and 1 flat-fan nozzle with 0 kV charging voltage.

Table 5 presents the volumetric droplet diameter distributions and a relative span for each tested nozzle at a charging voltage of 0 kV. To assess the influence of electrostatic charging on droplet size distribution, the same measurements were conducted at 20 kV. No significant differences were observed between the two voltage levels, indicating that the electrostatic charging did not alter the droplet size spectra. The differences in droplet volumetric diameters at the 10th percentile of the cumulative volume curve were relatively minor, with a maximum difference of 5.7 μm between the nozzles. However, at higher percentiles, the disparities in the droplet diameter became more pronounced. Specifically, at the 50th and 90th percentiles, the ALBUZ ATR 80 and TXVK-18 nozzles exhibited differences of 19.1 and 55.4 μm , respectively. This indicates that nozzle performance diverged significantly at the upper end of the droplet size distribution, highlighting the impact of the nozzle design on the droplet size characteristics.

Table 5. Measured droplet diameter distributions and spans produced from 5 hollow-cone nozzles and 1 flat-fan nozzle with 0 kV charging voltage.

Nozzle	Dv _{0.1} (μm)	Dv _{0.5} (μm)	Dv _{0.9} (μm)	Relative Span
TXVK-6	67.0	121.3	193.8	1.04
TXVK-12	72.7	133.0	214.8	1.07
TXVK-18	71.9	138.1	240.4	1.22
TXA8001VK	70.0	120.8	178.6	0.90
ALBUZ ATR 80	66.4	118.9	185.0	0.97
TP11001VK	69.1	133.0	237.8	1.27

3.2. Charge-to-Mass Ratio Analysis

Figure 6 displays the mean CMR for all the tested nozzles across the range of applied voltages. The CMR exhibited a generally linear increase with voltage, followed by a plateau between 16 and 20 kV, which is consistent with findings from previous studies [34]. The ALBUZ ATR 80 and TXVK-6 nozzles demonstrated the highest CMR values, where they achieved -0.429 and -0.434 mC kg⁻¹, respectively, when using electrode 1 at 20 kV. In contrast, the TXVK-12 and TXVK-18 nozzles produced the lowest CMR values under optimal conditions, with -0.216 and -0.163 mC kg⁻¹ at 20 and 16 kV, respectively. These differences were likely driven by variations in the droplet size: nozzles that produced finer sprays consistently yielded higher CMRs than those that generated coarser droplets. This can be attributed to the greater surface-area-to-mass ratio of smaller droplets, which enhanced the charge transfer efficiency by exposing more surface area to the electric field during charging. Moreover, finer charged sprays tend to have reduced coalescence, which likely reduced the charge neutralization and helped to preserve the net charge [35]. The use of electrode ring 1 consistently resulted in higher CMR values across all nozzles. The maximum CMR was generally observed at 20 kV, except for the TXVK-18 with electrode 1 and the TXVK-6 with electrode 2, which both performed optimally at 16 kV. This behavior could be attributed to the onset of a corona discharge when water droplets accumulated within the electrode, which potentially weakened the electric field strength and reduced the CMR [36].

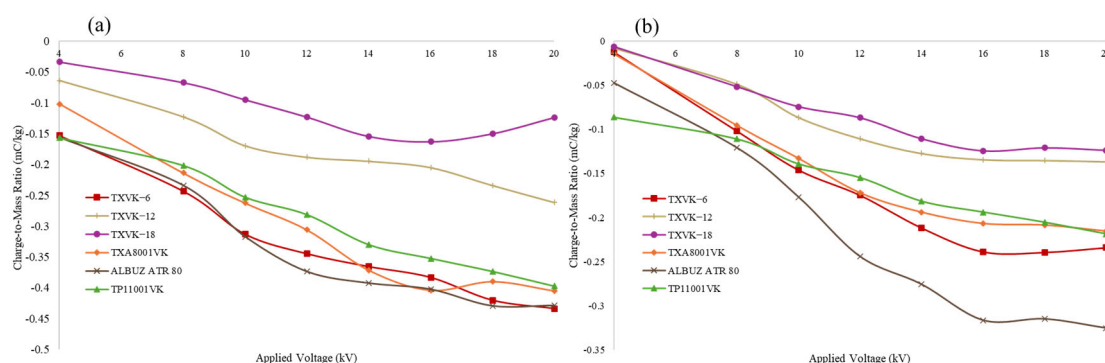


Figure 6. CMRs produced by 5 hollow-cone nozzles and 1 flat-fan nozzle using (a) electrode 1 and (b) electrode 2.

