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Evaluation of Electrostatic Spraying Equipment in a Greenhouse Pepper Crop

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Abstract: Greenhouse vegetable production is of great importance in southern Europe. It is a cultivation system characterised by a high planting density and environmental conditions that favour the development of pests and diseases. Although alternatives to chemical pest and disease control have been used over recent years in greenhouse crops, it is still mostly plant protection products that are used to protect crops and prevent crop losses. Hand-held spraying equipment is mainly used to apply plant protection products to this type of crop. This equipment is technologically basic, offering low deposition efficiency in the plant canopy, high losses to the ground, and a high risk of worker exposure. In this context, it is important to utilise technologies that reduce the problems associated with using the conventional hand-held sprayers in greenhouses. This study evaluated the deposition and uniformity in the plant canopy and the losses to the ground when applying plant protection products with an electrostatic hand-held sprayer; the results were then compared with applications carried out using a conventional hand-held sprayer. For this purpose, a colorimetric method has been used based on the application of a tartrazine solution. The tests showed that the electrostatic spraying equipment increased the plant canopy deposition by 1.48 times that of the hand-held spray gun, resulting in a 48% reduction in the application rate. There was also a 1.78-times increase in deposition on the underside of the leaves and a 36.36% reduction in losses to the ground. In general, the electrostatic hand-held sprayer improves the effectiveness of the plant canopy deposition and reduces losses to the ground compared to the hand-held spray gun commonly used in pest and disease control.

Keywords: plant protection products; electrostatic sprayer; greenhouse; hand-held sprayer; pepper

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1. Introduction

The foliar application of plant protection products is intended to deposit the necessary amount of active material in the plant canopy to control pests and diseases, distributed homogeneously, and with the fewest possible losses [1,2]. However, traditional spraying systems do not deposit all the sprayed liquid into the plant canopy. There is a fraction that drops to the ground and another fraction that is lost to drift [3,4]. This can cause significant damage to the environment, leave residues in food, and generate risks to human health [5,6].

Although alternative methods to chemical pest and disease control have been used over recent years in greenhouse crops, such as integrated pest management programmes (IPMs) [7,8], it is still mostly plant protection products that are used to protect crops and prevent harvest losses. In this context, it is important to reduce the use of phytosanitary products to guarantee food safety while maintaining the production level; this is because of the negative effects that these products have on the environment and human health, and also in response to the Farm to Fork Strategy [9] included in the European Green Deal [10], which sets a 50% reduction in the use and risk of pesticides by 2030.

In south-eastern Spain, greenhouse vegetable cultivation is of great importance; in the province of Almería alone, there is an effective area of 48,591 ha [11] under plastic, making it one of the principal vegetable production areas in Europe, amounting to 3.6 million tons in the 2020/21 season. This figure represents approximately 23% of vegetable production nationwide, with pepper being the most important crop, accounting for 27% of production, followed by tomato and cucumber at 20 and 15%, respectively [11]. It should be noted that the greenhouse area in the province of Almería only represents 12.7% of the national area dedicated to vegetable production (384,392 ha) [12], although it contributes to slightly more than one fifth of the production (23%). These figures give an idea of the economic and social importance of greenhouse production in the area.

This is a production system where the incidence of pests and diseases is elevated due to the high vegetation density and the environment inside the greenhouse, characterised by high temperatures, high relative humidity, and little air renewal. These circumstances give rise to frequent applications of plant protection products.

As with agriculture in general, in this type of crop, most plant protection products are applied with methods that have low canopy deposition efficiency and which struggle to reach the underside of the leaves where most pests and diseases develop. In greenhouses, the most used equipment are spray guns and lances [13,14], mainly due to their low acquisition and maintenance costs, as well as their ease of use. This equipment causes serious problems for the environment, due to the low effectiveness of the canopy deposition and the high losses to the ground that they produce [15,16]. Such equipment also leads to a high risk of worker exposure [17,18].

The growing concern regarding the use of phytosanitary products, given the risks they pose to human health and the environment, requires the optimization of phytosanitary treatments by employing strategies that allow one to maximize the deposition in the plant canopy and minimize losses to the ground or to drift. All this requires advances in aspects such as Crop Adapted Spraying (CAS), improved application techniques, and the use of new technologies such as electrostatic spraying.

