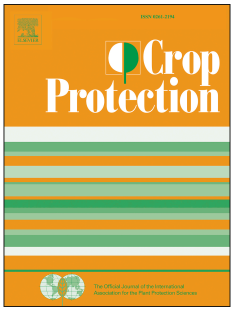

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Evaluation of leaf deposit quality between electrostatic and conventional multi-row sprayers in a trellised vineyard

Ramón Salcedo[a], Jordi Llop[a], Javier Campos[a], Michael Costas[b], Montserrat Gallart[a],
Paula Ortega[a], Emilio Gil[a,*]

[a]Universitat Politècnica de Catalunya, Department of Agri Food Engineering and Biotechnology, Esteve Terradas 8, Campus del Baix Llobregat D4, 08860 Castelldefels, Barcelona, Spain

[b]Department of Agricultural Sciences, Biotechnology and Food Science, Cyprus University of Technology, Arch. Kyprianos 30, 3036, Limassol, Cyprus

*Corresponding author: Prof. Emilio Gil; E-mail: emilio.gil@upc.edu

Abstract

Spray application technologies for specialty crops have developed considerably in recent years with regard to improved control, reduced cost, and ability to avoid environmental contamination. For example, new developments in electrostatic sprayers have been progressively introduced as an alternative for vineyard spray applications. This study investigated the efficiency of this emerging technology in a Spanish trellis vineyard. First, a complete characterization of an electrostatic sprayer was conducted under laboratory conditions. The liquid flow rate was measured using different restrictor configurations to obtain the outgoing air velocities in the diffusers. Second, field trials were conducted in a vineyard testing, two forward speeds (5.9 and 4.7 km h^{-1}, resulting in volume rates of 60 and 75 l ha^{-1}, respectively) and the activated or deactivated electrostatic system. Tartrazine was used as a tracer material to evaluate the spray quality over the canopy. These results were compared with similar trials using a standard multi-row sprayer with orientable outputs at 5.9 km h^{-1} and 190 l ha^{-1}. The results indicated that activated electrostatic treatments resulted in a greater amount of deposition on vegetation than the other trials. The activated system also produced a significant correlation between leaf deposition and forward speed ($p \leq 0.05$). The most homogeneous results were achieved by the activated electrostatic sprayer at 5.9 km h^{-1} and the reference sprayer. These results suggest that electrostatic sprayers could save up to 68% of applied volume with similar or better deposition of the liquid and achieve homogeneity over the whole canopy.

Keywords: electrostatic sprayer, hydro-pneumatic system, efficiency, product distribution, viticulture.

Abbreviations: PPP, plant protection product; CMR, charge-to-mass ratio; VMD, volume median diameter; LWA, leaf wall area.

1. Introduction

Spain is one of world's primary producers of grapes and wine, with more than 9.5 million ha of cultivated land (OIV, 2018) that need to produce high-quality fruits undamaged by biological agents. Despite recent advances in crop protection, numerous pests and diseases continue to affect vineyards (Pfeiffer et al., 2017), requiring the implementation of accurate control measures such as sustainable and precise PPPs. For this reason, many treatments use conventional orchard sprayers based on hydraulic systems for droplet production and air assistance for droplet transport and penetration into the canopy. As different vineyards have different training systems, a wide range of sprayers can be adopted, such as mist-blowers (Grella et al., 2017a), multi-row sprayers (Pergher and Zucchiatti, 2018), or individual outlet sprayers (Miranda-Fuentes et al., 2018). These machines atomize spray liquid using pressure nozzles, distributing the droplets on the vegetation using an artificial air current that moves the leaves, helping the droplets penetrate the internal canopy (Fox et al., 2008). In addition, such sprayers optimize treatment by requiring only a single tractor operator, reducing product loss by runoff, and shortening working time to allow for rapid action as needed (such as during an outbreak).

However, only a portion of the droplets reaches the target vegetation. Some percentage of the application volume is transferred directly to the ground (Grella et al., 2017b), more is lost to the atmosphere as spray or vapour drift caused by wind action

(Gil et al., 2007) and additional losses can occur through runoff (Khot et al., 2012) and rain wash-off (Rial et al., 2003). Of these, spray drift is considered the main source of contamination during treatment because droplets can move beyond the point of application to reach sensitive locations including populated areas, cropland (Otto et al., 2015), and other properties (Pivato et al., 2015), while causing increased economic costs for winegrowers (Ambrogetti et al., 2016).

Growing social awareness and concern for preserving the environment have stimulated important legislative actions promoting highly efficient pesticide applications and reducing the associated risks. This requires further progress toward optimizing such treatments, including researching new technologies and approaches such as the characterization of target vegetation (De Castro et al., 2018), variable rate application based on canopy characteristics (Gil et al., 2013), and the use of electrostatic sprayers (Patel, 2016).

The electrostatic spraying process (Law, 1987) uses an air current to spray liquid into a diffuser. The resulting droplets are then subjected to a positive electric field at the outlet that imbues them with a negative electric charge. The target vegetation has a neutral charge (positive/negative), but as the sprayed droplets approach, their negative charge faces the opposite direction, resulting in a positive charge on the leaves; this directly attracts the particles to both the upper and lower surfaces of the leaves (He et al., 2011).

In conventional sprayers, typical forces acting on droplets include gravity and inertia (Yarin, 2006). As the droplets involved in electrostatic spraying are quite small (Farooq et al., 2010), these forces become negligible and other actions such as surface tension and viscosity predominate (Zhu et al., 2018). In this way, new parameters must be considered when determining efficient application treatments such as droplet charging, charge retention, and the transient effects at the deposition target (Law, 2001).

Compared with conventional air-assisted sprayers, electrostatic sprayers remain relatively expensive for farmers (Tourino et al., 2017) and several parameters must be carefully controlled, such as distance to vegetation and the mass-charge ratio (Zhao et al., 2008; Sasaki et al., 2013). In addition, the effect of leaf shape on particle retention must be considered. In contrast, because an electrostatic sprayer is usually adjusted to spray a lower volume rate than a mist-blower, the resulting treatment losses are reduced; moreover, it improves the homogeneity of distribution and product penetration in the vegetation (Laryea and No, 2003; Jahannama et al., 2005, Maski and Durairaj, 2010;

Yang et al., 2015; Mermer et al., 2016, Patel et al., 2017). In addition, this technology is very versatile and has been previously applied to different types of crops (Arnold et al., 1984; Cayley et al., 1984; Abdelbagi and Adams, 1987; Western et al., 1994; Kabashima et al., 1995; Derksen et al., 2007; Gitirana Neto et al., 2015; Tourino et al., 2017; Tavares et al., 2017; Joseph and Bolda, 2018).

