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I think that the topic covered in the paper can be interesting for your Journal and I am ready to follow your suggestions in order to improve the work.

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Kindly acknowledge the reception of this mail.

Best regards
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Spray deposition in "tendone" vineyards when using an air-assisted electrostatic sprayer

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Keywords:

Electrostatic sprayer, "Tendone" trained vineyard, Crop protection, Bio stimulant for grape growth.

Highlights

- Evaluation of the effect of the electrostatic charge on foliar deposition in an Apulian tendone vineyard.
- Low volume pneumatic sprayer fitted with root blower, able to produce droplets in the range of 30−50 micrometres that may be electrostatically charged by induction.
- Spray liquid sheared into droplets by means of the high velocity produced by the expansion of compressed air.
- Behaviour of the sprayer characterized by poor deposition inside the canopy, but useful for targeted treatments to the grapes as pesticides or bio stimulants of growth.

1. INTRODUCTION

Apulia (Southern Italy) is Italy's leading region in the production of table grapes with a production of about 6.5×10^{8} kg, which accounts for 61% of the Italian total production (Istat, 2012). In this region the commonest employed vine training system for table grapes is the "pergolato" or "tendone", whose characteristic is the overhead canopy, supported by a trellis system consisting of a high stake at each vine with two orthogonal steel wires attached 1.7–1.8 m above ground level, and a grid of steel wires supporting the shoots. The standard vine spacing is 2.5 m × 2.5 m, giving a density of 1,600 vines hectare^{-1}; each vine has a 1.2–1.4 m high trunk, with two branches and two fruit-bearing shoots per branch, aligned orthogonally or parallelly on the grid.

The grid parts the upper area, exclusively assigned for the canopy, and the lower area, allotted to the bunches, distributed on all or part of the width of the inter-row. A further horizontal grid of steel wires divides the canopy allocated in the upper area into two levels (double-grid "tendone"); the higher level supports the growing shoots and the lower level supports the fruit-bearing shoots.

Only the lower side of the canopy is directly exposed to the spray during application of Plant Protection Products (PPPs) and the action of agrochemical treatments is affected by the spatial distribution of the canopy (in terms of height, thickness, leaf density, discontinuity along the rows) and bunches (Cerruto, 2008).

The sprayers generally used for pesticide treatments in Apulian "tendone" vineyards are conventional air-assisted sprayers equipped with arc-shaped spray boom and axial-flow fan and pneumatic sprayers fitted with air shear nozzles and centrifugal fan producing an air flow through fixed or adjustable diffusers along an arc of 180°. These machines require a correct adjustment to avoid non-uniform deposition, over dosage of the mixture, off-target spray and environmental pollution such as drift and run-off (Pascuzzi, 2013).

According to the characteristics of the “tendone” training system and of the product for the fresh market, various proposals for improvement, innovation, differentiations and specialization regarding the sprayers used in this type of vineyards are put forward. Further claims arise from the European Regulations concerning pest control (EC Directive 2009/128) and, with the progressive introduction of seedless cultivars, from the monitoring of the physiological processes of grapevines: sustainable use of synthetic pesticides, reduction of doses and volumes per hectare, use of microbial antagonists, distribution of bio stimulants of plant growth, etc.

These manifold requirements drive for new constructional solutions and employment of sprayers, able to link the effective improvement of the traditional qualitative parameters (improvements concerning uniformity of distribution, recovery, coverage, etc.) to the ability of a localized distribution of bio stimulants (cyanamide, gibberellic acid, etc.) or microbial antagonists without compromising vitality.

Air-assisted electrostatic sprayers may meet these needs, improving the overall deposition and the distribution on the canopy and reducing the spray drift (Machowski and Balachandran, 1997; Esehaghbeygi et al., 2010). Indeed, electrostatic force fields allow guiding and governing the droplet’s trajectories of charged sprays (Maski and Durairaj, 2010). Other studies report that electrostatic charging of spray droplets may also provide a better underside leaf deposition (Western et al., 1994; Wolf et al., 1996).

Despite substantial research on this matter, the use of charged agricultural sprays is yet very limited, even if the electrostatic spray technique is commonly used for industrial applications, where a charged cloud of droplets is sprayed towards an earthed substrate and deposited on it. Actually the characteristics of the agricultural electrostatic sprayers conflict with those of industry because the first ones must charge droplets of conductive liquids and then move them deeply into three-dimensional canopies. Furthermore, it needs to take into account the personnel safety hazards connected to untrained operators that use mobile systems for outdoor applications.

The widely used method for charging agricultural sprays is the induction charging, in which an electrode, positively charged by high-voltage, is positioned close to where the spray conductive liquid is emitted from a nozzle. The water-based pesticide spray, at earth potential, because of the attraction of electrons, undergoes a negative charge induced on the surface of the droplets and this charge is retained on them. The level of charge induced per unit area of surface is proportional to the voltage applied to the electrode (Matthews, 1989).

The amount of electrostatic charge carried by droplets affects the action of the charged spray. The chargeability of the droplets, that is their capability to acquire charge, is evaluated in terms of amount of electrostatic charge on droplet per unit mass or as Charge-to-Mass Ratio (CMR). The CMR defines the relative ability for the electrical forces to overcome the forces of gravity and the kinetic energy imparted to the droplets and then allows predicting the behaviour of a charged particle exposed to inertial, electrical and gravitational forces (Toljic et al., 2008; Maski and Durairaj, 2010). A high CMR is usually desired for air-assisted induction-charging pesticide spraying to guide the droplet's trajectories and so increase the underside leaf deposition (Zhao et al., 2008). On the other hand, the charge that can be retained by each droplet surface, and then the CMR, is restricted by the known Rayleigh limit beyond which the disintegration of the droplet occurs because the charge is so high that the inward stress due to surface tension cannot balance the outward stress due to the electric field.

As known, the motion of the droplets from the nozzle to the target is dominated by the drag force $\vec{F}_d$ raised from the surrounding air, the electromotive force $\vec{F}_e$ caused by the electrostatic field, and the gravity body force $\vec{F}_g$ (Colbert and Cairncross, 2005). According to the Newton's 2nd law of motion, the sum of these forces equals the rate of change of momentum:

$$\sum \vec{F} = \vec{F}_d + \vec{F}_e + \vec{F}_g = m\frac{d\vec{\mathbf{v}}}{dt} \qquad (1)$$

where:

- m: droplet mass;
- $\vec{v}$: droplet velocity.

Other forces need examination in multiphase flow models, particularly buoyancy, Basset forces and virtual mass. Nevertheless, these forces are assumed negligible in a gas-liquid multiphase system, where the density ratio is of the order of 10^{-3}. Furthermore, also the gravity body force is considered insignificant and then the final droplet motion equation is the following:

$$3\pi c_d \mu_a D_l \left(\vec{v}_a - \vec{v}\right) + q\vec{E} = m\frac{d\vec{\mathbf{v}}}{dt} \qquad (2)$$

where:

- c_d: drag factor;
- μ_a: air viscosity;
- D_l: droplet diameter;
- $\left(\vec{v}_a - \vec{v}\right)$: relative velocity between surrounding air ($\vec{v}_a$) and droplet ($\vec{v}$);
- q: droplet charge;
- $\vec{E}$: electric field.

However, a large number of droplets of the same polarity, repulsing each other, form a spray cloud that enlarges swiftly, creating an own electrical field that affects the trajectory of each droplet (Matthews, 1989).

The objective of this study concerned the evaluation of the effect of the electrostatic charge on foliar deposition in an Apulian tendone vineyard when using an innovative electrostatic air-assisted sprayer model, compared to the foliar deposition obtained employing the same sprayer but without the electrostatic charge. The sprayer was equipped with nozzles that link the pneumatic atomization of the liquid, obtained by means of compressed air, to the electrostatic induction charging, so producing a stream of electrostatically charged fine droplets. Furthermore, the sprayer distributed a low volume of mixture and the experimentation was carried out during a phenological stage characterized by high leaf density, so to evaluate the performance of the machine under operative conditions particularly hard.

2. MATERIAL AND METHODS

2.1. The sprayer

The trials involved a 3-point hitch mounted electrostatic sprayer of the brand ESS (Electrostatic Spray Systems) Model “150 RB14” with a 380 L tank (Figure 1): a modern model with respect to those traditionally used in Apulian “tendone” vineyards. This sprayer employs the pneumatic principle for formation and fractionation of the droplets and it uses the method of induction of charges for electrification of the drops.