Electrostatic spraying consists of subjecting the population of droplets to a positive electric field so that they become negatively charged. The vegetable canopy has a neutral charge, but as the droplets approach, the negative charge is displaced, resulting in positively charged leaves that attract the sprayed droplets [3]. This technique increases the deposition and uniformity of plant protection product distribution in the plant canopy and reduces environmental pollution [19,20]. It is a very versatile technique that has been applied to a diverse range of crops. Esehaghbeygi et al. [21] studied electrostatic spraying for weed control in a wheat crop, comparing it to equipment with centrifugal nozzles; the results obtained showed that electrostatic spraying provides better weed control and better penetration in high-density crops. In grapevines, different studies have been carried out in which an increase in the average deposition in the plant canopy was obtained [22,23], resulting in a potential reduction in the application volume of around 68% compared to conventional spraying, and more homogenous distribution of the plant protection product in the plant canopy [23]. Neto et al. [24] studied spray deposition on coffee leaves and losses to the ground from hydropneumatic spraying at different spray volumes, both with and without an electrostatic charge; they found that electrostatic spraying resulted in greater deposition on the lower part of the crop and fewer losses to the ground. Patel et al. [25] compared an electrostatic sprayer to different spraying equipment in a cotton crop, finding that the leaf coverage, droplet density, and biological effectiveness were better with the electrostatic spraying treatments than those carried out with the other equipment. Joseph and Bolda [26] studied the effect of electrostatic spraying on the control of *Lygus hesperus* in strawberries, finding that electrostatic spraying achieved a level of control similar to conventional spraying but using less water and at lower cost.

All the above-mentioned studies were carried out on outdoor crops. There are few studies on electrostatic spraying in greenhouses, other than the study carried out by Kabashima et al. [27], which used a spray gun equipped with an electrostatic nozzle to control aphids on chrysanthemums, concluding that the level of control was similar to a conventional treatment but using 40-times less water and posing less risk to those applying the treatment. Moreover, in a greenhouse chrysanthemum crop, Cerqueira et al. [28] used an electrostatic sprayer to control *T. urticae*, obtaining good results even though 20-times less volume was used compared to a conventional sprayer.

Horticultural production in greenhouses is very different in character to that taking place outdoors. These are crops that, when fully developed, have a high vegetation density in an environment with high temperatures and relative humidity, and with little air renewal. Furthermore, the large number of obstacles present in the greenhouse (supports and cultivation lines, etc.) hinder the use of vehicles for carrying out the cultivation tasks, leading to the use of manual equipment that results in less uniform operations and depends, fundamentally, on the operator's expertise. This does not apply to most outdoor crops, where vehicles and equipment can be used, allowing uniform working conditions. Therefore, it is necessary to determine the behaviour of electrostatic spraying in green-house horticultural crops using manual equipment so that operators can move easily be-tween the cultivation lines.

The objective of this work is to evaluate and compare the application of plant protection products on a greenhouse pepper crop, employing electrostatic spraying equipment and manual equipment that is commonly used in the area. In particular, we evaluated the deposition and distribution uniformity of plant protection products in the canopy and the losses to the ground when using an electrostatic hand-held sprayer, which we then compared to applications carried out using a conventional hand-held sprayer.

2. Materials and Methods

2.1. Spray Application Equipment

The spray application equipment indicated below was used to carry out the tests:

1. Hand-held electrostatic spray gun (Tecnostatic, Zaragoza, Spain), equipped with 3 electrostatic nozzles, connected by a double-tube hose to a central unit composed of a compressor and a boiler, which supply air and liquid to the nozzles as the operator moves between the crop lines (Figure 1).
2. Hand-held spray gun (Figure 2) with two steel flat-fan nozzles (NOVI-F, Novifam, Almeria, Spain) connected to a cart equipped with a membrane pump (M-30, Imovilli Pompe s.r.l., Reggio Emilia, Italy) and a 150 L tank.

The spray gun test conditions were established taking into account the usual operator practice. This was considered the application of reference; that is to say, the one that agricultural workers consider appropriate for controlling pests and diseases. The electrostatic sprayer was handled by an operator who was familiar with the equipment, and it was adjusted to achieve adequate broth deposition on the crop. Two different configurations have been considered for the electrostatic spray gun: charged (ESG) and without charge (ESG_WC). In the latter case, we intended to gauge the effect that the electrostatic charge had on distributing the plant protection product in the plant canopy. The working conditions for each of the configurations are shown in Table 1. Under the working conditions set, the population of droplets had a VMD (volume median diameter) of 40 μm, in accordance with the data provided by the manufacturer.

Table 1. Pressure, flow rate, forward speed, and volume rate in each of the tests carried out.

Equipment *	Pressure (bar)	Flow Rate (L min^{-1})	Forward Speed (m s^{-1})	Volume Rate (L ha^{-1})
ESG	1.50 (air); 4.00 (liquid)	0.82	0.68	201.16
ESG_WC	1.50 (air); 4.00 (liquid)	0.82	0.67	203.45
HHSG	26.70	3.60	0.81	742.62

* ESG: Electrostatic Spray Gun; ESG_WC: Electrostatic Spray Gun Without Charge; HHSG: Hand-Held Spray Gun.

Figure 1. Hand-held electrostatic spray gun.

Figure 2. Hand-held spray gun (NOVI-F).

For the hand-held spray gun, the pressure and flow rate were recorded at the pump outlet using a pressure sensor (ARAG s.r.l., Reggio Emilia, Italy) and a flow sensor (ORION Visual Flow, ARAG s.r.l., Reggio Emilia, Italy). To measure the air and liquid pressures in the electrostatic spray gun, pressure gauges placed in the air and liquid outlets of the central unit were used. To measure the flow rate, the liquid collected in a graduated test tube was measured over one minute.