Pascuzzi and Cerruto (2015) conducted field tests with an electrostatic sprayer in vineyards, finding that this could deliver greater deposits on leaves than a traditional air-assisted sprayer. The main significant differences were obtained on the exposed side of the leaves, while no differences between treatments were detected on the other side. They found no effect of different forward speeds on deposition. Although electrostatic spraying has great potential as a pesticide application technique (Post and Roten, 2018), it is necessary to continue improving this technology and to better understand the behaviour of electrostatic droplets in comparison with traditional spraying systems in vineyards (O'Donnell et al., 2017).

The objective of the present study was to characterize and evaluate an electrostatic sprayer equipped with an adapted air system that was designed for a vertical-trellis vineyard. First, the liquid and air distribution of the sprayer was studied in a laboratory. Second, field assays on vineyards were carried out to study the spray distribution over the canopy in different situations. Field trials combined two application volumes with the use or non-use of the electrostatic system. Finally, these data were compared with a conventional multi-row sprayer especially designed for vineyard spray applications.

2. Materials and methods

2.1 Spray application equipment

During the trials, a FEDE Electrostatic air-assisted sprayer was compared with a traditional multi-row sprayer (FEDE Tecnovid Qi 9.0) adapted for vineyard crops (Fig. 1); both were manufactured by Pulverizadores FEDE SL (Cheste, Spain). The sprayers were connected to a Landini Rex 90 (AgriArgo Ibérica, Valladolid, Spain).

[Insert Fig. 1]

The electrostatic sprayer had a tank with a nominal volume of 2000 L connected to four downpipes for applying the pesticide: outer right (OR), inner right (IR), outer left (OL), and inner left (IL) (Fig. 2). A total of 28 diffusers were distributed in groups of 4 and 3 within each downpipe; these were identified as 1 through 7, with 1 being closest to the ground and 7 furthest. Each diffuser had one CP4916-16 stainless-steel flow regulator (Spraying Systems Co., TeeJet Technologies, Springfield, IL, USA) connected to one electrode. In addition, the system was designed with a restrictor mounted in each liquid line (one for each downpipe) to limit the pressure from the sprayer pump. The air system consisted of a centrifugal turbine with a 500 mm diameter. The manufacturer-indicated relative air pressure in the diffusers ranged from 68–74 kPa, controlled by a pressure gauge on the sprayer, for proper control of droplet behaviour.

[Insert Fig. 2]

In addition, this sprayer was equipped with MaxCharge^{TM} technology (Electrostatic Spray Systems, St. Watkinsville, GA, USA) to induce the electric charge in the atomized droplets. During treatment, the compressed airflow generated by the turbine and the liquid from the tank were separately piped into each diffuser. Air and liquid converged in a turbulent process (Law, 1987), forming sprayed droplets smaller than those in a conventional sprayer. These particles were then passed through the charged electrode and applied to the vineyard through the airflow.

Coaxial cylinders were used to induce charge into the droplets. The liquid passed through an internal cylinder without interruption, while the external cylinder consisted of an annular brass electrode generating electric field gradients that transmitted free electrons (Law, 1978; Mamidi et al., 2013). The charged fields ranged from 1000–2000 V m^{-1} with an applied voltage of 1 kV. The capability of the droplets to acquire electrostatic charge per unit mass (CMR) had an approximate average value of 10 mC kg^{-1}.

The reference sprayer was a hydro-pneumatic sprayer adapted to a trellis vineyard. This had four downpipes as well, each with two adjustable outlets having two XR8001 flat fan nozzles (Spraying Systems Co., TeeJet Technologies, Illinois, USA) without restrictors for a total of 16 nozzles. The air system consisted of a centrifugal turbine with a 500 mm diameter. The manufacturer-estimated average velocity at the air outlet was 47.8 m s^{-1} and the airflow rate was 1200 m^3 h^{-1} with the sprayer operating at a PTO speed of 480 r min^{-1}, the manufacturer-recommended value.

2.2 Laboratory tests

Prior to the field assays, the electrostatic sprayer was adjusted and characterized. All tests were carried out at the Laboratory of Agricultural Mechanization at the Agropolis facility of Universitat Politècnica de Catalunya in Viladecans (Spain).

2.2.1 Restrictor selection

An appropriate restrictor was selected prior to the field trials. Two ceramic pellets from Albuz AMT (Saint-Gobain Solcera, Évreux, France) were chosen: AMT-1.0 and AMT-1.5. Thus, different measurements of the liquid flow rates were obtained using a diffuser pressure of 2×10^5 Pa for each case to achieve a nominal liquid flow rate of 110 mL min^{-1}. This value was within the manufacturer-specified pressure range (1.5–300 kPa) for achieving appropriate nozzle charging and efficient spray distribution. Restrictors AMT 1.0 and 1.5 had nominal flow rates of 0.65 and 1.42 L min^{-1}, respectively, at a working pressure of 200 kPa in the diffusers. Therefore, it was necessary in each case to adjust the pressure of the sprayer pump to achieve the desired pressure in the diffusers by means of the restrictors.

For each downpipe, the flow rate of the seven nozzles was measured by a mechanical flow meter (AAMS Salvarani, Maldegem, Belgium) with eight 2000 mL measuring glasses. There were three replications for each restrictor model, resulting in 21 measurements per downpipe (7 nozzles × 3 replications) and 84 for the whole sprayer (21 data × 4 downpipes) per restrictor model. First, the initial pressure in the pump was adjusted to achieve the appropriate pressure in the diffusers because of the limiting effect of the restrictor. Every repetition lasted 60 s. Using the obtained data, an average flow rate closer to the nominal value (110 mL min^{-1}) was chosen, achieving a more uniform distribution. The obtained test values could not deviate more than ±15.0%, in accordance with ISO 16122-3 (ISO, 2015).