3.3. Spray Deposition and Drift Analysis

3.3.1. Spray Coverage and Deposition

Table 6 presents the average coverage and deposition on samples placed within two plant canopies at a wind speed of 0 m s^{-1} . Notably, the coverage across all the tested canopy targets exhibited average relative increases from 24.6% to 56.5% when the nozzles were electrostatically charged. Correspondingly, the average relative increases in canopy deposition for these nozzles ranged from 74.2% to 239.5% under the same conditions. The coverage and deposition were generally the highest at the top of the canopy. An exception was observed with the TXA8001VK nozzle at 20 kV, where the bottom position recorded the deposition to be $0.04 \mu\text{g cm}^{-2}$ higher than the top. Although the coverage consistently ranked lowest at the bottom of the canopy, the deposition patterns did not always align, especially when the electrostatic spraying system was used. This may have occurred due to the formation of vortices or turbulence at the base of the plant, which resulted from the interaction between the airflow and plant canopy. In these scenarios, the deposition at the bottom often ranked as the second highest, following the top. The deposition for all of the nozzles with the electrostatic system at a wind speed of 0 m s^{-1} were found to be significantly higher than a non-electrostatic nozzle ($p \leq 0.05$). However, the coverage

for the nozzles with and without the electrostatic system had statistically insignificant differences ($p > 0.05$), although the nozzles with the electrostatic system had consistently higher coverage compared with the nozzles without the system. This observation could potentially be explained by the localized accumulation and coalescence of charged droplets, which might lead to higher concentrations of active material on specific targets despite the lower overall spray coverage. The non-uniform distribution suggests that droplets, when attracted to target areas, may accumulate and merge, enhancing deposition in those zones. Additionally, differences in measurement approaches, where the visual spray coverage may not capture the intensity of deposition measured quantitatively, might further contribute to the apparent discrepancy between the coverage and deposition levels.

Table 6. Canopy coverage and deposition at the top, center, and bottom positions of a boxwood canopy from 5 hollow-cone nozzles and 1 flat-fan nozzle charged at 0 and 20 kV at a wind speed of 0 m s^{-1} .

Nozzle	Position	Coverage (%)		Deposition ($\mu\text{g cm}^{-2}$)	
		0 kV	20 kV	0 kV	20 kV
TXVK-6	Top	24.4 (3.4)	28.8 (4.0)	1.76 (0.26)	2.60 (0.61)
	Left	11.8 (9.0)	17.6 (7.2)	0.17 (0.09)	0.90 (0.54)
	Right	4.5 (4.4)	5.6 (1.2)	0.41 (0.09)	1.43 (0.38)
	Bottom	0.7 (0.6)	3.1 (1.0)	0.55 (0.07)	1.90 (0.18)
TXVK-12	Top	42.4 (10.4)	42.5 (10.8)	3.65 (0.62)	3.91 (0.37)
	Left	14.3 (5.2)	21.6 (5.2)	0.16 (0.04)	1.32 (0.19)
	Right	8.5 (2.0)	16.7 (5.0)	0.63 (0.14)	1.38 (0.30)
	Bottom	1.7 (1.6)	6.6 (2.6)	0.76 (0.13)	2.46 (0.36)
TXVK-18	Top	45.4 (5.2)	55.9 (4.8)	3.74 (0.18)	4.60 (0.47)
	Left	16.0 (3.6)	18.2 (3.4)	0.22 (0.06)	1.37 (0.12)
	Right	4.2 (1.6)	6.9 (2.0)	1.13 (0.13)	1.98 (0.46)
	Bottom	2.8 (1.8)	4.2 (2.0)	0.46 (0.01)	2.29 (0.24)
TXA8001VK	Top	24.1 (2.8)	28.3 (4.2)	1.63 (0.05)	3.08 (0.31)
	Left	9.8 (3.0)	13.9 (1.2)	0.14 (0.02)	1.56 (0.36)
	Right	1.75 (0.8)	6.3 (2.0)	0.46 (0.04)	1.64 (0.45)
	Bottom	0.6 (0.4)	2.8 (1.2)	0.55 (0.01)	3.16 (0.41)
ALBUZ ATR 80	Top	26.5 (4.8)	36.0 (8.2)	2.27 (0.46)	3.12 (0.53)
	Left	10.6 (4.8)	16.3 (6.6)	0.93 (0.30)	2.03 (0.44)
	Right	2.5 (2.4)	7.4 (1.8)	0.77 (0.09)	2.20 (0.32)
	Bottom	0.4 (0.4)	2.6 (1.0)	1.14 (0.17)	2.99 (0.59)
TP11001VK	Top	18.2 (4.0)	23.8 (6.2)	1.51 (0.17)	3.10 (0.23)
	Left	9.2 (3.0)	14.4 (3.6)	0.60 (0.11)	2.34 (1.06)
	Right	2.4 (1.6)	6.8 (1.6)	0.61 (0.05)	2.45 (0.12)
	Bottom	0.3 (0.2)	2.1 (1.4)	0.32 (0.09)	2.43 (1.08)

The values in the table indicate the mean (standard deviation).