2.2. Experimental Design

The tests were carried out on a pepper crop (*Capsicum annuum*. Cv. Melchor) in an 1800 m^2 greenhouse located on the UAL-ANECOOP Foundation experimental farm in Almería (36°52′ N, 2°17′ W). The peppers were planted in paired lines on the ground, with a 2 m separation between lines and 0.5 m between each pair of plants, forming a density of 2 plants m^{-2}.

For each device tested, three repetitions were carried out following a random block design. A test area consisting of 3 blocks was delineated in the southern part of the greenhouse. Each block consisted of 5 crop lines, of which 3 were used to carry out the tests, separated by a line to avoid possible contamination (Figure 3).

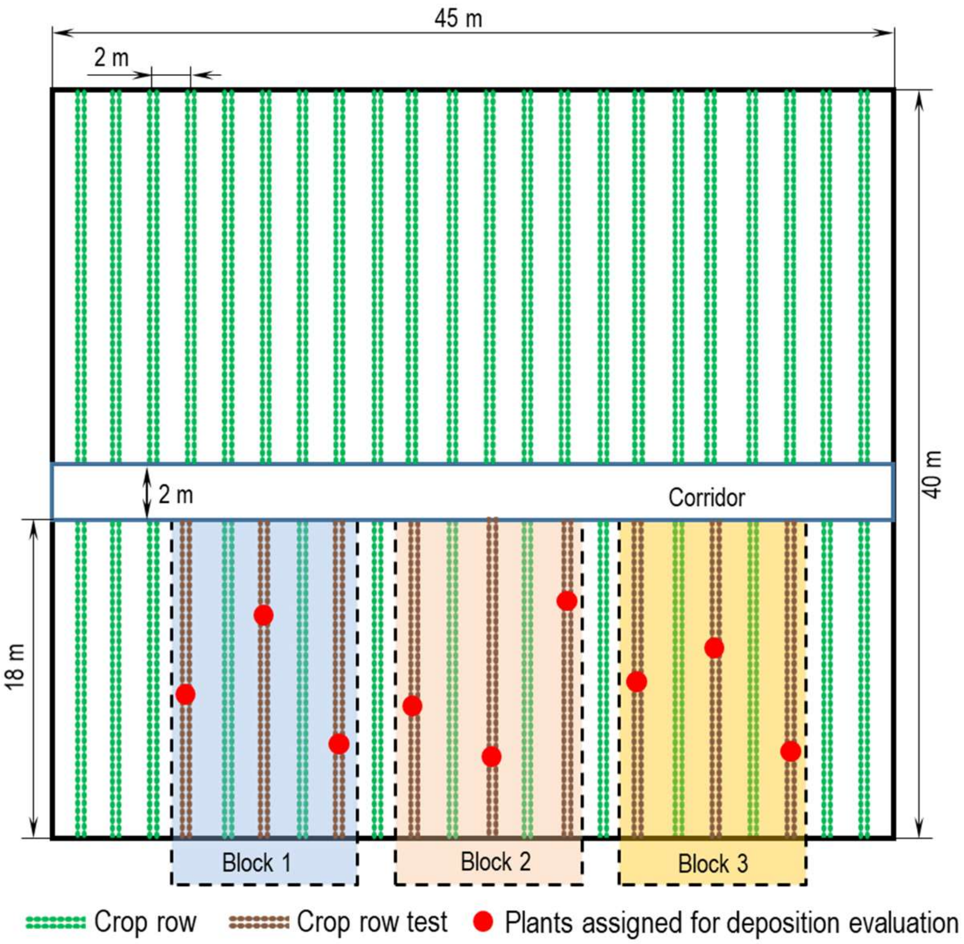

Figure 3. Distribution of the test blocks and location of the sampling areas.

In each block, 3 sprayings were applied, one for each of the devices in a different randomly assigned test line. In each test line, a pair of plants was selected at random from which samples were taken (the leaves) in 8 different zones (Figure 4), at 4 depths (D1, D2, D3 and D4), and 2 heights (H1 and H2). Additionally, in each area, artificial collectors were placed on the underside of the leaves. Collectors were also placed on the ground, 2 coinciding with the outer planes of the crop lines and another in the central zone between the pair of plants (Figure 4). Therefore, a total of 243 samples were taken ((12 zones × 2 [leaves and underside] + 3 soil samples) × 9 pairs of plants). The artificial collectors placed both on the underside of the leaves and on the ground consisted of 3 × 8 cm filter paper strips (Filter-Lab Ref. 1238, Filtros Anoia, S.A., Barcelona). In all the applications, the lines were sprayed on both sides, following the usual practice of operators in the area.