The machine was equipped with a gearbox multiplier (gear ratio 1:7), whose input was connected through the gimbal device to the tractor power take-off (PTO) and output, by driving belt and pulleys, to a roots blower for producing the airflow and to a centrifugal pump for moving the mixture available in the tank. The blower, by means of two lobe impellers mounted on parallel shafts and rotating in opposite directions, sucked air through a filter from the environment and pushed it first into a heat exchanger and then into a pressured reservoir, whose output was linked to the nozzles. A pop-off valve avoids overpressures.

According to the manufacturer’s instructions, the machine, for properly working, requires an air relative pressure of 100 kPa, detected by a pressure gauge placed on the sprayer, to produce an airflow rate of 195 $m^3 h^{-1}$. At the beginning of the treatment, the operator must adjust the engine rotation speed until the air pressure reaches the required value at the desired forward speed. The tractor operated at 41.8 rad s^{-1} of the PTO during the trials.

The liquid flow rate delivered by the machine can be adjusted in the range 1.68–2.80 L min^{-1} by using different flow disks fitted with calibrated holes and modifying the liquid pressure in the range 150–300 kPa by means of a valve that restricts the return flow of liquid to the tank (liquid pressure valve). According to the manufacturer's instructions, outside this range of liquid flow rate, nozzle charging is poor and spray deposition is low. Setting the liquid flow rate in the range 1.68–2.24 L min^{-1} attains the optimum performance. The liquid pressure, detected by a pressure gauge, decreases opening the valve and increases closing it. In case of fully closed valve, a hole present at its inside allows some liquid to return to the tank to maintain tank agitation. Motorized ball valves, individually governed by the operator, control the liquid flow rate delivered by each group of 7 nozzles placed respectively on the left and right boom of the machine, whose positioning can be adjusted according to the needs. Each nozzle, by means of a brass swivel, enjoys of wide possibility of orientation, but it is not allowed shutting its supply; it is only possible to exclude the whole left or right boom of the machine.

Field tests were executed setting the operative pressure at the value usually employed by the farmer and suggested by the manufacturer, that is 170 kPa, which corresponded to a flow of each nozzle of 156 mL min^{-1} and an overall flow rate of 2.18 L min^{-1}.

According to the operating instructions of the sprayer, the nozzles need to be approximately 0.5 m from the crop so that the air stream is able to push the charged spray into the canopy and to provide adequate overlap of the spray cloud from each nozzle. A closer distance between spray boom and crop does not allow the development of the spray cloud and the coverage is uneven. On the other hand, the spray may not penetrate the canopies when the nozzles are too far away from the target.

The adjustment of the spray arms is accomplished by modifying the height of the tractor's 3-point hitch of the machine, the orientation of each boom and/or its width and extension. During the field tests, the orientation of the spray arms was settled primarily considering the shape of the canopy and the bulk of the bunches and then the size (height and width) of the vineyard inter-rows that allowed the transit of the machinery without obstacles. Therefore the spray arms were arranged like the equal line segments of an isosceles triangle (Figure 2).

The main components of this sprayer are the patented MaxCharge™ nozzles, so called embedded-electrode electrostatic-induction nozzles, where the spray liquid is sheared into droplets by the impact with a high-speed air stream and electrostatically charged for induction.

2.2. Action of the MaxCharge™ nozzle

The compressed air and the liquid enter separately into the nozzle (Figure 3) and at its inside the liquid, in the form of a thin cylindrical shell, draws from a central tube and shears into droplets thanks to the viscous and turbulent energy transfer from the surrounding near-sonic speed air stream, emerging through an exterior annulus from the converging section of the nozzle (Law, 1977).

In this context, the concept of a steady, isentropic (i.e., at constant entropy), frictionless, and adiabatic one-dimensional compressible flowing fluid of an ideal gas through a convergent-divergent nozzle may be involved. As known, this gas at a given pressure and temperature, due to the principle of mass conservation, increases its velocity when passes into a lower pressure environment through a restriction such as the throat of a convergent-divergent nozzle or a valve in a pipe. At the same time, this "Venturi effect" causes the static pressure, and then the density, to decrease downstream past the restriction. At upstream fixed pressure, the mass flow rate increases when the downstream pressure environment decreases until the so-called "choked flow", that occurs when at the throat the velocity is sonic or at a Mach number of 1 (Sutton and Biblarz, 2001). In this condition the mass flow rate is independent of the downstream pressure, depending only on temperature and pressure on the upstream side of the restriction. Furthermore, at the steady-state choked flow the pressure at the throat p_{th} is related to the upstream pressure p_{up} by the following equation (Stepanoff, 1955):

$$\frac{p_{th}}{p_{up}} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \quad (3)$$

where $k = c_p/c_v$ is the ratio of the specific heat under constant pressure (c_p) to that under constant volume (c_v); k = 1.4 for the air. Therefore, if the throat is at atmospheric pressure, p_{th} = 101.325 kPa and Equation (3) allows calculating the absolute upstream pressure p_{up} that produces the choked flow: p_{up} = 191.801 kPa.

Furthermore, the air speed at the throat of the nozzle v_{th} may be estimated with the following equation (Stepanoff, 1955):

$$v_{th} = \sqrt{\frac{2 \cdot k}{k-1} \cdot \frac{p_{th}}{\rho_a} \cdot \left[\left(\frac{p_{up}}{p_{th}}\right)^{\left(\frac{k-1}{k}\right)} - 1\right]} \quad \text{m s}^{-1} \quad (4)$$

where the air density ρ_a = 1.2 kg m^{-3} at 15 °C (ISO, 1975).

The absolute operative pressure produced by the roots blower (201.325 kPa) is then higher than the calculated p_{up}, and then, even if the loss flow between blower outlet and nozzle inlet would be evaluated, it could be reached the choked flow at the throat if a suitable convergent nozzle is used.

Even if the inside of the MaxCharge™ nozzle is not properly designed to obtain sonic condition at its throat, nevertheless very high speed air stream are achieved. Actually, the output hole of the nozzle has a diameter ϕ of 4.5 mm and considering an air flow rate for each nozzle Q_a = 195/14= 13.93 $m^3\ h^{-1}$= 232.17 L min^{-1}, the speed of the air stream at the exit of the nozzle v_{out} is calculated according to Equation (5):

$$v_{out} = \frac{4 \cdot Q_a}{\pi \cdot \phi^2} = 243\,\mathrm{m\,s^{-1}} \tag{5}$$

The average Sauter Diameter D_{as} [μm] of a spray obtained by means of pneumatic atomization of a liquid may be evaluated according to the Equation (6) (Musillami et al., 1982):

$$D_{as} = \frac{585000 \cdot \sqrt{\gamma_l}}{v_a \cdot \sqrt{\rho_l}} + 8054 \cdot \left(\frac{\mu_l}{\rho_l \cdot \sqrt{\gamma_l}} \right)^{0.45} \cdot \left(1000 \cdot \frac{Q_l}{Q_a} \right)^{1.5} \tag{6}$$

where:

- γ_l, ρ_l and μ_l: surface tension [N m^{-1}], density [kg m^{-3}] and viscosity [Pa s] of the liquid;
- v_a: air velocity [m s^{-1}];
- Q_l and Q_a: liquid and air flow rate [$m^3\ s^{-1}$].

Assuming the liquid as water and then $\gamma_l = 72 \cdot 10^{-3}$ N m^{-1}; ρ_l = 1000 kg m^{-3}; $\mu_l = 10^{-3}$ Pa s and considering Q_a = 232.17 L min^{-1}; Q_l = 0.156 L min^{-1}, v_{out} = 243 m s^{-1}, Equation (6) allows to calculate the corresponding D_{as} = 36.4 μm. This result is in compliance with the operating instructions of the sprayer, which refer a spray with volume median diameter (VMD) in the range 30–50 μm.

Inside the nozzle the droplets of the conductive liquids during their formation are charged by electrostatic induction (Law, 1978). To this end, coaxial cylinders set up the charging zone of the nozzle: the inner cylinder being the unbroken liquid jet emerging along the axis from the grounded orifice of the central tube and an annular brass electrode embedded in the wall of the cylindrical dielectric air channel composes the outer coaxial cylinder (Law, 1977).

The brass electrode, completely protected from external electrical short, is located very close to the droplet formation zone (less than 1.27 mm) so to obtain strong electric field gradients able to convey a wealth of free electrons onto the inner liquid cylinder with moderately low values of positive potential (Mamidi et al., 2013).

2.3. Measure of the flow rate delivered by the spray nozzles

The flow rate of each individual nozzle was evaluated collecting the liquid delivered during a working time of 60 s and the mean value from five measurements was assumed (ISO, 1997). To this end, the nozzles were subdivided between left and right side of the sprayer and numbered (1 to 7) starting from the nozzle placed at top, closer to the median plane of the machine (Figure 2).