2.2.2 Air outlet characterization

The air velocity magnitudes from the outlet diffusers were measured and used to estimate the airflow rate of the sprayer. Each downpipe had seven measurement points (28 total); at each, three repetitions were made using a Meteo Digit I propeller anemometer (Lambrecht Meteo GmbH, Göttingen, Germany) with a 1 Hz frequency. The acquisition time was 60 s at each measurement point. For each repetition, velocities were obtained averaging all values recorded over that time; measurements were obtained from the centre of each diffuser. To calculate the airflow rate, the air outlet hole diameter was considered to be 6 mm. The sprayer was always operated at the manufacturer-recommended 480 r min^{-1} PTO speed. The electrostatic system was disconnected during this test. These air characterizations were based on similar work for air-assisted sprayers adapted to vineyards (Gil et al., 2015; Badules et al., 2018).

2.3 Field experiments

Five field assays were conducted in the viticulture zone of Valencia, an official wine-producing zone in Spain. A representative parcel of 1 ha was selected in Cheste (39°30'25.7"N, 0°41'34.8"W) for the experiments. Vines of the Moscatel variety were planted at distances of 2.0 m along the rows and 2.8 m between the rows, resulting around 1800 plants ha^{-1}. The Double Royat trellis system was adopted, with two wires for each row of vines. The growth stage corresponded to BBCH 19 (Nine or more leaves unfolded), according to Meier (1997). The canopy was characterized before the tests; the mean vegetation height was 0.9 m (total height was 1.6 m) with a width of 0.8 m. Considering the number of tests, five different zones were delimited within the study plot. In total, each treatment covered between 60 and 70 plants.

Following the methodology defined by Pascuzzi and Cerruto (2015), four different trials or treatments were applied using the electrostatic sprayer by combining two forward speeds of 1.3 and 1.6 m s^{-1}, respectively, with the electrostatic system operational or not (Table 1), in order to evaluate the interactions between these factors on the leaf deposit. The same working pressure as that in the laboratory tests (200 kPa) was maintained at the diffusers and remained unchanged across the treatments with the electrostatic sprayer, resulting in two volume rates of 60 and 75 L ha^{-1}. With these working parameters, a VMD of 30–60 µm was expected according to the manufacturer’s specifications.

[Insert Table 1]

In addition, a fifth treatment used the conventional multi-row sprayer with a volume rate of 190 L ha^{-1}. This volume was determined by means of the DOSAVIÑA® decision support system (Gil et al., 2019) for mist-blowers and multi-row sprayers in vineyard crops. This system is based on a modified version of the LWA method (Walklate and Cross, 2012). This volume was also used by local farmers for conventional sprayers. Comparing volumes, the electrostatic sprayer implied a reduction between 60% and 68%. The nominal flow rate for the XR8001flat fan nozzles in these working conditions was 10.4 L min^{-1}. For this case, VMD was estimated at ~150 µm based on experiments performed by Sidahmed (1998) and van de Zande et al. (2008).

The field assays were conducted in accordance with best management practices recommended for safe spray application (TOPPS–Prowadis, 2014), such as a wind velocity < 3 m s^{-1} during application (BOE, 2012). To record weather variables during the field trials, a WatchDog automatic weather station was used (Model 2550, Spectrum Technologies, Inc., USA). The station was placed 25 m downwind from the test pilot at a height of 2.0 m. The mean wind velocity during the static trials was 0.9 m s^{-1}, and the mean direction was 213° relative to the travel direction of the sprayer. The mean temperature and relative humidity were 14.9 °C and 47.1%, respectively.

Leaf deposition was calculated using real vine leaves as natural collectors, following methodology used in previous vineyard assays (Gil et al., 2007; Gil et al., 2011). Owing to the difficulty of completely randomising the sampling zones, nine vines were selected along the two treated canopy rows, four in one row and five in the other (Fig. 3a). For each plant, the total canopy height was divided into three equal parts with 0.3 m steps from 0.7 m to 1.6 m representing the bottom, central, and top parts of the canopy (Fig. 3b). Every section was then subdivided into three depths within the canopy: external left (Ext-L), centre, and external right (Ext-R). This procedure resulted in a total of nine sections (3 heights × 3 depths) covering the entire canopy of a vine. From each section, 2–4 leaves (depending on size) were carefully collected randomly after spraying and placed in individual closed plastic bags.

[Insert Fig. 3]

A water-based solution of the yellow dye Tartrazine (E-102) with a concentration of 4.0 g L^{-1} was used in all assays. Tartrazine is considered suitable for deposit assessment because it is non-toxic, involves simple laboratory procedures, has a high recovery rate, and it is relatively photostable (Pergher, 2001). After each treatment, the tracer amount deposited per unit leaf area (µg cm^{-2}) was determined based on previously used methodology (Gil et al., 2007; Landers, 2008; Gil et al., 2011). ~20 mL of deionised water was added to the plastic bag for tracer extraction. After 1 min of mixing, a sample was drawn and measured with a colorimeter (Thermo Scientific Genesys 20, Thermo Fisher Scientific Inc., Waltham, USA) at a wavelength of 427 nm.

At the beginning and end of every treatment, samples from the tank were extracted to normalize the results.

2.4 Sample analysis

The leaf area of each sample was calculated to convert the tracer concentrations into tracer amount per unit leaf surface. Individual leaf areas were determined by the weight ratio (Cross et al., 2001; Gil et al., 2007; Gil et al., 2011). All ratios were obtained by measuring the weights and surface areas of 30 samples previous to the assays and from the bottom, middle, and top parts of the canopies (Fig. 4). The surface area (only on one side) was calculated with a LI-COR LI 3100C electronic planimeter.

[Insert Fig. 4]

The amount of tracer deposited on each sample was determined by dividing the water solution volume to extract the tracer by the area of the collector, as proposed by Gil et al. (2007) and Llorens et al. (2010):

$$d = (T_{cl} \times w)/S_a \tag{1}$$

where d is the actual deposit (µg cm^{-2}), T_{cl} is the tracer concentration in the washing solution of the sample (mg L^{-1}), w is the deionized water volume (mL), and S_a is the sample surface area (cm^2).