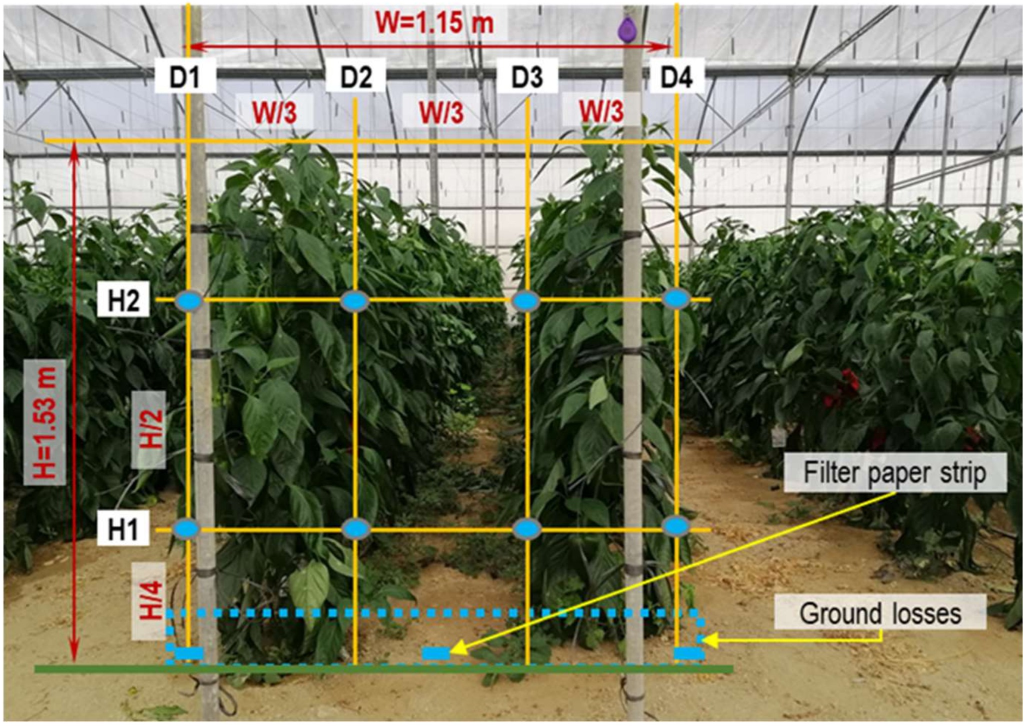

Figure 4. Sampling areas for quantifying the deposition on the plant canopy and the losses to the ground.

During the tests, the temperature and relative humidity were measured using an EE 210 temperature and humidity sensor (E + E Elektronik, Engerwitzdorf, Austria) placed in the centre of the test area at a height of 1.5 m. Table 2 shows the environmental conditions in the greenhouse during the testing. The mean temperature and relative humidity values were 22.3 °C and 64%, respectively.

Table 2. Environmental conditions inside the greenhouse.

Parameter	Minimum	Maximum	Mean
Temperature (°C)	20.7	23.9	22.3
Relative humidity (%)	66	62	64
Wet Temperature [1] (°C)	16.51	18.76	17.64

[1] Determined using a psychometric chart (http://www.sc.ehu.es/nmwmigaj/CartaPsy.htm, accessed on 20 April 2022).

2.3. Characterisation of the Plant Canopy

At the time of testing, the plants had an average height of 1.53 m and an average width of 1.15 m, measured from 6 pairs of plants chosen at random in the greenhouse.

To measure the Leaf Area Index of the crop, 4 pairs of plants were randomly selected; these were completely deleafed to measure the surface of the leaves with a digital planimeter (WinDias, Delta-T Devices Ltd., Cambridge, UK). An LAI of 2.66 was obtained.

2.4. Measurement of Deposition in the Plant Canopy

Tartrazine (Roha Europe, S.L.U., Torrent, Spain) was utilised in the tests as a tracer; this is a water-soluble dye authorized for use in food in the European Union (E-102) and in the USA (FD&C Yellow No. 5), so its handling, both in the field and in the laboratory, does not present any risk to health. This dye is frequently used in such studies [29–32].

Before testing, 10 leaves were collected from each block, taken randomly from different plants and positions; these were used as blank samples to determine the amount of tartrazine present prior to the applications. A tartrazine solution was also prepared in a 50 L tank which was then distributed among the equipment tanks used in the tests.

Once the tests had been carried out in the greenhouse, 1 or 2 leaves were taken from each of the sampling areas indicated above (Figure 5), according to their size, to try to ensure the samples had approximately the same surface area; these were placed in a self-closing bag (20 × 32 cm). Likewise, the filter paper strips were collected and individually inserted into 12 × 18 cm self-sealing bags.