These evaluations were carried out at the highest allowed pressure (300 kPa) and with the same flow-disks, fitted with a 1.2 mm calibrated hole, used for the field tests (ISO, 1997). The flow-rates were checked with a measuring error of less than ±2.5% of the true value (ISO, 2013). According to the technical standard, it was verified that the flow rate of each nozzle did not deviate by more than 10% from the mean flow rate of all the same nozzles mounted on the sprayer (ISO, 2013).

The results obtained, reported in Figure 4, show a mean discharged flow rate of 178.4 mL min^{-1} and that 5 nozzles did not comply with the standard because diverged by more than 10% from this value.

For a better characterization of the machine performance, even if non-included in the normative, these evaluations were executed with the same modality also at the lowest allowed pressure (150 kPa). The results are reported in Figure 5 and highlight a mean discharged flow rate of 136.1 mL min^{-1} and that also with this operative condition there are nozzles that deviate from the mean value by more than 10%.

2.4. The vineyard

The treatments were carried out in a "tendone" vineyard ("Pizzutello" seedless variety) located in a farm of Castellaneta (Taranto Province – Apulia – Italy) territory, where the production of grapes for the fresh market is very widespread. The vineyard was fitted with an anti-hail net and a plastic cover to delay the ripening and then the harvest (Figure 1). The vines, 14 years old, were about 2.50 m × 2.50 m apart, giving a density of 1,600 plants per hectare.

Each vine had four fruit-bearing shoots aligned parallelly to the transit direction of the sprayer, supported by a suitable structure at 1.70 m above the ground level which in turn was held up by 2.60 m wood pillars located just next to the trees. The structure was made by means of crossed iron wires so to obtain rectangular meshes and to realize three sectors in crosswise direction and five rows in lengthwise direction with respect to the forward movements of the sprayer (Figure 6). This grid separates an upper zone, exclusively reserved to the canopy, from a lower zone assigned to the bunches and directly exposed to the spray during Plant Protection Products application.

A second structure (double grid "tendone"), made by crossed iron wires and held up by the same aforesaid wood pillars, was located about at 1.90 m above ground level and supported the shoots in growth.

The protection of this vineyard requires about thirty treatments carried out in the space of eight months, from the end of April to the end of November, using volume application rates in the range 500–1000 L ha^{-1}.

The experimental plan was executed in the phenological stage “Softening of berries” (code 85 of the BBCH - Biologische **B**undesanstalt, **B**undessortenamt und **CH**emische Industrie - scale, October 28) (Eichhorn, 1984).

2.2.1. Morphological measurements

The evaluation of the distribution of the mixture and its penetration into the vegetation were made by arranging the canopy of the inter-row in three contiguous Sectors (hereafter known as S_1, S_2, S_3), separated by the four horizontal lengthwise steel wires of the first grid (Figure 6) and subdividing these Sectors into two Layers (higher canopy layer L_h, lower canopy layer L_l), by means of the second grid (Figure 7). Considering that during the phenological stage of the test the vegetation did not envelop entirely the middle Sector S_2, this latter was still further subdivided into two sub-sectors S_{2a} and S_{2b} engaged by the canopy arising respectively from the shoots placed on the left and right rows (Figures 7). Therefore eight Areas were globally considered for the characterization of the vegetation of the vineyard.

Thickness of the canopy along vertical direction and Leaf Area Index (LAI) were measured to characterize the vineyard. The day before the field tests, the following measurements were carried out on the canopy along the cross-section of the inter-rows selected for the sprayer transit at the level of the vine trunks: minimum and maximum vegetation heights, canopy thickness, minimum and maximum height and width of the fruit-bearing area. Furthermore, all the leaves from 15 randomly chosen shoots were picked and for each of them in laboratory the surface (S_i) and the mass (m_i) were evaluated by means of a digital camera (Nikon D60 with 10.75 Mpixel), a measuring software (Image Pro Plus, Media Cybernetics), and a precision balance. This procedure allowed calculating the following average ratio r_{av}, representative for the phenological stage:

$$r_{av} = \frac{1}{n}\sum_{i=1}^{n}\frac{S_i}{m_i}, \quad (7)$$

being n the number of sampled leaves. The LAI was then calculated for each sector of the canopy, picking and weighing (m_0) all the leaves in a parallelepiped volume with a known ground surface (S_0), according to:

$$\text{LAI} = \frac{r_{av} \cdot m_0}{S_0} \quad (8)$$

The average LAI profiles were adopted as reference to visually adjust the adaptable positioning of the boom sprayers.

2.3. The experimental design

Spray applications were carried out at three forward speeds: 1.11, 1.39, and 1.67 m s^{-1} (4, 5, and 6 km h^{-1}). The electrostatic system was switched on and off, so to evaluate its effect on the foliar deposit when varying the forward speed. The flow rate at the nozzles was kept unchanged across the tests, resulting in different spray volume application rates. The main environmental parameters were measured during the tests: air temperature, wind speed, and relative humidity. Table 1 reports a summary of the operating parameters.

The experimental design included two first-level factors (tractor speed and activation of the electrostatic system) and two second-level factors (Sector and Layer, referring to the sampling location of the leaves on the canopy). Each test condition was replicated three times. Each experimental plot consisted in three adjacent rows about 10 m long and sampling was carried out in the central row (Figure 8). Plots were separated by three unsprayed rows in order to avoid possible overlapping due to spray drift. Spray mixture contained a food dye tracer (yellow tartrazine, Sigma Chemical) at a concentration of 4 g L^{-1}.

2.4. Foliar sampling and data analysis

Four leaves were sampled from each Area, totalling 32 leaves per replication and then 96 leaves per treatment. Each leaf was placed in a Petri dish, suitably labelled according to the sprayer setup, the replicate, and the location on the canopy. Additionally, 10 untreated leaves were picked in order to assess the background deposit.

The unitary foliar deposition was measured in laboratory by means of a spectrophotometric technique. Each leaf was washed with 50 mL of distilled water and the absorbance of the washing mixture was measured by means of a spectrophotometer (6300 model, Jenway Ltd). The unitary deposit was calculated according to the Equation (9):

$$d = \frac{ABS - ABS_b(S)}{ABS_m} \cdot \frac{V_L}{2S} \cdot 1000, \qquad (9)$$

where:

- d: deposit per square centimetre of foliar surface, μL cm^{-2};
- V_L: amount of water used to wash each sample leaf, mL;
- S: foliar surface (one side only), cm^2;
- ABS: absorbance of the sample washing solution;
- ABS_b: corrective absorbance, to take into account the background noise. The correction was adjusted in function of the foliar surface S by using the linear regression equation established analysing the untreated leaves: $ABS_b = 0.0001 \cdot S + 0.0571$;
- ABS_m: absorbance of the mixture sprayed in field.

The surface S of each sampled leaf was estimated by using the same equipment used for computing the LAI, that is digital camera and measuring software.

In order to account for the differences in the spray volume rates and to make consistent the comparisons among the treatments, all deposits were normalized to a common reference volume rate V_R according to the Equation (10):

$$d_n = \frac{d}{V_s} V_R , \qquad (10)$$

where:

- d_n: normalized unitary deposit, μL cm^{-2};
- V_s: sprayed volume rate, L ha^{-1};
- V_R: reference volume rate, L ha^{-1}. V_R was set equal to 100 L ha^{-1}, roughly the average value of the volume rates sprayed in all the treatments.

Deposits d_n were statistically analyzed by applying the hierarchical analysis of variance according to the experimental design: two first-level factors (forward speed, with three levels (4, 5 and 6 km h^{-1}), and electrostatic system, with two levels (on and off)), and two second-level factors (sector, with four levels (S_1, S_{2a}, S_{2b}, S_3), and layer, with two levels (lower L_l and upper L_h)). Raw data were transformed according to the power equation $d'_n = d_n^{0.1}$ so to meet the prerequisites for the application of the analysis: normal distribution of the residuals, assessed by means of the Shapiro-Wilk normality test, and constant variance of the residuals, assessed by means of the Breusch-Pagan test. Plots report mean values of untrasformed data. Mean separation was performed according to the Tukey's HSD (honestly significant difference) test at 5% level of significance. All statistical analyses and graphical representations were carried out by using the open source software *R* (R Core Team, 2012).

3. RESULTS AND DISCUSSION

3.1. Morphological measurements on the vineyard

The fruit-bearing shoots alignment allowed an average profile of the canopy uniform along the inter-rows and the thickness of the vegetation along the vertical direction was conditioned both by the plastic cover, that influenced the upper outline of the canopy, and the green pruning (defoliation, secondary shoots thinning) carried out to eliminate nearly all the leaves and the non-fruit-bearing shoots from the lower canopy level.