Since the tracer concentration in the tank could change between treatments, the normalized deposition was calculated following the methodology for vineyards previously proposed by Gil (2001) and Llorens et al. (2010):

$$d_n = 10^5 \times d/(V \times T_{cs}) \tag{2}$$

where d_n is the normalized deposit (µg cm^{-2} leaf/µg cm^{-2} ground), d is the actual deposit (µg cm^{-2}), V is the volume rate application (L ha^{-1}), T_{cs} is the tracer concentration in the tank for each treatment (mg L^{-1}) and 10^5 is a conversion factor. This normalized deposit method has been successfully used to compare different technologies and/or field conditions during pesticide applications in previous research (Cross et al., 2001; Viret et al., 2003; Siegfried et al., 2007; Llorens et al., 2010; Gil et al., 2011).

The proportion of spray retained on the leaves D_l (%) was calculated following Pergher and Gubiani (1995), Gil et al. (2007), and Llorens et al. (2010):

$$D_l = (d \times 10^7 \times LAI)/(V \times T_{cs}) \tag{3}$$

where 10^7 is a conversion factor and *LAI* is the leaf area index (m^2 m^{-2}). This parameter was obtained by collecting 20–25 leaves per height (bottom, centre, top) in a stretch of 2.0 linear meters. Every leaf area was measured using the planimeter. LAI could then be calculated as:

$$LAI = \sum S_i / (a \times b) \tag{4}$$

where S_i (m^2) is the individual leaf area measured with the planimeter, a (m) is the averaged distance along the rows and b (m) that between the rows. These last two parameters corresponded to plant layout values (2.0 and 2.8 m for *a* and *b*, respectively). The final value was 0.98 m^2 m^{-2}. Following the methodology used by Gil et al. (2011), only a single *LAI* value for the crop was considered.

Statistical analyses were carried out using Statgraphics Centurion XVI software (Statpoint Technologies, Warrenton, Virginia, USA). Depositions d_n were examined by variance analysis (ANOVA), followed by a Student–Neuman–Keuls test ($P \leq 0.05$) to study the mean differences. Analysis presented two first-level factors (forward speed and system operational status) and two subfactors (height and depth). Prior to the analysis, the normal distribution of the residuals was checked by means of the Shapiro-Wilk normality test and the homogeneity variance of residues were checked using a Levene’s test.

3. Results

3.1 Electrostatic sprayer characterization

3.1.1 Restrictor adjustment

At a diffuser pressure of 2×10^5 Pa and a nominal flow rate of 110 mL min^{-1}, the total average liquid flow rate for the AMT-1.0 and AMT-1.5 restrictors was 118- and 126-mL min^{-1}, respectively, a mean deviation from the nominal liquid rate of 6.2% and 13.1%, respectively. The pump pressure was 900 and 450 kPa, respectively.

The liquid flow rate for AMT-1.5 was higher than 120 mL min^{-1} in every downpipe (Table 2). The mean flow rate for the inner right downpipe was 129 mL min^{-1}, a mean deviation of 15.9% from the nominal flow rate; this was higher than the limit of 15.0% established by the ISO 16122 (ISO, 2015). For AMT-1.0, the deviation was lower than 12.0% (2.5% in the downpipe on the right); in addition, the variation coefficient indicated that the flow rate variability was lower than AMT-1.5. The difference between the largest and lowest coefficient was 0.8% AMT-1.0 and 2.2% for AMT-1.5.

[Insert Table 2]

Regarding the distribution of flow rate over the entire spray leg (Fig. 5), the smallest differences between the restrictors occurred in the nozzle closest to the ground (diffuser 1). Overall, AMT-1.5 had a greater flow rate. For both restrictors, the flow rates were higher in the left-hand downpipes, while diffuser 1 always had lower values than diffuser 7. A more uniform distribution of liquid flow rate was obtained with AMT-1.0 than AMT-1.5 (Table 2). The former required a higher pump pressure but the flow rate was adjusted more and the variation coefficients were lower. Given these results, AMT-1.0 was chosen for subsequent field tests.

[Insert Fig. 5]

3.1.2 Airflow rate and velocity profiles

The average air velocities near the air outlets (Table 3) varied between 45.0 m s^{-1} (inner downpipe on the left) and 51.9 m s^{-1} (outer downpipe on the right). The total airflow rate obtained was 137.3 m^3 h^{-1}, of which 51.2% corresponded to the right side of the sprayer at a mean velocity of 49.3 m s^{-1}, while 48.8% corresponded to the left side of the sprayer at a mean velocity of 47.0 m s^{-1}. These velocities were similar to the reference sprayer (47.8 m s^{-1}) but the rate was nine times smaller than the nominal airflow rate (1200 m^3 h^{-1}) due to the lower surface section of the air outlet for the electrostatic sprayer.

[Insert Table 3]

The air velocities showed two relative maximum values in the rest of the downpipes except at the outer downpipe on the right (Fig. 6): one at diffuser 2 and the other between diffusers 4 and 5, meaning that the speed increased, then decreased, and then increased again from diffusers 1 to 7. For the remaining downpipe, the three highest values were observed at diffusers 1, 4, and 6. The velocity mostly ranged from

40.0–50.0 m s^{-1}. In every downpipe, the variation coefficient was < 10% and the standard deviation was < 5.0 m s^{-1} (Table 3). Despite the differences between the left and right sides, the influence of the fan's airflow on the droplets over the canopies was similar on both sides of the sprayer.

[Insert Fig. 6]

3.2 Assessment of spray quality

3.2.1 Leaf deposits in different tests

The activated electrostatic sprayer treatments achieved higher normalized leaf deposits (Table 4). The deposit amount was greater at 4.7 km h^{-1} than 5.9 km h^{-1} (0.77 and 0.72 µg cm^{-2} leaf/ µg cm^{-2} ground, respectively). For the remaining tests, the average values varied between 0.47–0.57 µg cm^{-2} leaf/ µg cm^{-2} ground. The proportion of spray retained (D_l) was similar for all tests. The activated electrostatic achieved the highest retentions (above 70%) as compared with the system switched off (45%) and the reference sprayer (55%). In addition, the spatial uniformity of the normalized deposit over the whole canopy, expressed by the variation coefficient of the deposit samples for each treatment, indicated that the conventional sprayer achieved the most uniform result (13.2%), while the deactivated electrostatic sprayer had values above 25%.