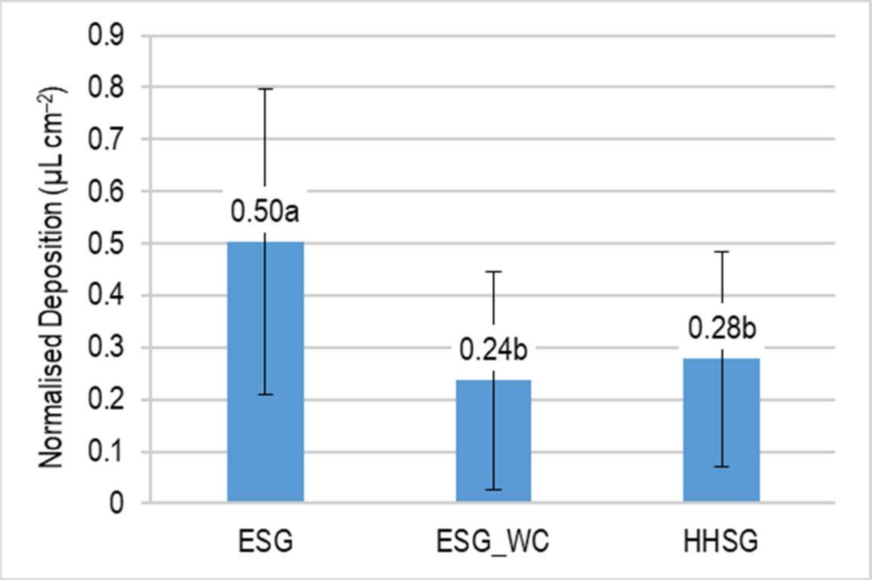

Figure 5. Normalised deposition on the underside of the leaves (μL cm^{-2}). The same letter signifies no significant differences (Duncan's test, $p < 0.05$). Bars signify the means ± SD of the data. ESG: Electrostatic Spray Gun; ESG_WC: Electrostatic Spray Gun Without Charge; HHSG: Hand-Held Spray Gun.

To extract the dye, the leaves were washed with 50 mL of distilled water in the same self-sealing bag for 30 min, after shaking them for 1 min. During the wash time, the samples were stored in a closed container to avoid light degradation. After the washing process, the leaves were removed from the bags, dried on filter paper, and the surface was measured in a planimeter (WinDias, Delta-T Devic-es Ltd., Cambridge, UK). The filter paper strips were washed following a similar procedure but using 25 mL of distilled water and a washing time of 1 h. After washing, the amount of tartrazine in the washing solution was quantified by spectrophotometry based on the Lambert-Beer Law at a wavelength of 425.5 nm using a double-beam UV–visible spectrophotometer (Helios Zeta, Thermospectronic, Cambridge, UK). In this way, the tracer concentration in the washing solution was determined (C_s in μg mL^{-2}). With these data, the wash volume (W in mL), and the sample surface analysed (A in cm^2), the deposition per surface unit (d in μg cm^2) was determined, according to Equation (1).

$$d = \frac{C_S \cdot W}{A} \tag{1}$$

To measure the tracer concentration in the spraying equipment tank, solution samples from the nozzle outlets were taken, obtaining a concentration of 7.79 g L^{-1}; these were measured at a wavelength of 425.5 nm using the UV–visible spectrophotometer, as indicated above.

To compare the results obtained from each device (namely, the depositions quantified for the different plant canopy areas and those on the ground), the results were normalised to eliminate the effect of the different application volume rates used in each of the tests. An application rate volume of 700 L ha^{-1} was taken for the normalisation, which corresponds to the application rate of the hand-held spray gun commonly used in the area; Equation (2) was then used to obtain the normalised deposition (μL cm^{-2}).

$$d_n = \frac{d \cdot V_n}{C_T \cdot V} \tag{2}$$

where d_n is the normalised deposition per unit area (μL cm^{-2}), d is the deposition measured per unit area (μg cm^{-2}), V_n is the reference application rate (700 L ha^{-1}), V is the application rate in the test (L ha^{-1}), and C_T is the tracer concentration in the equipment tank (g L^{-1}). The normalised losses to the ground were calculated according to the above procedure but taking into account the surface of the artificial collector placed on the ground.

2.5. Statistical Analysis

To compare the results of the plant canopy deposition and the losses to the ground, an analysis of variance (ANOVA) was performed, and significant differences were determined using the Duncan test. The normality of the data and the homogeneity of the variances were previously determined using the Kolmogorov–Smirnov ($p < 0.05$) and Levene tests, respectively. All statistical analyses were performed with SPSS v27.0 software (SPSS Inc., an IBM Company, Chicago, IL, USA).

3. Results

3.1. Spray Deposition on the Crop Canopy

The absorbance measured in the blank leaf samples in the three blocks forming the test zone was lower than the spectrophotometer's limit of detection (Abs < 0.0001). Nevertheless, the solution from washing the blank samples was used as a baseline.

The highest normalised deposition in the plant canopy occurred with the electrostatic spray gun, followed by the hand-held spray gun, and the electrostatic spray gun without charge, with values of 0.86, 0.58, and 0.54 μL cm^{-2}, respectively (Table 3). The value obtained with the electrostatic spray gun presented significant differences with respect to the values obtained with the other equipment.

Table 3. Normalised deposition per unit leaf area (mean ± SD) in μL cm^{-2} (d_n) and the coefficient of variation (CV) for the deposition distribution in the crop canopy, in %.