Considering the amount of spray applied and its distribution within the canopy, the ALBUZ ATR 80 nozzle demonstrated the highest average canopy deposition and coverage relative to its flow rate when using the electrostatic spraying system, with values of $2.59 \mu\text{g cm}^{-2}$ and 15.6%, respectively, between the nozzles tested. Similarly, the TP11001VK nozzle

showed substantial deposition and coverage, with values of $2.58 \mu\text{g cm}^{-2}$ and 11.8%. These results suggest that the use of nozzles that produced a finer spectrum of droplets, which corresponded to a higher CMR, will result in a higher deposition and coverage relative to their flow rates, making them a suitable choice for use on electrostatic pesticide spraying systems. However, this increase likely comes with an increased risk of airborne drift.

Additionally, it should be noted that there were several sampling points, typically located at the bottom of the canopy, where the coverage appeared to be low relative to the canopy deposition. This discrepancy could have resulted from the dense and irregular foliage of the boxwood plants, which could have disrupted the airflow and created variability in the droplet impaction and runoff across the canopy. These variations within the plant structure could lead to inconsistencies between the deposition and coverage measurements at specific sampling points. It is also possible that a few large droplets could have fallen on the deposition targets located at the bottom of the canopy from the upper section, which potentially inflated the measured deposition. It is also possible that there could have been potential sample contamination from droplet splash or runoff. Although even if this did occur, there was still a strong trend indicating the electrostatic spraying system performed better than the conventional spraying system.

Table 7 presents the average canopy coverage and deposition on samples collected from two plant canopies at a wind speed of 2.24 m s^{-1} . The use of the electrostatic spraying system resulted in average relative increases in the canopy coverage that ranged from 6.9% to 34.4%. Similarly, the average relative increase in the canopy deposition for these nozzles ranged from 21.4% to 183.9%. The highest levels of coverage and deposition were consistently observed at the top of the canopy, whereas the middle and bottom canopy positions exhibited comparable deposition levels. However, the coverage on the bottom targets was consistently lower than that on the middle targets. Additionally, the deposition and coverage varied more between the two plants compared with the results obtained at 0 m s^{-1} wind speed. Notably, the plant located farther from the initial spray release exhibited a higher deposition and coverage, particularly at the top of the canopy, compared with the plant closer to the spray source. This disparity contributed to the high amount of variance in the data.

The use of a TXVK-18 nozzle resulted in the highest deposition and coverage when the electrostatic system was active at all the tested points compared with the other nozzles. This nozzle produced larger droplets with higher inertia compared with the other tested nozzles, which made them less susceptible to wind-induced drift and more capable of maintaining their initial trajectory [37]. Consequently, this allowed them to better penetrate the canopy and reach the inner and lower canopy sections. Furthermore, these larger droplets experienced a stronger gravitational settling force, which likely enhanced the vertical transport through the canopy layers, even under moderate wind conditions. Under such wind conditions, inertial and gravitational forces are likely more impactful than the electrostatic forces, which explains the reduced relative impact of electric charging on the droplet deposition and coverage in the middle and bottom sections of the canopy compared with when there was no wind. However, despite a lessened impact, the effect of charging the spray droplets was still found to significantly increase ($p \leq 0.05$) the deposition, especially for the nozzles that produced smaller droplets, such as the ALBUZ ATR 80. Gravitational forces combined with electric charging contributed to the observed improvement in the deposition and coverage for the TXVK-18, particularly at elevated wind speeds, where aerodynamic dispersion tends to reduce the ability of smaller droplets to reach the crop canopy.

Table 7. Canopy coverage and deposition at the top, center, and bottom positions of a boxwood canopy from 5 hollow-cone nozzles and 1 flat-fan nozzle charged at 0 and 20 kV at a wind speed of 2.24 m s^{-1} .