Using these experimental data, three homogeneous groups were assessed with the Student–Neuman–Keuls test ($p \leq 0.05$) to determine which treatments were significantly different: the first group was subjected to two treatment methods with the electrostatic system activated (group *A*), the second group was subjected to the remaining treatments at 5.9 km h^{-1} (with the electrostatic system deactivated and the conventional sprayer) (group *B*) and the third group was subjected to treatment with the electrostatic system deactivated at 4.7 km h^{-1} (group *C*). No statistically significant differences were observed within each group.

[Insert Table 4]

When the electrostatic system was activated, treatment at 4.7 km h^{-1} had the greatest number of sections with a normalized deposition > 0.70 µg cm^{-2} leaf/ µg cm^{-2} ground (Table 5), surpassing even the conventional treatment that had a greater application volume (75 L ha^{-1} compared to 190 L ha^{-1} used by the reference sprayer).

Under these conditions, no significant differences were detected between the extremes (left and right) of the canopy and the central section. Neither were differences were observed for each depth. The deposition was lower when the forward speed was increased to 5.9 km h^{-1}. The volume rate was reduced to 60 L ha^{-1}, but the average deposition was larger between 0.0–0.3 m and especially between 0.6–0.9 m. As the maximum value of the velocity generally occurred in the highest diffusers (Fig. 6), increasing the speed of the sprayer produced changes in the angle of the outgoing currents from the fan and could influence spray deposition on the vegetation (Triloff, 2018; Salcedo et al., 2019).

One explanation could be that sprayer-generated turbulence concentrated the air streams in the upper central part of the canopy, pushing the droplets towards that position. At 5.9 km h^{-1} there were differences between depths at heights of 0.6–0.9 m. On the other hand, when the electric system was deactivated, deposition decreased in all sections, mainly in the bottom of the canopy. This reduction was more intense at 4.7 km h^{-1}. However, this speed had a higher application volume, deposition was higher at 5.9 km h^{-1} and there was more deposition in the upper central section. In addition, deposition distribution was more uniform at 5.9 km h^{-1} and there were no differences between depths and heights. Future research should explore the interaction between air currents and electrostatic equipment particles in vineyard treatments. Finally, the conventional system (with the greatest volume rate) resulted in deposition values ≤ 0.60 µg cm^{-2} leaf/ µg cm^{-2} ground in all sections except halfway up the canopy. Despite this, and a similar theoretical VMD to the electrostatic system deactivated and larger than activated, the convention system produced the most homogenous treatment throughout canopy, penetrating all sections.

[Insert Table 5]

The spatial distribution of leaf deposit d_n within the canopy (Fig. 7) showed a low uniformity in all cases, regardless of spraying technique used or working conditions. As previously noted, the highest differences in product distribution occurred with the electrostatic sprayer activated and deactivated (Table 4) and the highest deposition values occurred with the electrostatic system activated. In this case, the droplets could penetrate further into the canopy at 5.9 km h^{-1} (Fig. 7a) than at 4.7 km h^{-1} (Fig. 7c), especially at the top. With the electrostatic sprayer deactivated, deposits were smaller

(Fig. 7c, d), especially in the lower half of the canopy. With the conventional sprayer (Fig. 7e), the penetration of the droplets was less than for the electrostatic sprayer at the same forward speed. A comparison of both the treatments showed more leaf deposit on the right side than the left side of the sprayer. On the other hand, the convention sprayer had the lowest differences between sections for the same depth (Table 4).

[Insert Fig. 7]

Plotting the percentage of the total emitted output (D_l) against the coefficient variation for all treatments showed that an increase in leaf recovery had a slight but clear correspondence with reduced variation (Fig. 8). The maximum values for normalized leaf recovery clustered around the activated electrostatic system at either speed, while the D_l for the deactivated system dropped quickly with a slight increase in variation for the higher, then lower, speed. The conventional sprayer plotted below this relationship.

[Insert Figure 8]

3.2.2 Interactions during electrostatic spraying

The variability of normalized leaf deposition was significantly influenced by the electrostatic system (Table 6) at a confidence level of 95.0%, depending on the forward speed of the sprayer. The influence of canopy depth was also significant. Whether the system was activated or not, forward speed was also significant depending on depth. No significant correlation with height was detected. This contrasted with the results of Pascuzzi and Cerruto (2015), who showed that forward speed did not significantly affect leaf deposition and that only the vines nearest the electrostatic sprayer were affected during activation. These differences could be due to different training systems (tendone vs. trellis) or plant characteristics. Thus, further field testing with electrostatic sprayers is required in order to determine more precise conclusions in the context of such variables.

[Insert Table 6]

Conclusions

The activated electrostatic system resulted in a greater amount of leaf deposition than treatments when deactivated or when the conventional sprayer was used. The most homogeneous and uniform treatments were observed at a higher forward speed and when using the activated electrostatic sprayer or a multi-row sprayer. When using the activated electrostatic sprayer, a significative correlation between leaf deposition and forward speed ($p \leq 0.05$) was detected as well as between canopy depth and both charge and speed separately. The conventional sprayer produced the best deposition uniformity and homogeneity, but the activated electrostatic sprayer at 4.7 km h^{-1} produced a greater amount of deposition and uniformity with similar homogeneity. This particular electrostatic sprayer could thus reduce the volumetric flow rate by up to 68% with better deposition and a greater proportion of spray retained along with similar homogeneity and uniform deposition in the canopy. While these results are promising for more efficient and environmentally friendly spray management in vineyards, further research is required to assess other varieties, growth stages, and LAI conditions.

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Figure captions

Fig. 1. Sprayer types used in this study: (a) electrostatic sprayer and (b) multi-row.

Fig. 2. Schematic of downpipe position (outer left, OL; inner left, IL; inner right, IR; outer right, OR) and diffusers 1–7 for the electrostatic sprayer.

Fig. 3. Field trial layout: (a) sampling zones within the vegetation and (b) map view of sprayer operation within a row with location of randomly sampled canopies (S1–S9).

Fig. 4. Relationship between leaf area and leaf weight obtained for vineyard vegetation.

Fig. 5. Average liquid flow rate distribution for the AMT-1.0 and AMT-1.5 restrictors in each downpipe; bars represent standard deviation.

Fig. 6. Average air velocities in the diffusers for each downpipe; bars represent standard deviation.