Equipment *	d_n (μL cm^{-2})	CV (%)
ESG	0.86 ± 0.51a	59.35
ESG_WC	0.54 ± 0.32b	59.10
HHSG	0.58 ± 0.34b	57.89

* ESG: Electrostatic Spray Gun; ESG_WC: Electrostatic Spray Gun Without Charge; HHSG: Hand-Held Spray Gun. Means in the same column with the same letter do not differ significantly ($p < 0.05$; Duncan's test).

Regarding the liquid distribution uniformity in the plant canopy, the coefficients of variation presented very similar values for the different equipment tested, with values between 57.89% and 59.35% (Table 3). The most uniform distribution was obtained with the hand-held spray gun, and the least uniform with the electrostatic spray gun.

The normalised deposition on the underside of the leaves followed a similar trend to that of the canopy deposition. The highest value was obtained for the electrostatic spray gun, followed by the hand-held spray gun, and the electrostatic spray gun without charge, with values of 0.50, 0.28, and 0.24 μL cm^{-2}, respectively (Figure 5). In this case, there were also significant differences between the value obtained with the electrostatic spray gun and the rest of the equipment tested.

Figure 6 shows the deposition distribution in the plant canopy between the outer zones (mean of the depositions quantified at depths D1 and D4, Figure 4) and the inner zones (mean of the depositions quantified at depths D2 and D3, Figure 4). For all the equipment tested, the deposition in the outer zone was at least twice that of the deposition in the inner zone. The greatest deposition was obtained with the electrostatic spray gun, both in the outer and inner zones, with values of 1.21 and 0.51 µL cm^{-2}, respectively. For the rest of the equipment, the values were lower in both zones, and there were no significant differences between them, although they were different from those obtained with the electrostatic spray gun.

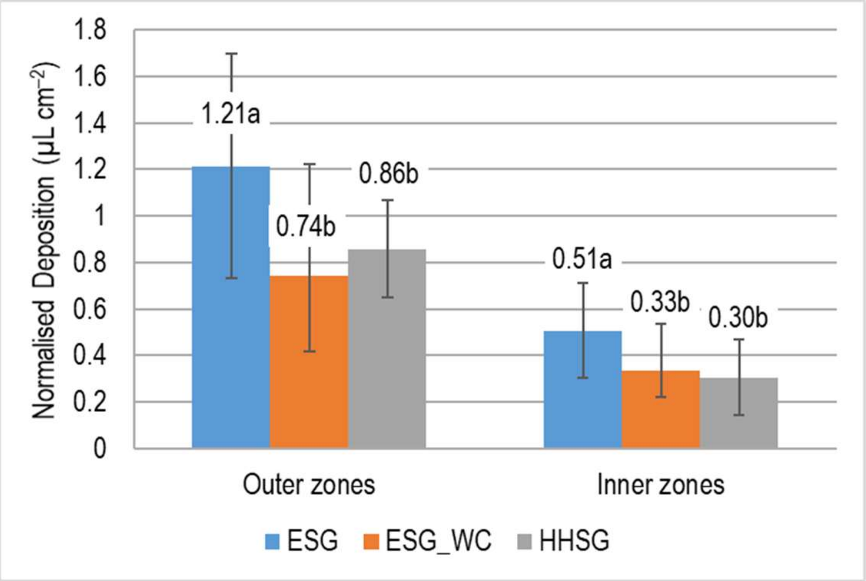

Figure 6. Normalised deposition per unit leaf area in the outer and inner zones of the canopy (µL cm^{-2}). The same letter in the same group of bars signifies that there were no significant differences. (Duncan's test, $p < 0.05$). Bars signify the means ± SD of the data. ESG: Electrostatic Spray Gun; ESG_WC: Electrostatic Spray Gun Without Charge; HHSG: Hand-Held Spray Gun.

3.2. Losses to the Ground

The lowest normalised losses to the ground occurred with the electrostatic spray gun, followed by the electrostatic spray gun without charge, and the hand-held spray gun, with values of 2.12, 2.62, and 3.28 µL cm^{-2} (Figure 7). The values lost to the ground with the electrostatic spray gun, with or without charge, were not statistically different. However, the values obtained with the hand-held spray gun compared to the other equipment tested were statistically different.

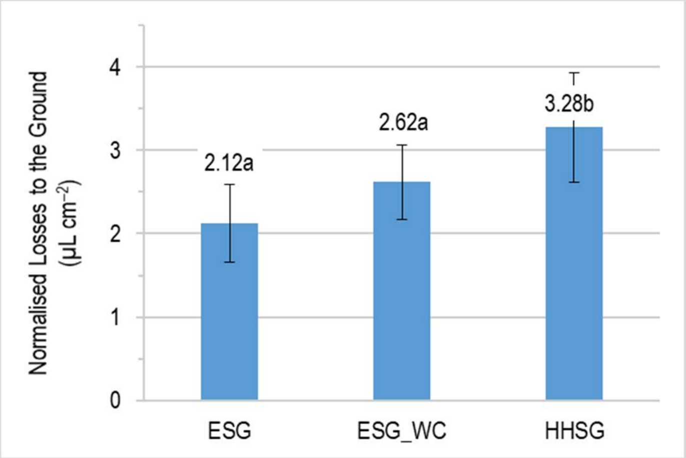

Figure 7. Normalised losses to the ground (µL cm^{-2}). The same letter signifies no significant differences (Duncan's test, $p < 0.05$). Bars signify the means ± SD of the data. ESG: Electrostatic Spray Gun; ESG_WC: Electrostatic Spray Gun Without Charge; HHSG: Hand-Held Spray Gun.