Nozzle	Position	Coverage (%)		Deposition ($\mu\text{g cm}^{-2}$)	
		0 kV	20 kV	0 kV	20 kV
TXVK-6	Top	16.0 (11.5)	17.1 (11.8)	0.85 (0.13)	0.99 (0.41)
	Left	3.4 (2.3)	3.7 (2.3)	0.08 (0.02)	0.11 (0.03)
	Right	1.1 (1.1)	2.4 (1.5)	0.06 (0.09)	0.26 (0.25)
	Bottom	0.8 (0.7)	1.3 (0.3)	0.14 (0.08)	0.43 (0.22)
TXVK-12	Top	25.3 (16.7)	27.6 (18.2)	2.17 (1.24)	2.22 (1.20)
	Left	5.6 (3.5)	5.2 (2.1)	0.14 (0.03)	0.40 (0.26)
	Right	2.4 (1.2)	3.3 (1.9)	0.13 (0.03)	0.40 (0.19)
	Bottom	1.4 (0.3)	2.0 (0.4)	0.13 (0.02)	0.47 (0.23)
TXVK-18	Top	39.7 (22.2)	41.1 (24.2)	2.82 (1.38)	3.12 (1.61)
	Left	10.2 (4.1)	11.2 (4.4)	0.37 (0.09)	0.58 (0.11)
	Right	2.9 (1.9)	3.8 (2.1)	0.68 (0.30)	0.76 (0.39)
	Bottom	3.0 (0.5)	3.6 (0.4)	0.32 (0.07)	0.63 (0.27)
TXA8001VK	Top	13.5 (11.2)	15.0 (11.0)	0.83 (0.52)	1.22 (0.61)
	Left	2.0 (1.5)	2.3 (1.5)	0.01 (0.00)	0.56 (0.48)
	Right	0.8 (0.3)	1.8 (0.8)	0.03 (0.01)	0.19 (0.10)
	Bottom	0.2 (0.1)	1.0 (0.3)	0.00 (0.00)	0.50 (0.37)
ALBUZ ATR 80	Top	12.4 (9.3)	15.4 (10.9)	0.81 (0.48)	1.15 (0.63)
	Left	1.5 (0.7)	2.3 (1.3)	0.00 (0.00)	0.55 (0.32)
	Right	1.1 (1.0)	2.2 (2.0)	0.11 (0.04)	0.29 (0.15)
	Bottom	0.4 (0.1)	0.8 (0.2)	0.03 (0.01)	0.49 (0.35)
TP11001VK	Top	15.6 (7.7)	17.2 (8.6)	1.02 (0.43)	1.29 (0.58)
	Left	2.4 (0.7)	2.9 (1.5)	0.07 (0.03)	0.21 (0.02)
	Right	1.1 (0.4)	1.7 (0.7)	0.28 (0.26)	0.34 (0.13)
	Bottom	0.5 (0.4)	0.8 (0.7)	0.02 (0.00)	0.18 (0.07)

The values in the table indicate the mean (standard deviation).

When comparing the canopy deposition at wind speeds of 0 and 2.24 m s^{-1} , a marked reduction in performance was observed across all the canopy levels when using the electrostatic spraying system. Specifically, depositions on the top, middle, and bottom sections of the canopy decreased by 53.2%, 76.6%, and 81.9%, respectively, at 2.24 m s^{-1} relative to 0 m s^{-1} . Similarly, the spray coverage was reduced by 39.0%, 70.1%, and 56.2% at these respective positions. This decline in deposition and coverage was more pronounced for nozzles that produced finer droplets. For instance, the ALBUZ ATR 80 nozzle exhibited average relative decreases in the deposition and coverage of 76.6% and 61.1%, respectively, compared with 56.0% and 31.0% for the TXVK-18 nozzle. Despite the observed efficacy of the electrostatic system at higher wind speeds, the substantial reductions in the deposition and coverage suggest that the performance may be significantly lessened under field conditions with higher wind speeds. These findings highlight the need for system optimization when used under non-still air environments and suggest that electrostatic spraying may be

more suitably applied in controlled environments, such as greenhouses, where the airflow can be more tightly regulated.