The measured average profile of the canopy with two fruit-bearing areas is reported in Figure 9. Along the cross-section of the inter-rows, the canopy was thicker at the level of the vine trunks and its thickness decreased moving from Sectors S_1 and S_3 respectively towards S_{2a} and S_{2b}. The middle area included between these two latter Sectors was without vegetation; this spatial distribution of the canopy was due to the type of pruning, with the fruit-bearing shoots aligned in parallel (Figure 6).

The used winter pruning system and the parallel alignment of the fruit-bearing shoots affected the LAI variability along the cross-section of the inter-row (Table 2). Peak LAI values were registered in Sectors S_{2a} and S_{2b}, that is near the fruit-bearing shoots, and not at the level of the vine trunks (Sectors S_1 and S_3 respectively) where, on the contrary, the greatest canopy thickness was recorded (Table 2 and Figure 9).

3.2. Foliar deposition

Figure 10 reports the mean deposit values at each level of each factor included in the experiment. The overall mean was 0.075 µL cm^{-2} (normalized at 100 L ha^{-1}). A similar research (Cerruto et al., 2008), conducted by using a conventional sprayer (arc-shaped spray boom, hydraulic pulverization, axial fan), reports a mean deposit of 0.270 µL cm^{-2} (normalized at 350 L ha^{-1}). Even if the two experiments are not directly comparable because of the different vineyard features, though the deposits, taking into account the two reference volume rates, are very similar (0.075 vs. 0.077 µL cm^{-2} when normalized at 100 L ha^{-1}). This result shows the capability of ensuring, with this model sprayer, deposits comparable with those achievable by using conventional sprayers, so increasing its versatility.

The mean deposits at the three tractor speeds ranged from 0.067 µL cm^{-2} at 4 km/h up to 0.080 µL cm^{-2} at 5 km/h. The box plots show similar variability in the deposits and no significant differences among the three mean values (Figure 11). Similar results are common in literature when testing the effects of forward speed. Pergher and Lacovig (2005) report that, increasing the forward speed from nearly 6 to nearly 9 km/h in a Casarsa-trained vineyard, does not significantly affect mean spray deposition and deposit variability. The same result is reported in Cerruto (2007) when working from 3 up to 10 km/h in a cordon trained and spur-pruned vineyard.

The effect of the electrostatic system seems to be significant: on average, when it was activated, the mean foliar deposit increased from 0.061 up to 0.088 µL cm^{-2} (+44%) (Figures 10 and 11). This confirms the aims of the electrostatic spraying: an electrostatic charge on droplets improves total deposition (Matthews, 1989; Law, 2001; Zhao et al., 2008; Singh et al., 2013).

Some differences existed among the sectors (Figures 10 and 11): on average, foliar deposits on left and right side of the sampling zone (sectors S_1 and S_3) were higher than those in the central zone (sectors S_{2a} and S_{2b}).

Finally, the highest difference was that observed between the two layers: 0.133 µL cm^{-2} on the lower layer and 0.017 µL cm^{-2} on the upper one. This difference is very difficult to reduce in "tendone" vineyards as the canopy is sprayed on the lower side only (Cerruto et al., 2008; Pascuzzi, 2013).

Table 3 reports the main results of the analysis of variance. They confirm the observations that emerged from the mean-plot and box-plot analysis.

Foliar deposition was not affected by the tractor speed and this result was influenced neither by the electrostatic system nor by the sampling location (Tables 3 and 4). The variability, expressed in terms of coefficient of variation (CV), was quite high (from 107% (5 km/h) up to 121% (6 km/h)), a very common result when working with low volume rates (Cross et al., 2001).

The electrostatic system had a significant effect on the foliar deposition, but the effect was different depending upon the sampling location. The increase in the foliar deposit was located on the lower layer only, while the electrostatic system had no effect on the upper one (Figure 12). This is also confirmed by the cumulative distribution of the deposits, that in the upper layer was the same when switching ON or OFF the electrostatic system (Figure 13). The deposit on the lower layer was 0.106 μL cm^{-2} when the electrostatic system was switched OFF and 0.159 μL cm^{-2} when it was switched ON (+50%); the corresponding values were 0.016 μL cm^{-2} and 0.018 μL cm^{-2} (+12.5%) on the upper layer. So, the electric charge increased the deposit on the most external foliar layer only, without effect on the internal one.

The differences among the sectors were also significant (Figure 14): the mean foliar deposit at the extremities left and right of the sampling zone (sectors S_1 and S_3) was 0.086 μL cm^{-2}, significantly higher than that in the central zone (sectors S_{2a} and S_{2b}, mean value of 0.063 μL cm^{-2}). This result is due to the arrangement of the two spray booms and the direction of the nozzles, oriented towards the lateral zones. The coefficient of variations ranged from 104% (sector S_1) up to 121% (sector S_{2b}).

4. CONCLUSIONS

The results obtained in these first trials allow some remarks about this machine and its use in “tendone” vineyards, even if further experimental tests are required for a better assessment of the sprayer’s performance.

The electrostatic sprayer ESS “150 RB14” is designed to employ low volume of mixtures and to produce droplets in the range of 30−50 micrometers that may be electrostatically charged by induction through an electrode placed inside each nozzle. The spray liquid is sheared into droplets by means of the high velocity due to the expansion of compressed air. Even if the way the liquid is pneumatically atomized by this sprayer is substantially different from that realized in conventional sprayers employed in “tendone” vineyards, the results of this research show that this machine is able to produce overall mean foliar deposits comparable with those obtained with the traditional sprayers.

The forward speed, evaluated in the range 1.11−1.67 m s^{-1}, did not affect significantly the mean foliar deposition and this result was influenced neither by the electrostatic system nor by the sampling location. On the other hand, the arrangement of the two spray booms and the direction of the nozzles, oriented towards the lateral zones of the inter-rows, produced significant differences among the mean foliar deposits at the extremities left and right of the sampling zone and those in the central zone. But the highest differences were observed between the lower layer of the canopy and the upper one, even if this difference is very difficult to reduce in “tendone” vineyards as the canopy is sprayed on the lower side only. The ratio between the deposits measured at the two canopy levels was approximately 7 when the electrostatic system was switched OFF and 9 when it was switched ON. The activation of the electrostatic system produced a significant increase in the mean foliar deposit located on the lower layer only, while it had no effect on the upper one: the electric charge increased the deposit by 50% on the lower layer and only by 12.5% on the upper layer.

These results highlight that the employment of this sprayer to carry out agrochemical treatments in “tendone” vineyards is no more effective than the commonly used traditional sprayers. Conversely, the behaviour of the sprayer, that is the poor deposition inside the canopy with or without the activation of the electrostatic system, can be useful for targeted treatments, as for example those ones concerning the application of bio stimulants of bunches growth, commonly carried out in table grape vineyards. As known, these hormones act by contact and then a right treatment of bio stimulants aimed at the bunches may be performed by means of a suitable adjustment and orientation of each nozzle of the booms towards the area of bunches, in combination with the activation of the electrostatic system. Furthermore, thanks to the electrostatic system, off-target losses are minimized and then likely hormones imbalance, that can cause loss of the ensuing fruit production. On the other hand, being the main objective of pesticide treatments for table grape vineyards the protection of the bunches of grapes, once again the sprayer under test can be effectively used for these targeted treatments, taking into account that the little size of the droplets do not cause marks on the grapes, which would reduce the quality of the product and its commercial value.

Finally, the dense canopy typical of “tendone” vineyards, especially in the later stages of growth, makes hard the penetration of the spray inside the canopy also for the conventional air-assisted sprayers commonly used; even if their airflow rates are remarkably higher (ranging also from 5 to 9 $m^3\ s^{-1}$), they do not ensure sufficient deposition on the top of the canopy. On the other hand, the high air flow rates of these sprayers do not allow targeted treatments as the trial sprayer and then this machine may be regarded as suitable for use in this kind of vineyard, especially if the purpose of spraying is to make treatments to the bunches.

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Table captions

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Table 2. Leaf area index evaluation.

Table 3. Main results of the analysis of variance.

Table 4. Mean values (d_n) and coefficients of variation (CV) of foliar deposits as affected by speed and electrostatic system.

Figure captions

Figure 1. The mounted electrostatic sprayer ESS Company “150 RB” under test.

Figure 2. Arrangement of the spray arms of the electrostatic sprayer ESS Company “150 RB” during the field tests.

Figure 3. The ESS embedded-electrode electrostatic-induction nozzle.

Figure 4. Flow rate discharged by each nozzle at the highest liquid pressure allowed by the sprayer (300 kPa).