Fig. 7. Spatial distribution of averaged normalized deposit (d_n) by forward speed and sprayer type.

Fig. 8. Relationship between sprayer type, leaf recovery, and variation coefficient. Circle diameters are proportional to the average normalized deposit values.

TABLES

Table 1 Working conditions and treatments.

Sprayer	Activation	Forward speed (km h^{-1})	Volume rate (L ha^{-1})	Flow rate (L min^{-1})	Number of nozzles	Working pressure (kPa)
Electrostatic	ON	5.9	60	3.3	28	200
Electrostatic	OFF	5.9	60	3.3	28	200
Electrostatic	ON	4.7	75	3.3	28	200
Electrostatic	OFF	4.7	75	3.3	28	200
Conventional	-	5.9	190	10.4	16	800

Table 2 Average liquid flow rated (standard error within parentheses), deviation from the nominal liquid flow rate (110 mL min^{-1} at 200 kPa), and variation coefficient in each downpipe.

Downpipe		**Liquid flow rate (mL min^{-1})**		**Deviation from the nominal liquid flow rate (%)**		**CV (%)**	
Side	**Position**	**Restrictor 1.0**	**Restrictor 1.5**	**Restrictor 1.0**	**Restrictor 1.5**	**Restrictor 1.0**	**Restrictor 1.5**
Left	Outer	122 (1)	124 (3)	10.1	12.1	0.9	2.3
	Inner	124 (1)	127 (3)	11.5	14.8	0.8	2.0
Right	Outer	112 (1)	122 (4)	0.9	9.5	0.7	3.2
	Inner	114 (2)	129 (1)	2.3	15.9	1.5	1.0

Table 3 Average air velocity magnitudes (standard error within parentheses) and coefficient of variation from the diffusers.

Downpipe Side	Downpipe Position	Airflow rate ($m^3\ h^{-1}$)	Distribution airflow rate (%)	Air velocity ($m\ s^{-1}$)	CV (%)
Left	Outer	32.1 (1.9)	23.4	45.0 (4.0)	8.8
	Inner	34.9 (1.3)	25.5	49.0 (4.1)	7.9
Right	Outer	37.0 (0.5)	26.9	51.9 (4.8)	8.8
	Inner	33.3 (3.7)	24.3	46.7 (4.1)	9.2

Table 4 Average normalized deposits (d_n - µg cm^{-2} leaf/ µg cm^{-2} ground) (standard error within parentheses), leaf recovery (D_l), variation coefficients (affected by forward speed and sprayer type), and homogeneous groups (*A*, *B*, and *C*) obtained by the Student-Neuman-Keuls test ($p \leq 0.05$). Treatments identified by the same letter did not differ statistically.

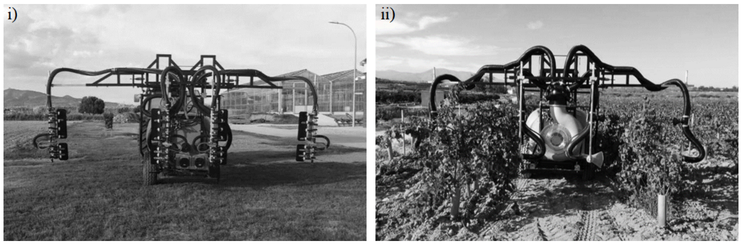
Forward speed (km h^{-1})	**Electrostatic sprayer**						**Conventional sprayer**		
	Switch ON			**Switch OFF**					
	d_n	D_l **(%)**	**CV (%)**	d_n	D_l **(%)**	**CV (%)**	d_n	D_l **(%)**	**CV (%)**
4.7	0.77 (0.09) a	75.06	18.3	0.47 (0.06) c	45.85	30.6	-	-	-
5.9	0.72 (0.07) a	70.99	20.6	0.57 (0.08) b	55.80	26.0	0.56 (0.06) b	55.34	13.2

Table 5 Detailed sections. Average normalized deposits (standard error within parentheses) and results obtained using the Student-Neuman-Keuls test ($p \leq 0.05$) for each section and treatment method. Sections identified by the same letter did not differ statistically.

Forward speed (m/s)	**System**	**Height (m)**	**Normalized deposit (μg cm^{-2} leaf/ μg cm^{-2} ground) per depth**		
			Ext-L	**Center**	**Ext-R**
4.7	Electrostatic activated	0.6-0.9	0.98 (0.14) b	0.74 (0.09) ab	0.91 (0.12) a
		0.6-0.3	0.77 (0.06) ab	0.75 (0.09) ab	0.83 (0.11) b
		0.3-0.0	0.71 (0.10) ab	0.45 (0.07) a	0.75 (0.07) ab
	Electrostatic deactivated	0.6-0.9	0.60 (0.06) ef	0.72(0.09) f	0.47 (0.07) cde
		0.6-0.3	0.45 (0.06) cde	0.56 (0.05) def	0.52 (0.05) cdef
		0.3-0.0	0.29 (0.04) c	0.27 (0.04) c	0.32 (0.05) cd
5.9	Electrostatic activated	0.6-0.9	0.77 (0.06) hi	1.00 (0.13) j	0.88 (0.09) ij
		0.6-0.3	0.70 (0.05) ghi	0.70 (0.07) ghi	0.65 (0.06) gh
		0.3-0.0	0.65 (0.06) gh	0.57 (0.04) g	0.55 (0.04) g
	Electrostatic deactivated	0.6-0.9	0.57 (0.09) kl	0.92 (0.18) l	0.60 (0.10) kl
		0.6-0.3	0.59 (0.05) kl	0.60 (0.07) kl	0.56 (0.08) kl
		0.3-0.0	0.48 (0.08) k	0.48 (0.04) k	0.33 (0.04) k
	Conventional	0.6-0.9	0.49 (0.06) m	0.47 (0.03) m	0.55 (0.02) m
		0.6-0.3	0.54 (0.06) m	0.66 (0.09) m	0.71 (0.06) m
		0.3-0.0	0.60 (0.07) m	0.48 (0.06) m	0.58 (0.05) m

Table 6 Significant interactions during electrostatic sprayer treatments at 95.0% confidence level.