The losses to the ground in the outer zone of the plant canopy (depths D1 and D4, Figure 4) were at least 1.3-times higher than those quantified in the inner zone (Table 4). In both zones, the losses to the ground were lower for the electrostatic spray gun, with values of 2.36 and 1.64 μL cm^{-2} in the outer and inner zones, respectively. Conversely, the greatest losses to the ground occurred with the hand-held spray gun, with values of 3.66 and 2.51 μL cm^{-2}, in the outer and inner zones, respectively.

Table 4. Normalised losses to the ground in the outer and inner zones (mean ± SD) in μL cm^{-2}.

Equipment *	Outer	Inner
ESG	2.36 ± 0.38a	1.64 ± 0.06a
ESG_WC	2.85 ± 0.31b	2.17 ± 0.30ab
HHSG	3.66 ± 0.28c	2.51 ± 0.44b

* ESG: Electrostatic Spray Gun; ESG_WC: Electrostatic Spray Gun Without Charge; HHSG: Hand-Held Spray Gun. Means in the same column with the same letter do not differ significantly (Duncan's test, $p < 0.05$).

4. Discussion

4.1. Plant Canopy Deposition

The highest normalised deposition was obtained with the electrostatic spray gun (Table 3), with a value of 0.86 μL cm^{-2}; this represents a 1.48-times increase compared to the reference application (that carried out with the hand-held spray gun), reflecting the usual practice of agricultural workers in the area. This result indicates that electrostatic spraying could achieve depositions similar to conventional spraying, but with 48% less volume, thus reducing the use of plant protection products and the risk of environmental contamination. These results are in line with studies carried out with electrostatic spraying in other crops, where deposition increases of the order of 0.5 to 2.5 times were quantified, compared to conventional spraying systems [23–26,33].

With regard to the electrostatic spray gun test with the charge turned off, the normalised deposition values (Table 3) did not differ significantly from conventional spraying (the reference application). Comparing the obtained normalised deposition from the electrostatic equipment, with or without charge, significant differences were observed between the obtained values. The charged equipment resulted in a deposition 59.26% higher than in the equipment without charge. Similar results were obtained by Salcedo et al. [23] and Patel et al. [34] in studies carried out on other crops. These results indicate that the charge has an important effect on the retention of droplets in the vegetation, allowing one to use small droplet populations that provide better plant canopy deposition [35]. Otherwise, small droplet populations would find it difficult to reach the vegetation in greenhouse environments, as they would evaporate rapidly. The electrostatic spray gun generates a population with a VMD of 40 μm droplets (data provided by the manufacturer) which, for the environmental conditions, found in the greenhouse during the test (Table 2) would have a lifetime to extinction of 4.3 s, calculated using Equation (3), where t is the lifetime to extinction (in s), d is the diameter of the droplets (in mm), and ΔT is the temperature difference (°C) between the wet and dry temperature [36]. For this reason, when the charge is deactivated, the deposition in the plant canopy is significantly lower than when the charge is activated.

$$t = \frac{d^2}{80 \cdot \Delta T} \tag{3}$$

The spatial uniformity of the normalised deposition in the plant canopy, quantified by the coefficient of variation (CV) of the samples from each treatment (Table 3), indicates that all the equipment tested generated uneven distributions, with coefficients of variation between 57.89 and 59.35%. These are values typical of manual spraying equipment used in greenhouse crops that have significant vertical development, where the uniformity of the spatial distribution is highly conditioned by the variation in the advancement speed and the regularity of the movement of the operator's arm [16,32]. However, the best uniformity was obtained with the conventional application, followed by the charged and without charge equipment. In a study carried out on grapevine by Salcedo et al. [23], better uniformity was also obtained with conventional application equipment compared to an electrostatic sprayer.

Another aspect that contributes to the lack of spatial deposition uniformity is the difficulty in reaching the inner zones of the canopy. Figure 6 shows the distribution of the normalised deposition between the outer (depths D1 and D4, Figure 4) and inner (depths D2 and D3) zones of the plant canopy. In all the equipment tested, the majority of the quantified deposition was concentrated in the outer zones, with similar distribution between the outer/inner zones of approximately 70/30%. Therefore, none of the equipment tested improved penetration into the plant canopy although the electrostatic spray gun generated inner zone deposition at least 1.5-times higher than that obtained by the equipment without charge, the differences being significant. This is a difference of the same order as that obtained in the normalised deposition for the entire plant canopy.