Figure 5. Flow rate discharged by each nozzle at the lowest liquid pressure allowed by the sprayer (150 kPa).

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Figure 7. Canopy arrangement in the inter-row (sizes in cm). Sectors (S_1, S_{2a}, S_{2b}, S_3) and Layers (L_h, L_l).

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Tables

Table 1. Operating parameters.

	Treatments					
Parameter	T1	T2	T3	T4	T5	T6
Tractor speed, km h^{-1}	4	4	5	5	6	6
Flow rate, L min^{-1}	2.18	2.18	2.18	2.18	2.18	2.18
Electrostatic system	OFF	ON	OFF	ON	OFF	ON
Volume per tree, mL	82	82	65	65	54	54
Volume rate, L ha^{-1}	131	131	105	105	87	87
Average air temperature, °C	22	22	22	22	22	22
Average HR, %	67	67	67	67	67	67
Average wind speed, m s^{-1}	0.3	0.3	0.3	0.3	0.3	0.3

Table 2. Leaf area index evaluation*.

Sectors			
S_1	S_{2a}	S_{2b}	S_3
4.56	5.21	5.78	4.82

* The middle area of the Sector S_2 without canopy was not considered when computing the LAI.

Table 3. Main results of the analysis of variance.

Source of variation	numDF	denDF	F-value	*p*-value	Significance
Tractor speed (TS)	2	12	2.41	0.1321	ns
Electrostatic system (ES)	1	12	12.78	0.0038	**
TS × ES	2	12	0.85	0.4535	ns
Sector (S)	3	84	3.00	0.0353	*
Layer (L)	1	84	719.22	< 0.0001	***
TS × S	6	84	0.72	0.6363	ns
S × L	2	84	0.11	0.8980	ns
ES × L	1	84	7.64	0.0070	**

numDF: source of variation degree of freedom; denDF: error degree of freedom

ns: not significant; *: significant for $p = 0.05$; **: significant for $p = 0.01$; ***: significant for $p = 0.001$

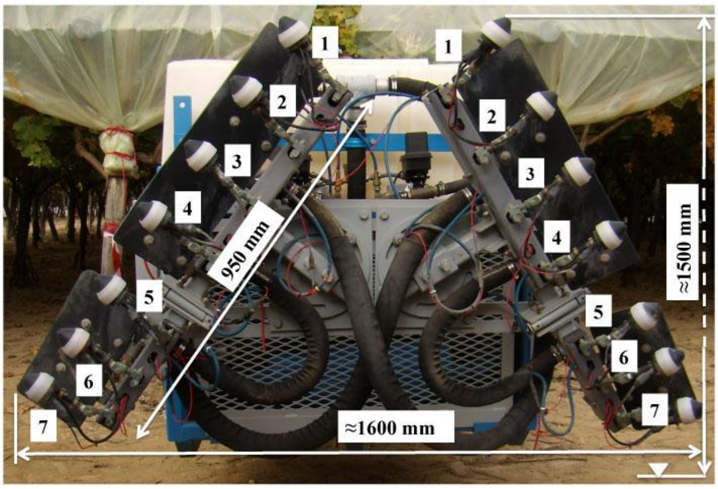
Table 4. Mean values (d_n) and coefficients of variation (CV) of foliar deposits as affected by tractor speed and electrostatic system.

	Electrostatic System OFF		Electrostatic System ON		Mean	
Speed, km/h	d_n, μL cm^{-2}	CV, %	d_n, μL cm^{-2}	CV, %	d_n, μL cm^{-2}	CV, %
4	0.055^{ns}	108	0.080^{ns}	112	0.068^{ns}	114
5	0.066^{ns}	112	0.094^{ns}	100	0.080^{ns}	107
6	0.063^{ns}	108	0.091^{ns}	122	0.077^{ns}	121

Comparisons among speeds; ns: not significant at p=0.05

Figures

Figure 1. The mounted electrostatic sprayer ESS Company “150 RB” under test.



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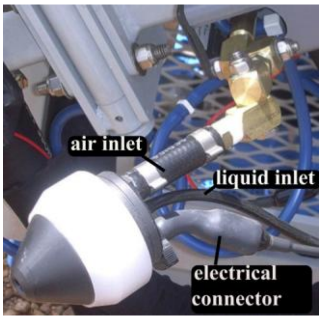

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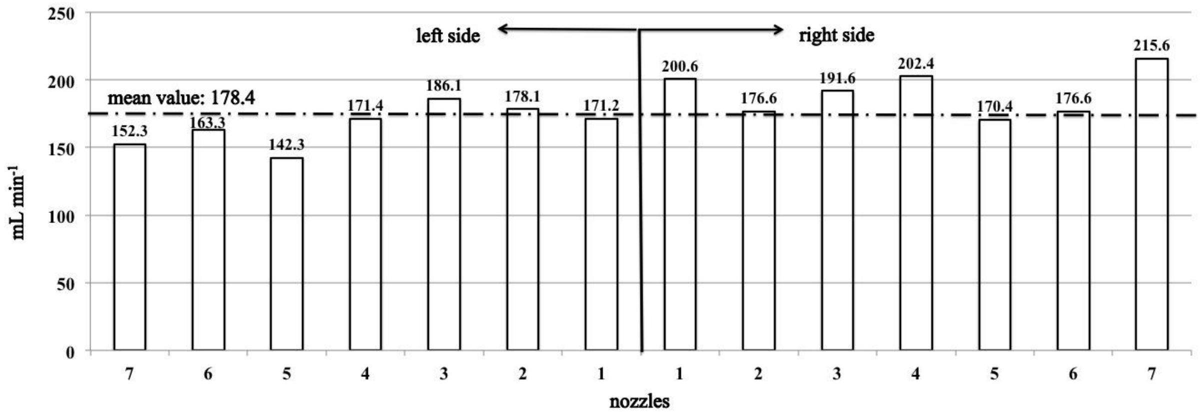

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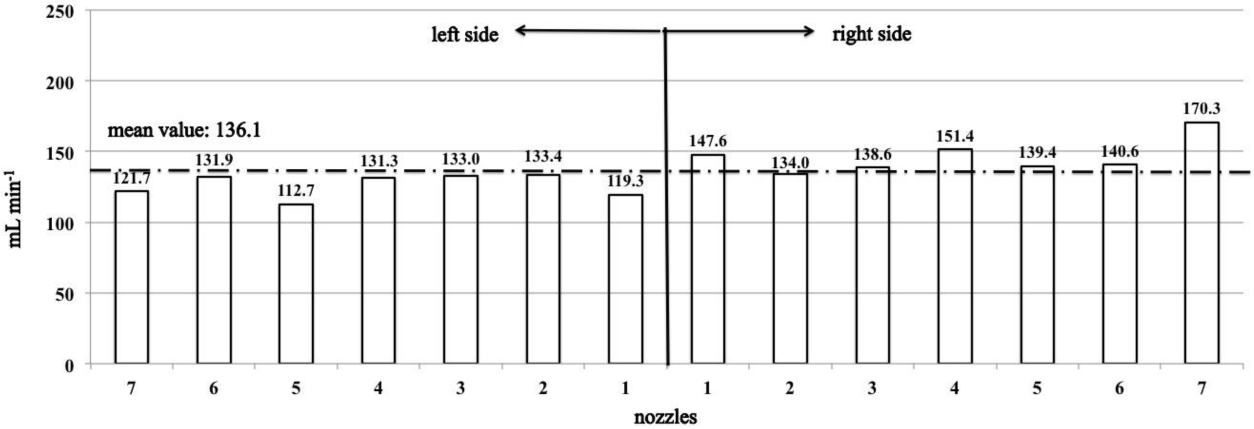

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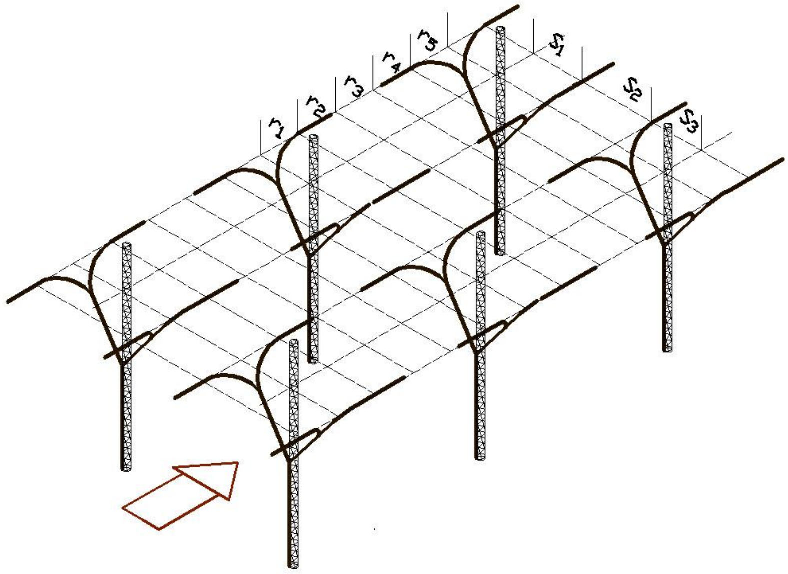