3.3.2. Linear Regression Model to Predict Canopy Deposition

Since these assumptions were satisfied, a linear regression model was developed to evaluate the average deposition within a crop canopy for both the conventional and electrostatic hollow-cone nozzles to identify the key variables that influenced the deposition and their significance (Equation (3)):

$$\text{Deposition} = 38.036 - 0.3681 \times FR - 0.2997 \times VMD \times CMR - 1.1212 \times CMR \times WS - 27.518 \times CMR^2 - 8.9255 \times FR^2 \quad (4)$$

where *Deposition* is the average measured deposition in the canopy ($\mu\text{g cm}^{-2}$); *VMD* is the volume median diameter of the droplets (μm); *CMR* is the charge-to-mass ratio of the droplets (mC kg^{-1}); *WS* is the speed of the air (m s^{-1}); and *FR* is the flow rate of the nozzle (L min^{-1}).

The deposition predicted by the model exhibited a strong correlation with the measured deposition values in the boxwood shrubs, which achieved a coefficient of determination of 0.927 and a root mean square error of 0.207. Although based on a limited dataset, the model provides valuable insights into optimizing deposition within crop canopies. Figure 7 shows a scatter plot that compares the experimental and model-predicted values of the canopy deposition in a boxwood plant.

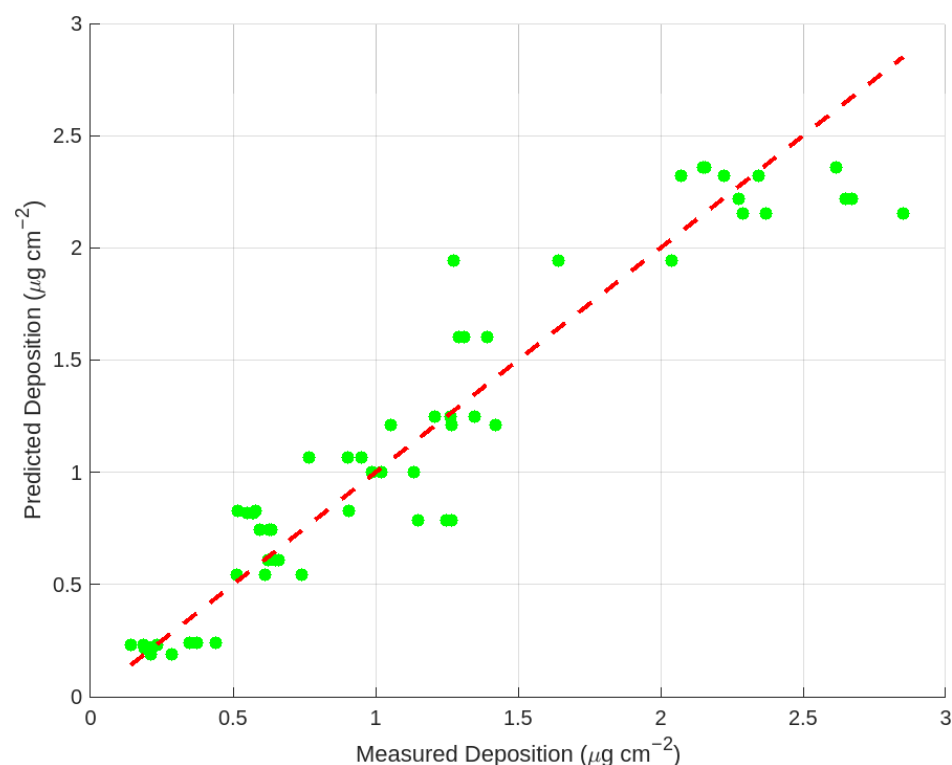


Figure 7. Scatter plot that examines the difference between the measured and linear regression model predicted deposition values in a boxwood plant.

Figure 8 presents a contour plot illustrating the influence of the CMR and volume median diameter (VMD) on the average canopy deposition at wind speeds of 0 and 2.24 m s^{-1} . At 0 m s^{-1} , the canopy deposition generally increased with higher CMR values. This effect was more significant for nozzles that produced droplets with a smaller VMD, as

these droplets had a lower mass and were more susceptible to electrostatic attraction to the canopy elements [30]. At a wind speed of 2.24 m s^{-1} , the average deposition within the canopy was lower, particularly for the nozzles that produced smaller VMD droplets. In contrast, the nozzles that generated larger VMD droplets exhibited significantly better deposition performances. Furthermore, increasing the CMR did not lead to a substantial improvement in the canopy deposition compared with the 0 m s^{-1} wind condition. This suggests that the electrostatic forces responsible for droplet attraction were insufficient to counteract the combined effects of wind-induced inertia and gravitational forces acting on the droplets. These findings indicate that electrostatic spraying systems are likely to be more effective in controlled environments where external factors, such as wind, do not impede their performance.