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-Ratio**	**p-value**
Switch	4.157	1	4.157	71.04	0.0000
Speed	0.073	1	0.073	1.25	0.2653
Height	4.290	2	2.145	36.66	0.0000
Depth	0.067	2	0.033	0.57	0.5650
Switch × speed	0.415	1	0.415	7.09	0.0082
Switch × height	0.065	2	0.032	0.55	0.5750
Switch × depth	0.483	2	0.241	4.13	0.0171
Speed × height	0.086	2	0.043	0.74	0.4798
Speed × depth	0.472	2	0.236	4.04	0.0187
Height × depth	0.508	4	0.127	2.17	0.0725
Switch × speed × height	0.047	2	0.023	0.40	0.6716
Switch × speed × depth	0.143	2	0.071	1.22	0.2964
Switch × height × depth	0.121	4	0.030	0.52	0.7231
Speed × height × depth	0.517	4	0.129	2.21	0.0679
Residual	17.088	292	0.059		
Total (corrected)	28.532	323			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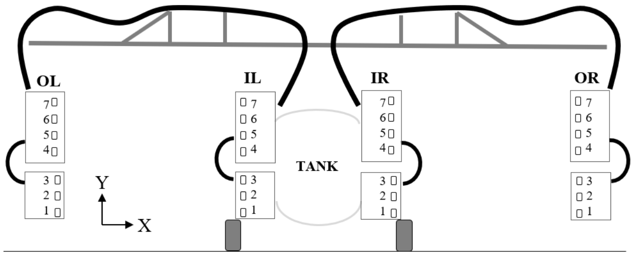
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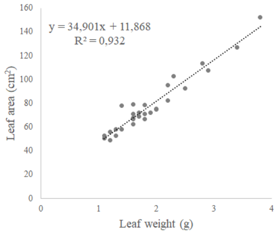
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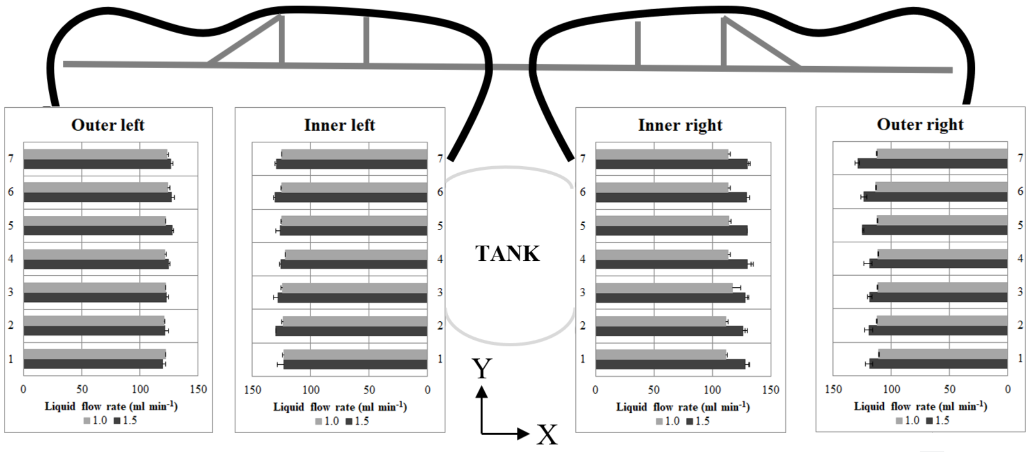
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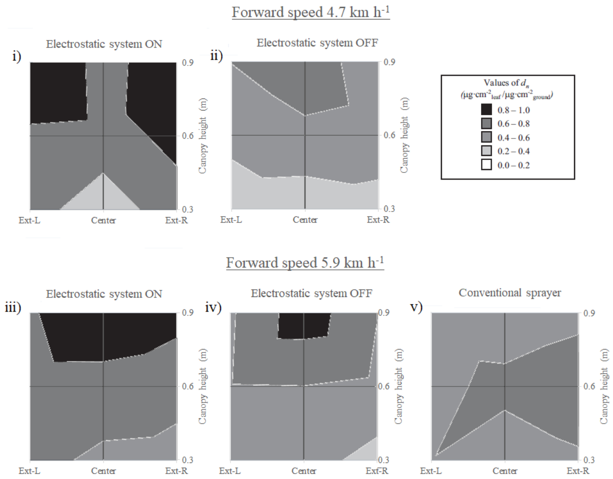
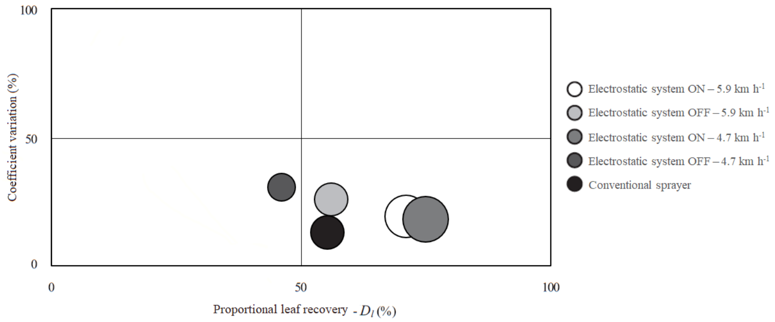
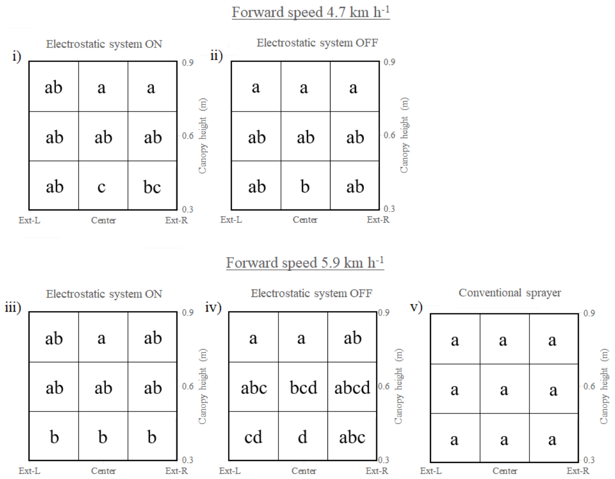
TANK
7
6
5
4
3
2
1
0
50
100
150
Liquid flow rate (ml min-1)
1.0
1.5
Y
X