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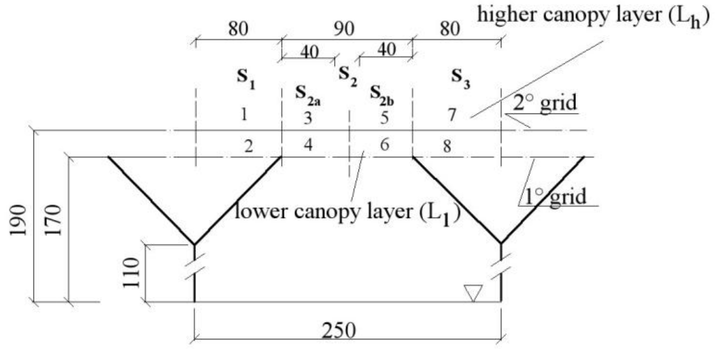

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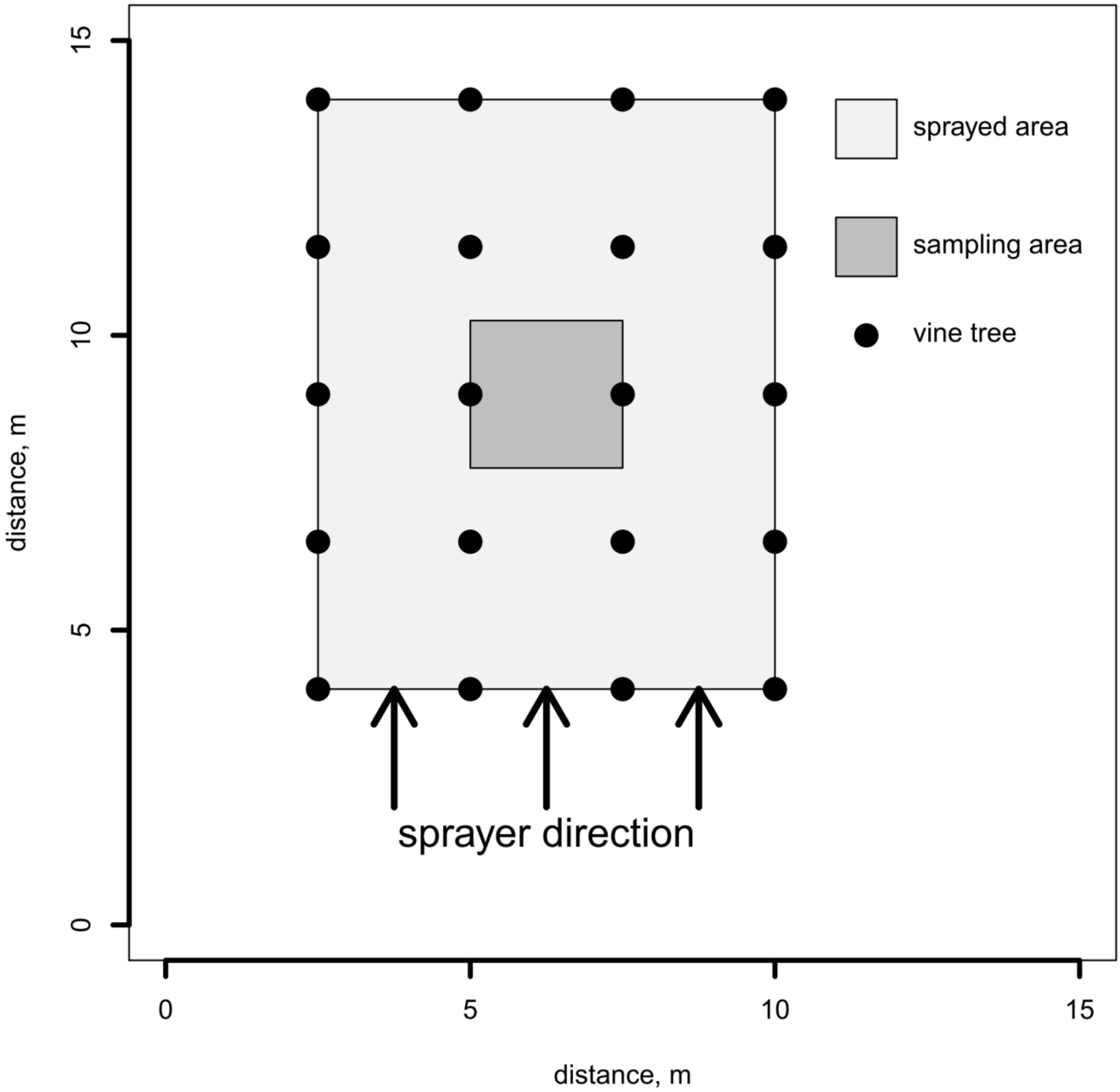

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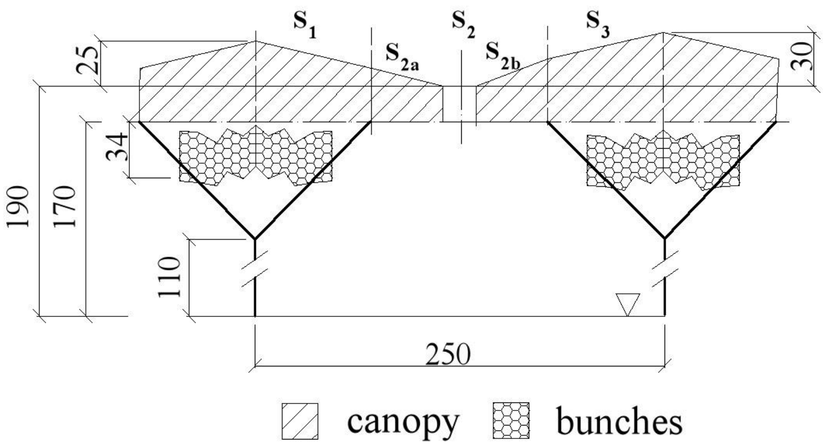

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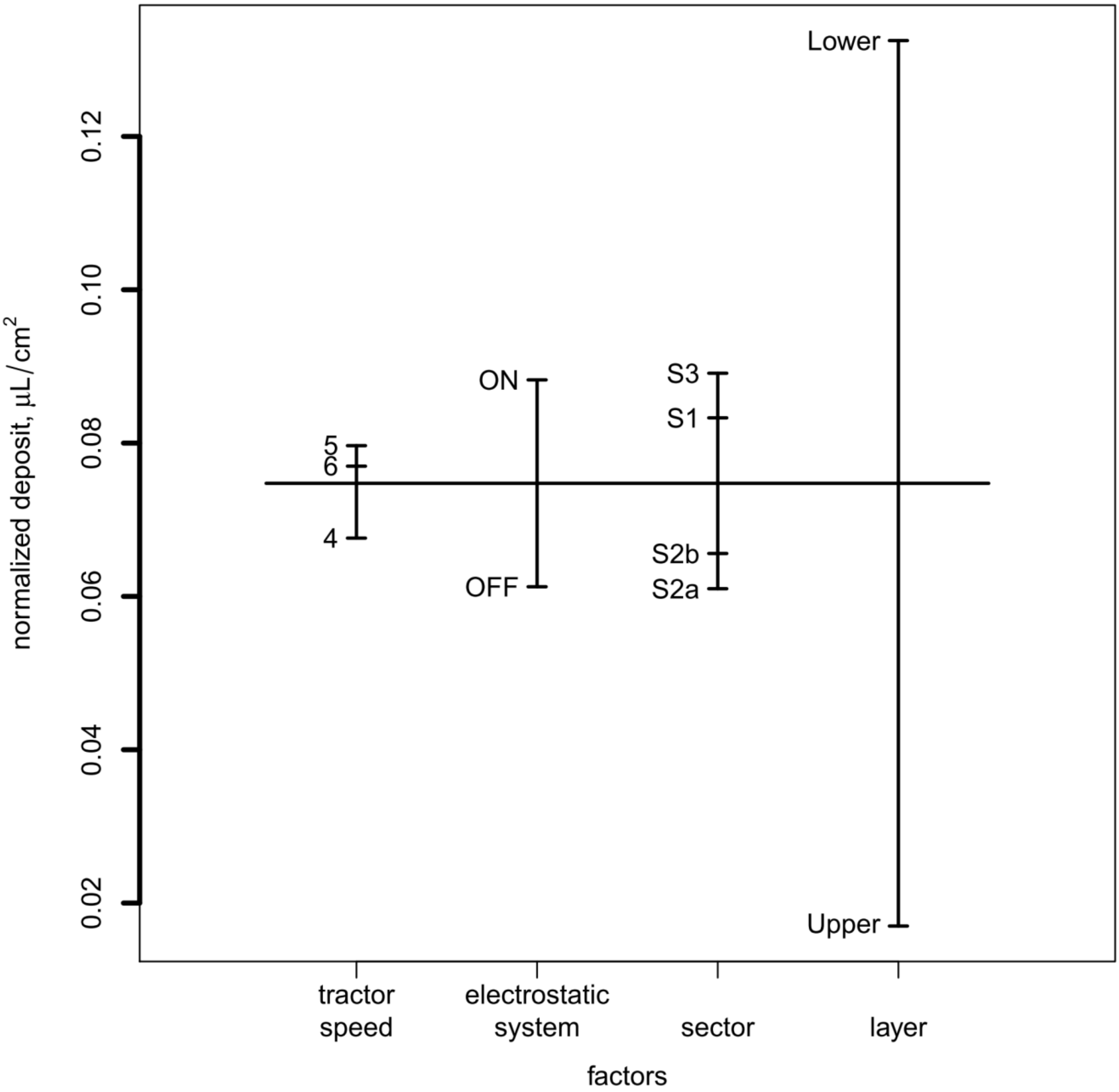