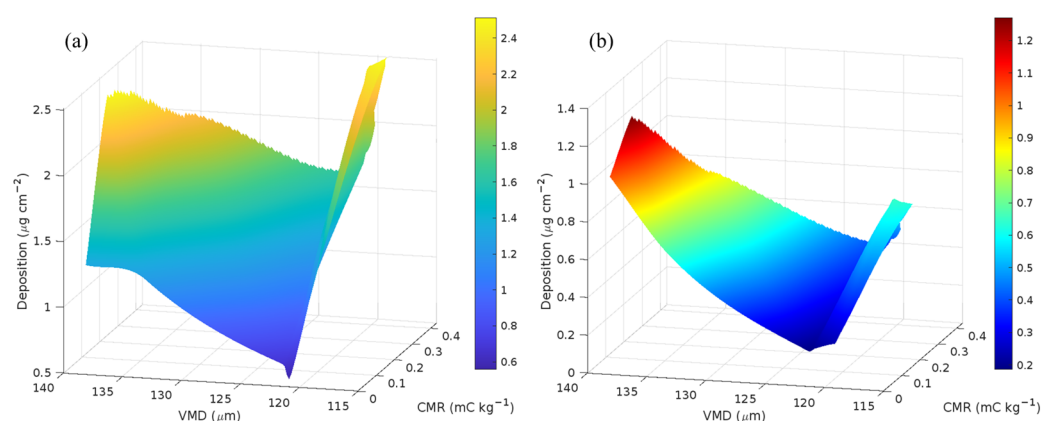


Figure 8. Contour plot of how canopy deposition was impacted by charge-to-mass ratio (CMR) and volume median diameter (VMD) for hollow-cone nozzles at wind speeds of (a) 0 m s^{-1} and (b) 2.24 m s^{-1} .

Additionally, it is important to account for the fact that the hollow-cone nozzles that produced droplets with a larger VMD also had higher mass flow rates. Increased mass flow rates contribute to a higher canopy deposition, as a greater volume of droplets is introduced into the canopy. To isolate the effect of the CMR on the deposition across the nozzles that produced droplets of varying VMDs, the deposition values were normalized by the nozzle's mass flow rate, as shown in Figure 9. At a wind speed of 0 m s^{-1} , the canopy deposition was more strongly influenced by the CMR when smaller-VMD droplets were used. Notably, electrostatic charging had a significant effect only when the nozzle produced droplets with a VMD smaller than 130 µm . This trend was also observed at a wind speed of 2.24 m s^{-1} , though the overall impact of electrostatic charging on the deposition was considerably reduced compared with the 0 m s^{-1} condition.

3.3.3. Potential Airborne Drift

Table 8 presents the average coverage and deposition on drift targets located 2 m downwind at a wind speed of 2.24 m s^{-1} . The use of the electrostatic spraying system resulted in an average relative decrease in the coverage on drift targets at a height of 0.1 m that ranged from 6.1% to 59.8% . Similarly, the average drift deposition at the same height saw decreases that ranged from 29.4% to 76.2% . At a height of 0.35 m , the electrostatic system reduced the relative coverage on drift targets by 3.0% to 59.5% . However, at this height, the drift depositions increased by 100.0% , 11.1% , and 40.9% for the TXVK-6, TXVK-18, and TP11001VK nozzles, while they decreased by 20.5% , 42.7% , and 46.4% for the TVXK-12, TXA8001VK, and ALBUZ ATR 80 nozzles. This discrepancy can be explained by slight differences in factors such as the electrostatic forces, spray angle, droplet trajectory, and initial momentum, which influenced how the droplets traveled and settled at varying

heights. At a height of 0.7 m, the use of the electrostatic system resulted in increased relative coverages on drift targets of 14.3% to 200.0%. However, the drifted deposition at 0.7 m and 1.05 m, as well as the coverage at 1.05 m, showed minimal or no change when the electrostatic system was active.