A major challenge for plant protection product application equipment is to generate adequate deposition on the underside of the leaves to ensure pest and disease control. The data for the normalised deposition on the underside of the leaves (Figure 5) show that the electrostatic spray gun generated deposition in this zone that was 1.78 and 2.08 times higher than that of the conventional spraying equipment and the system without charge, respectively, the differences being significant. There are no significant differences between the conventional spraying equipment (the hand-held spray gun) and the electrostatic system without charge. These results indicate that using a population of small (40 μm, according to the manufacturer), electrostatically charged droplets allows the underside of the leaves to be reached more efficiently than the spraying systems without charge. Maski and Durairaj [37] and Gan-Mor et al. [38] obtained similar results when comparing an electrostatic system with and without charge. Specifically, Gan-Mor et al. [38] recorded a deposition two-times higher on the underside of the grapevine when using an electrostatic system compared to using one without charge. This behaviour is mainly due to the wraparound effect, which is generated in an electrostatically charged spray, allowing better coverage of the back surface [3,20,39].

4.2. Losses to the Ground

Figure 7 shows the losses to the ground values that occurred with the different equipment tested. In general, losses to the ground were high for all the equipment tested, with values between 2.12 and 3.28 $\mu L\ cm^{-2}$, for the electrostatic spray gun and the hand-held spray gun, respectively. Most of the losses occurred in the outer zone (depths D1 and D4, Figure 4) of the canopy, with values at least 1.3-times higher than those in the inner zone, for all the equipment tested (Table 4).

The greatest losses to the ground were generated when using the hand-held spray gun, a value of 3.28 $\mu L\ cm^{-2}$, which is of the same order as that obtained by Sánchez-Hermosilla et al. [32] in a pepper crop sprayed with a similar hand-held spray gun. In the case of hand-held spray guns, this type of loss occurred mainly from the droplets being directly projected during the downward movement of the operator's arm, from falling droplets that did not reach the plant, and from droplets running off the leaf surfaces [32].

In the case of electrostatic spray guns with and without charge, the losses to the ground did not differ significantly and were lower than those obtained with the reference application (the hand-held spray gun). Specifically, with the charged system, losses to the ground were 36.36% lower than those of the reference application. Due to the small size of the droplet population generated by the electrostatic spray gun, most of the losses occurred from the droplets being directly projected downwards with the movement of the operator's arm. It is unlikely that there is run-off of the droplets that reach the vegetation, due to their small size, which significantly reduces the gravitational action. Similarly, droplets that fail to reach the vegetation are also unlikely to fall to the ground—the small size of the droplets and the environmental conditions inside the greenhouse make them evaporate quickly; therefore, they travel only very short distances before evaporating. The theoretical distance

(D, in cm) that a drop of diameter d (d, in mm) travels as a consequence of gravity before evaporating is given by Equation (4) [36].

$$D = \frac{1.5 \cdot 10^{-3} \cdot d^4}{80 \cdot \Delta T} \quad (4)$$

where ΔT is the temperature difference (C) between the wet and dry temperature (Table 2), which for the tests carried out has a value of 4.65 °C. Under these conditions, the 40 μm droplets would travel a maximum distance of 10.3 cm before evaporating. Considering that the canopy has a height of 1.53 m, the probability that the droplets that do not reach the vegetation fall to the ground is very low. Therefore, as indicated above, in the case of the electrostatic spray gun, the losses to the ground mainly occur by direct projection of the droplets.

5. Conclusions

The tests carried out have shown that the electrostatic spraying equipment improves plant canopy deposition by 1.48 times compared to the hand-held spray gun. This is a significant increase that would reduce the application rate by 48% while achieving the same deposition as the hand-held spray gun commonly used in pest and disease control, thus reducing the use of plant protection products and the risk of environmental contamination.

The increased plant canopy deposition when using electrostatic equipment is mainly due to the electrostatic charge effect. When the same equipment is used with the charge deactivated, the deposition is significantly reduced, with values similar to those of the reference application (the hand-held spray gun).

In general, the spatial deposition in the canopy was not uniform, with coefficients of variation higher than 57% for all the equipment tested, due, fundamentally, to reaching the internal vegetation zones. In this case, electrostatic spraying performed somewhat worse than the hand-held spray gun.

The electrostatic equipment more efficiently reached the underside of the leaves. The deposition on the underside generated by the electrostatic equipment was 1.78 times greater than that obtained with the hand-held spray gun. This improvement is due to the characteristic wraparound effect of electrostatically charged droplets, permitting greater deposition on the underside of the leaves, since the same equipment without charge generated underleaf deposition similar to that obtained with the reference application.

Regarding losses to the ground, in general, they were high for all the tested equipment. However, the electrostatic equipment generated losses to the ground 36.36% lower than the reference application.

Generally, it can be concluded that the electrostatic equipment generated more efficient applications, with greater depositions in the canopy, lower losses to the ground, and better reach to the underside of the leaves, compared to the hand-held spray gun commonly used in the area for the control of pests and diseases.

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