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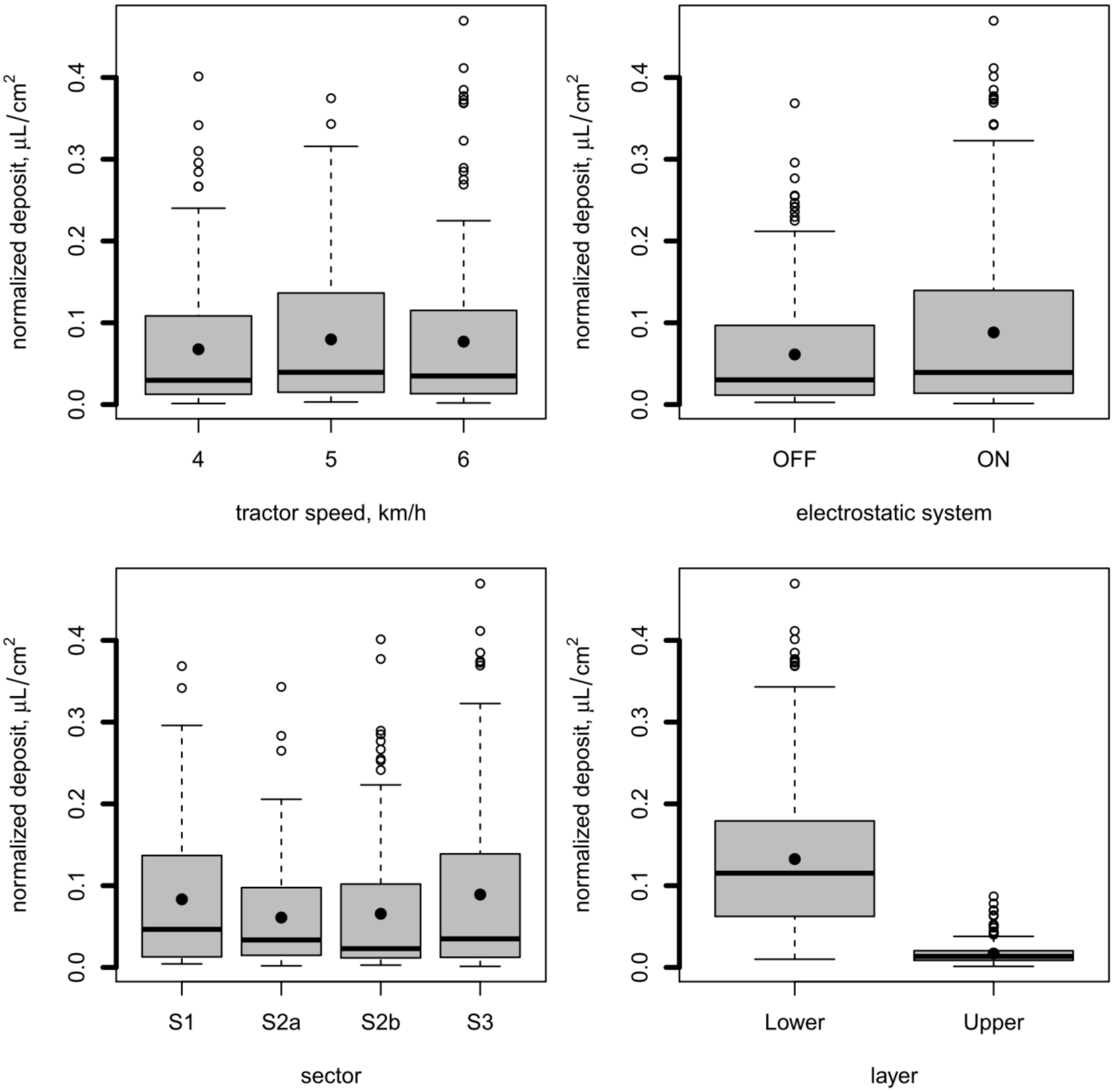

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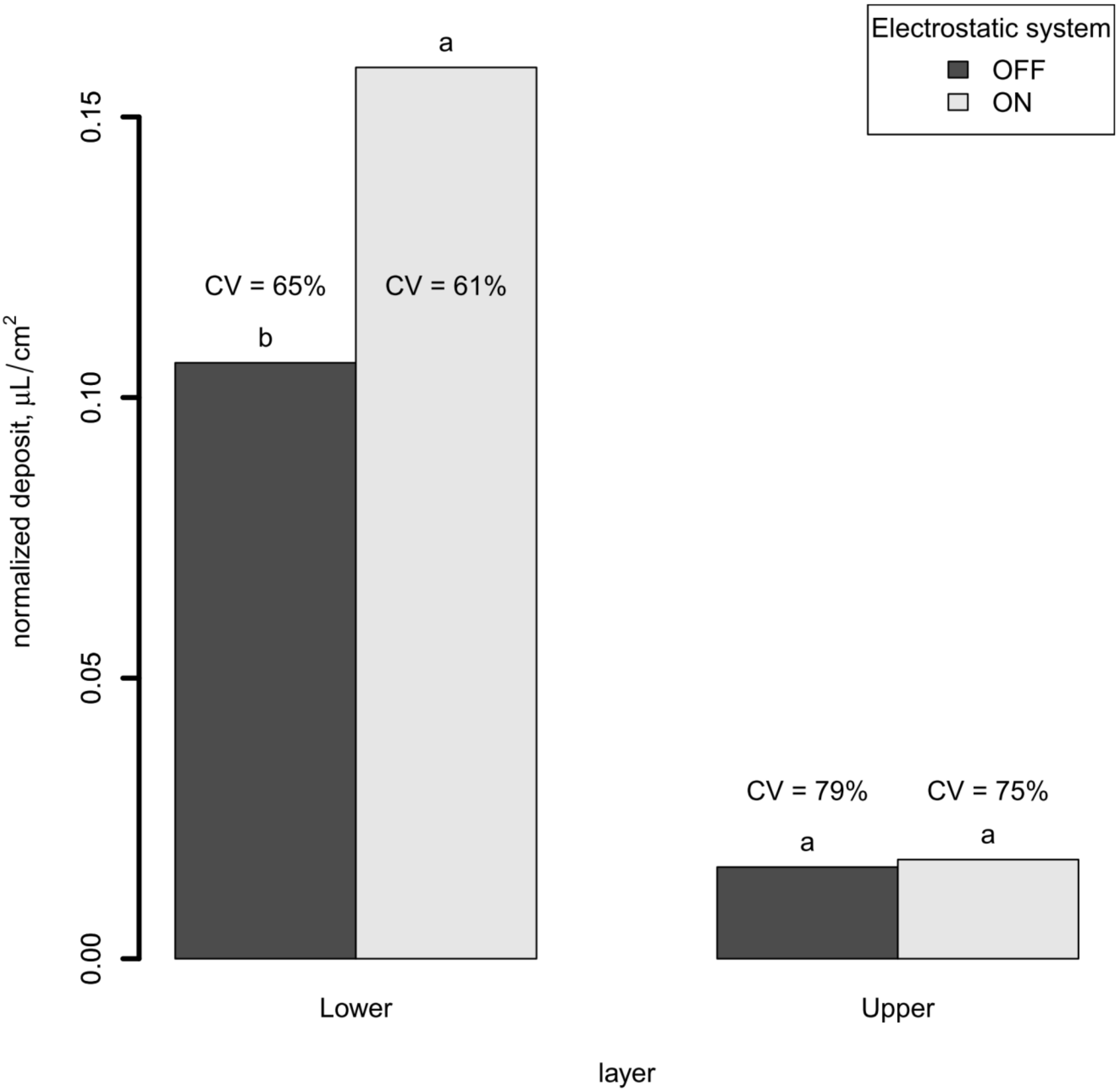