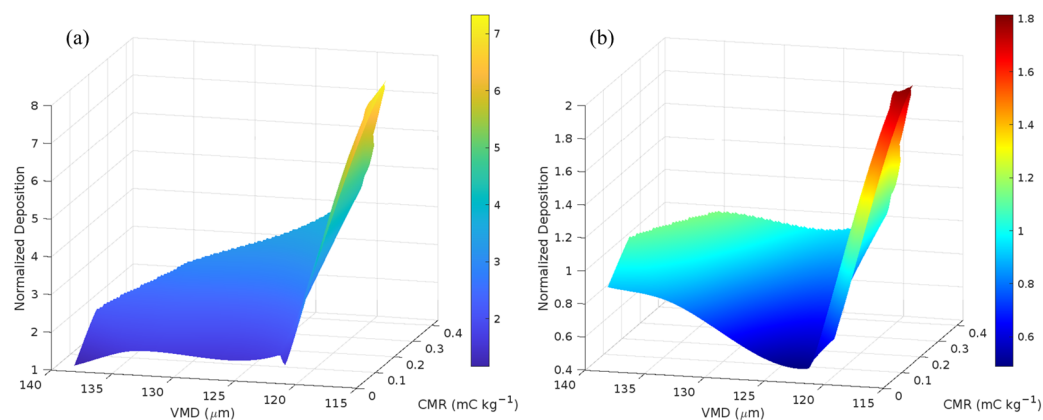


Figure 9. Contour plot of how the canopy deposition divided by the flow rate of the nozzle (normalized deposition) was impacted by the charge-to-mass ratio (CMR) and volume median diameter (VMD) for the hollow-cone nozzles at wind speeds of (a) 0 m s^{-1} and (b) 2.24 m s^{-1} .

Overall, the drifted deposition was inversely related to the height above the ground for both the conventional and electrostatic systems. The data suggest that increasing the applied voltage from 0 to 20 kV likely increased the size and uniformity of the spray plume. As the charged droplets experienced electrostatic repulsion, they were dispersed more widely, which allowed the wind to carry a greater portion of the spray upwards and led to an increased coverage and drift deposition at higher elevations. This redistribution may result in reduced drift deposition at heights below 0.35 m and increased deposition above this threshold. However, the increase in deposition at heights of 0.7 m or higher due to electrostatic charging was not statistically significant ($p > 0.05$), where it was $0.1 \mu\text{g cm}^{-2}$ or less. This suggests that while some electrostatic forces on the charged droplets were sufficient to counteract gravitational settling, most of the droplets still descended relatively quickly after being sprayed.

In non-controlled environments with significant air movement, it is crucial to evaluate both the deposition and drift when selecting the optimal nozzle for a given application. Among all the tested configurations at a wind speed of 2.24 m s^{-1} , the TXVK-18 nozzle at 20 kV exhibited the highest average canopy deposition and coverage across all the canopy positions, with values of $1.27 \mu\text{g cm}^{-2}$ and 14.9%, respectively. In terms of the downwind drift, this nozzle showed the highest drift at a height of 0.1 m and the second highest at 0.35 m. This was likely due to the larger droplets falling more quickly under gravity and the droplet movement due to electrostatic repulsion. The combination of minimal drift and high deposition rates made the TXVK-18 nozzle the most effective performer at a wind speed of 2.24 m s^{-1} . Additionally, it should be noted that to maximize the effectiveness of the electrostatic charging system, it is suggested that the system be operated at low boom heights, as the influence of the electric field diminished rapidly with increased distance between the spray and the target. Consequently, this system is best suited for applications involving crops with relatively uniform canopy heights, where the spray height can be precisely controlled to optimize the deposition and minimize losses due to dispersion.

Table 8. Downwind drift coverage and deposition at heights of 0.1 to 1.05 m above the ground from 5 hollow-cone nozzles and 1 flat-fan nozzle charged at 0 and 20 kV with a wind speed of 2.24 m s^{-1} .