Forward speed 4.7 km h-1
i)
Electrostatic system ON
ii)
Electrostatic system OFF
Values of d_n
($\mu g \cdot cm^{-2}{}_{leaf}$ / $\mu g \cdot cm^{-2}{}_{ground}$)
■ 0.8 – 1.0
■ 0.6 – 0.8
▨ 0.4 – 0.6
□ 0.2 – 0.4
□ 0.0 – 0.2
Forward speed 5.9 km h-1
iii)
Electrostatic system ON
iv)
Electrostatic system OFF
v)
Conventional sprayer
Canopy height (m)
0.9
0.6
0.3
Ext-L
Center
Ext-R


100
50
0
Coefficient variation (%)
0
50
100
Proportional leaf recovery - D_l (%)
○ Electrostatic system ON – 5.9 km h-1
● Electrostatic system OFF – 5.9 km h-1
● Electrostatic system ON – 4.7 km h-1
● Electrostatic system OFF – 4.7 km h-1
● Conventional sprayer



Forward speed 4.7 km h^{-1}

i) Electrostatic system ON

Ext-L	Center	Ext-R
ab	a	a
ab	ab	ab
ab	c	bc

ii) Electrostatic system OFF

Ext-L	Center	Ext-R
a	a	a
ab	ab	ab
ab	b	ab

Forward speed 5.9 km h^{-1}

iii) Electrostatic system ON

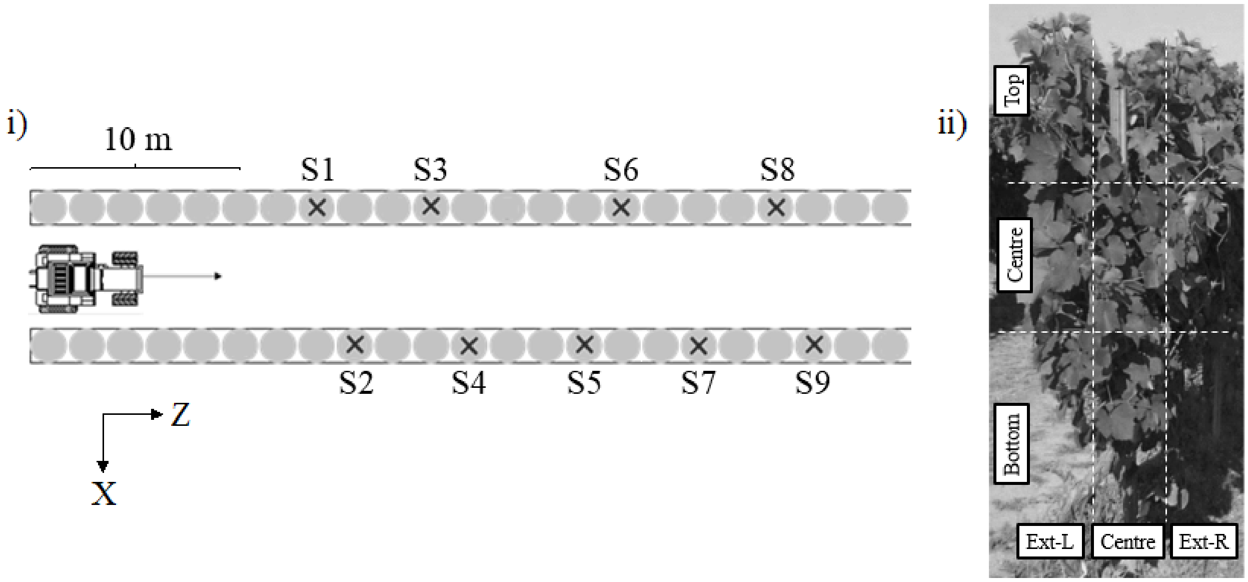
Ext-L	Center	Ext-R
ab	a	ab
ab	ab	ab
b	b	b

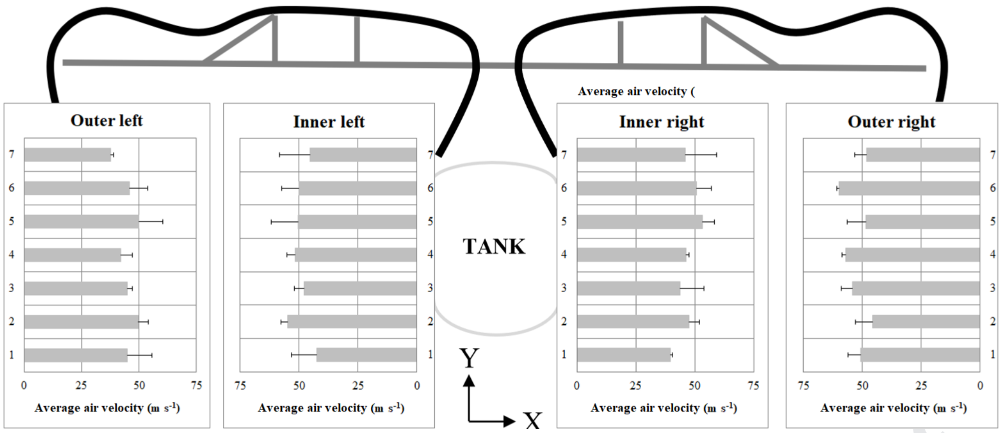
iv) Electrostatic system OFF

Ext-L	Center	Ext-R
a	a	ab
abc	bcd	abcd
cd	d	abc

v) Conventional sprayer

Ext-L	Center	Ext-R
a	a	a
a	a	a
a	a	a


i)
10 m
S1
S3
S6
S8
S2
S4
S5
S7
S9
Z
X
ii)
Top
Centre
Bottom
Ext-L
Centre
Ext-R


Average air velocity (
Outer left
Inner left
Inner right
Outer right
TANK
7
6
5
4
3
2
1
0
25
50
75
Average air velocity (m s^{-1})
Y
X

Evaluation of leaf deposit quality between electrostatic and conventional multi-row sprayers in a trellised vineyard

Highlights

- This study compared electrostatic and conventional spraying in a Spanish vineyard
- Electrostatic treatment increased deposition level and homogeneity on vegetation
- This could save up to 68% of applied volume with cost and environmental benefits
- Further research is needed on differing trellis systems and grape varieties