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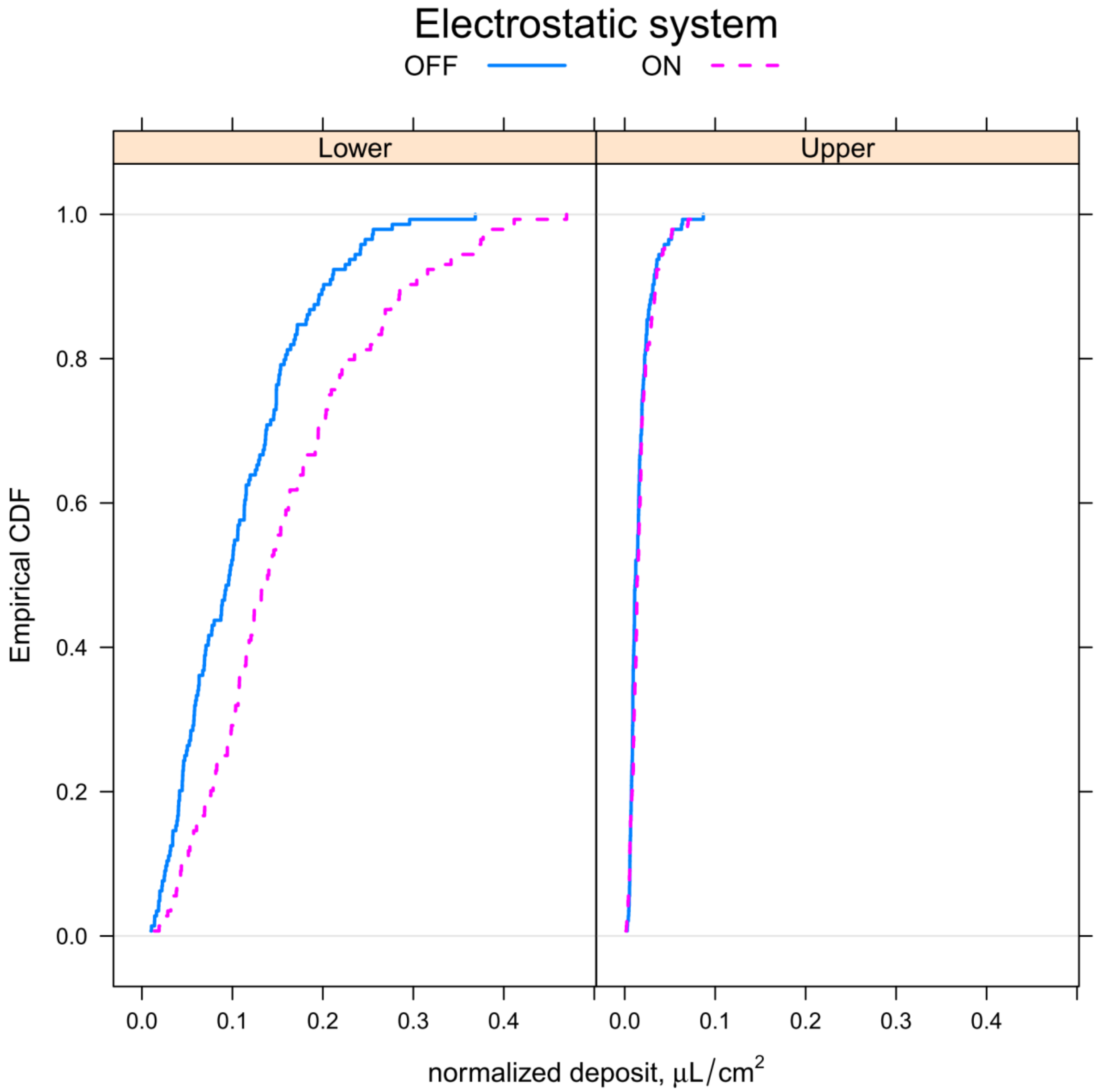

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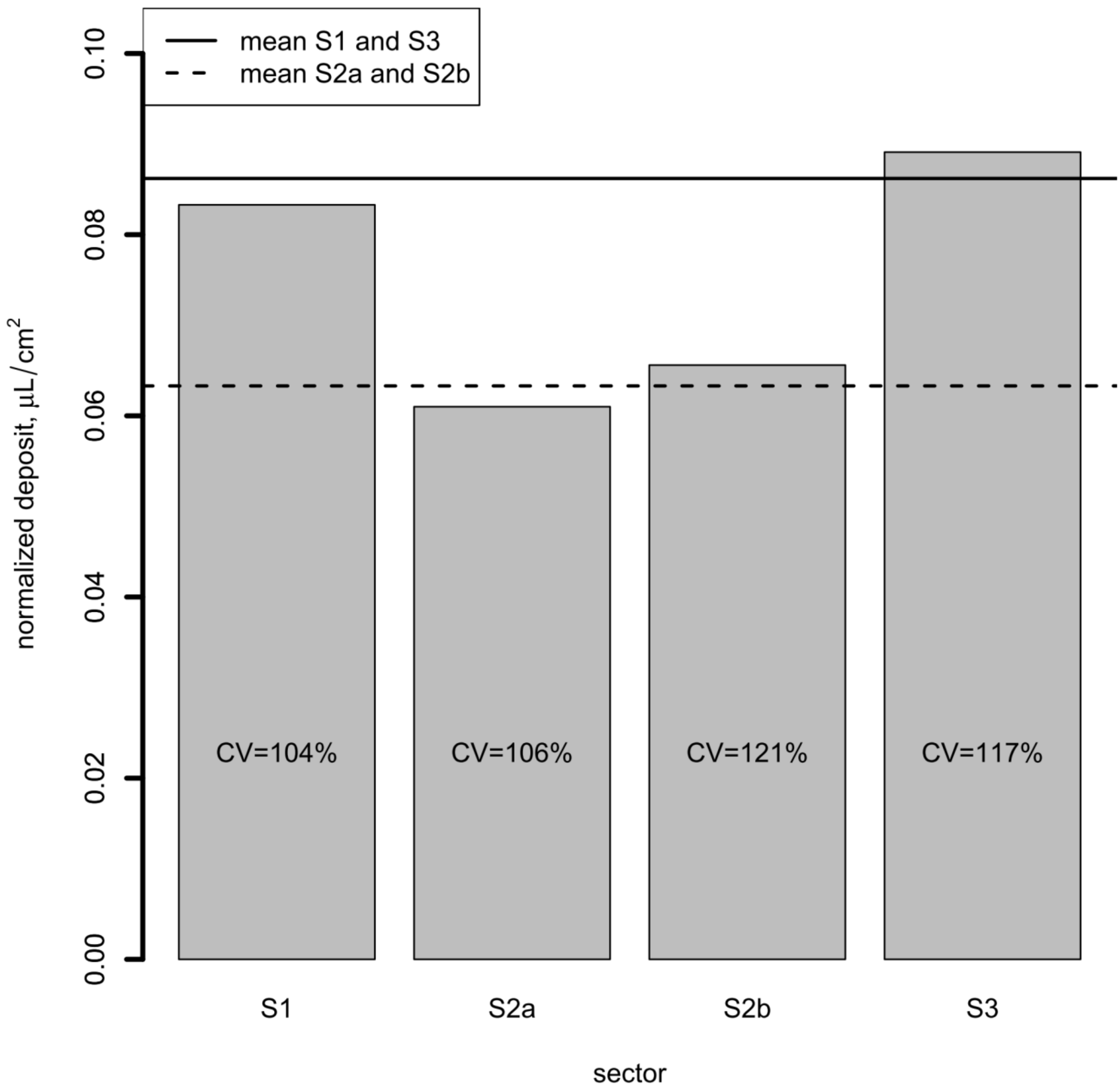

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