Nozzle	Height (m)	Coverage (%)		Deposition ($\mu\text{g cm}^{-2}$)	
		0 kV	20 kV	0 kV	20 kV
TXVK-6	0.1-Side	5.7 (1.4)	3.5 (0.3)	0.83 (0.08)	0.42 (0.02)
	0.1	40.3 (7.4)	16.2 (2.1)	1.34 (0.10)	0.57 (0.04)
	0.35	33.3 (1.2)	13.5 (1.7)	0.10 (0.03)	0.20 (0.02)
	0.7	4.2 (0.9)	4.8 (1.3)	0.01 (0.0)	0.0 (0.0)
	1.05	0.0 (0.0)	1.7 (0.3)	0.0 (0.0)	0.0 (0.0)
TXVK-12	0.1-Side	7.7 (1.7)	6.2 (0.1)	0.17 (0.03)	0.25 (0.13)
	0.1	35.9 (2.3)	32.7 (4.1)	0.34 (0.09)	0.24 (0.01)
	0.35	25.9 (1.7)	22.6 (3.3)	0.83 (0.09)	0.66 (0.05)
	0.7	4.2 (0.7)	8.9 (1.8)	0.14 (0.06)	0.15 (0.01)
	1.05	0.0 (0.0)	0.9 (0.1)	0.0 (0.0)	0.0 (0.0)
TXVK-18	0.1-Side	7.4 (3.2)	6.6 (2.4)	0.31 (0.10)	0.15 (0.02)
	0.1	37.3 (7.7)	35.0 (1.5)	1.05 (0.06)	0.98 (0.10)
	0.35	23.0 (4.9)	22.3 (2.5)	0.45 (0.03)	0.50 (0.09)
	0.7	1.9 (0.3)	5.7 (0.1)	0.0 (0.0)	0.07 (0.01)
	1.05	0.0 (0.0)	0.7 (0.2)	0.0 (0.0)	0.0 (0.0)
TXA8001VK	0.1-Side	6.5 (1.2)	2.8 (0.1)	0.19 (0.05)	0.07 (0.01)
	0.1	36.0 (2.3)	17.4 (1.1)	1.30 (0.09)	0.74 (0.04)
	0.35	28.5 (4.2)	14.1 (0.6)	0.82 (0.03)	0.47 (0.02)
	0.7	2.9 (0.7)	4.4 (0.4)	0.03 (0.0)	0.23 (0.01)
	1.05	0.0 (0.0)	1.3 (0.1)	0.0 (0.0)	0.0 (0.0)
ALBUZ ATR 80	0.1-Side	6.6 (2.6)	2.9 (0.6)	0.25 (0.01)	0.03 (0.01)
	0.1	34.5 (1.6)	15.2 (1.4)	1.43 (0.11)	0.34 (0.03)
	0.35	29.3 (1.9)	14.2 (2.2)	0.84 (0.06)	0.45 (0.07)
	0.7	3.7 (0.4)	4.4 (0.3)	0.09 (0.01)	0.10 (0.02)
	1.05	0.0 (0.0)	1.6 (0.3)	0.0 (0.0)	0.03 (0.0)
TP11001VK	0.1-Side	4.9 (1.8)	3.9 (0.6)	0.14 (0.04)	0.10 (0.02)
	0.1	31.1 (1.0)	25.2 (0.9)	1.07 (0.16)	0.31 (0.05)
	0.35	25.8 (1.7)	21.5 (1.2)	0.66 (0.02)	0.93 (0.02)
	0.7	2.2 (0.4)	3.6 (0.7)	0.0 (0.0)	0.60 (0.01)
	1.05	0.0 (0.0)	0.8 (0.1)	0.0 (0.0)	0.07 (0.01)

The values in the table indicate the mean (standard deviation).

4. Conclusions

The nozzle selection, charging voltage, and wind speed significantly affected the effectiveness of an electrostatic spraying system. The droplet diameter distribution, CMR, canopy deposition, canopy coverage, and downwind drift were compared for six different spray nozzles under various test conditions. The optimized designs with electrode 1 charged to 20 kV with the ALBUZ ATR 80 and TXVK-6 nozzles yielded the highest CMRs of -0.429 and $-0.434 \text{ mC kg}^{-1}$, respectively. The ALBUZ ATR 80 coupled with the electrode ring 1 charged to 20 kV demonstrated the highest canopy deposition and coverage

throughout the plants at 0 m s^{-1} wind speed, where they averaged $2.59 \mu\text{g cm}^{-2}$ and 15.6%, respectively. While only having a CMR of $-0.402 \text{ mC kg}^{-1}$, the TP11001VK nozzle performed better than the TXVK-6 nozzle, where the canopy deposition and coverage averaged $2.58 \mu\text{g cm}^{-2}$ and 11.8%. At a wind speed of 2.24 m s^{-1} , the TXVK-18 nozzle emerged as the best-performing nozzle, where it delivered the highest average deposition and coverage of $1.27 \mu\text{g cm}^{-2}$ and 14.9%, respectively. The electrostatic system significantly enhanced the canopy deposition, where it achieved average relative increases that ranged from 74.2% to 239.5% and 21.4% to 183.9% at wind speeds of 0 and 2.24 m s^{-1} , respectively. The canopy coverage had a similar trend by increasing the coverage by 24.6% to 56.5% and 6.9% to 34.4% in the same tested conditions. Therefore, electrostatic spraying systems can improve spray deposition for spray boom applications.

Future research should investigate the integration of air-assisted sprayers to further improve canopy penetration and mitigate the decrease in charging potential that could occur due to electrode wetting during prolonged use. Additionally, field experiments should be conducted in environments where electrostatic spraying systems could be viable, such as a greenhouse.

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