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Evaluation of the Effect of Different Hand-Held Sprayer Types on a Greenhouse Pepper Crop

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Abstract: The cultivation of vegetables in greenhouses is characterised by high planting density and environmental conditions that favour the development of pests and diseases. These are mainly controlled using plant protection products applied with a hand-held sprayer. This is inefficient low-tech equipment that is difficult to calibrate. The study evaluates one hand-held spray gun and two hand-held spray lances that are widely used in greenhouse vegetable crops. The tests were carried out on a pepper crop at two different developmental stages. Plant canopy deposition and losses to the ground were quantified using a colorimetric method based on applying a tartrazine solution. The results show that the flat-fan spray lance obtains a more uniform spray distribution in the plant canopy and results in losses to the ground that are between 2 and 2.75 times less than when using the other hand-held sprayers tested.

Keywords: greenhouse; hand-held sprayer; plant protection products; crop protection

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1. Introduction

In south-eastern Spain, greenhouse vegetable cultivation has increased substantially over recent years, with the cultivated surface area now amounting to around 32,234 ha [1]. This has made Almería province one of the leading vegetable cultivation areas in Europe, with a total production of 3.62 million tonnes in the year 2019–2020, representing approximately 25% of the national vegetable production. Pepper is the most important crop, accounting for 26% of the production, followed by tomato and cucumber, at 22% and 16%, respectively [1]. This sector has been very competitive in recent years compared to other production areas due to the relatively low production costs.

Pest and disease control in this type of crop is mainly carried out through the use of plant protection products, although in recent years the implementation of integrated pest management programs (IPMs) has contributed to their reduction [2–6]. However, IPM practices are still only implemented on a small scale and given the high concentration of greenhouses in the area, the risk of environmental pollution due to pesticide use has increased. There are studies that have detected the presence of pesticides in the soil [7,8] as well as in surface and groundwater.

The negative effects of plant protection products on the environment and human health has led to the development of important legislative initiatives. At the European level, Directive 2009/128/EC [9] on the sustainable use of pesticides was launched in 2009, with the aim of establishing a framework to reduce the risks to human health and the environment and to encourage the use of pest control techniques that reduce or eliminate the use of pesticides. More recently, in 2019, the European Commission presented its Green Deal communication [10], which strives to achieve a sustainable economy in the European

Union, supported by various strategies such as the Farm to Fork Strategy, which sets out a 50% reduction in the use and risk of pesticides by 2030 [11].

In general, the foliar application of plant protection products is considered an inefficient process because only a fraction of the sprayed liquid is retained on the vegetal canopy whilst the rest is lost to the ground or to drift [12,13]. Likewise, an application is considered adequate when the spray deposition on the vegetal canopy is close to the control threshold for the infestation or disease and is homogenously distributed, yet with minimal losses to the ground or to drift [13,14]. Therefore, to study spraying equipment in the field, it is necessary to quantify the quantity and spatial distribution of the spray deposition on the vegetal canopy and the losses produced, mainly to the ground and to drift. In the case of greenhouse crops, the major losses are to the ground, since drift losses do not occur given the closed nature of the facilities.

Numerous studies have shown that the spraying equipment is one of the most influential factors regarding the rational use of plant protection products on different crop types, including greenhouse horticultural crops [14–21]. The equipment most used on greenhouse horticultural crops are hand-held spray guns and spray lances [22–25] as these are low-cost, easily maintained devices that adapt well to different crop configurations and greenhouse types. Agricultural workers usually work with this type of equipment at high pressures (>20 bar) and high application rates [16,26,27]. For these reasons, and because this equipment is difficult to calibrate and its handling is influenced by the operator's expertise, inefficient spraying occurs, which poses an important risk to the environment. Generally, the distribution of plant protection products on the vegetal canopy using hand-held sprayers is not very uniform and significant losses to the ground occur [14,21,27]. Furthermore, using this equipment results in a high risk of operator exposure [19,28–32], which can lead to adverse health effects.

The abovementioned drawbacks have prompted the use of other greenhouse application equipment over recent years, based on vertical spray booms mounted on manual trolleys [14,33], on self-propelled vehicles [21,34] or on autonomous vehicles [18,24,35]. Employing vertical spray booms allows one to optimise the application of plant protection products by reducing the application rate and ground losses [21,36]. However, this equipment has still only been used on a few greenhouse horticultural crops.

The objective of this work is to analyse and compare the distribution of plant protection products from the hand-held sprayers present in a pepper crop plant canopy along with the losses to the ground caused by each of them. The tests were carried out with the most common hand-held sprayers used on greenhouse crops in south-eastern Spain. Specifically, we have evaluated the deposition in plant canopy and ground losses originating from one hand-held spray gun and two hand-held spray lances, each of which are widely used in the area.

2. Materials and Methods

2.1. Spraying Equipment Used

In the tests, one hand-held spray gun and two hand-held spray lances that are widely used in the area have been evaluated. Their characteristics are described below:

1. Trigger spray gun (Braglia Srl, Reggio Emilia, Italy): this spray gun (Figure 1a) is equipped with a nozzle consisting of a hexagonal brass body with helical grooves and an outlet hole (1.5 mm in diameter). It has a side lever that moves an internal rod, allowing the liquid to be driven through the central part of the nozzle or through the helical grooves. This produces an adjustable spray pattern, from a straight concentrated stream to a hollow cone. A trigger opens or closes the liquid outlet.
2. Rotating-handle spray lance (Sirfran S.L., Alicante, Spain): this spray lance (Figure 1b) is equipped with a cone nozzle that has a variable turbulence chamber and an outlet hole (1.5 mm in diameter). It has a rotating handle to switch the spray lance valve from the closed to the maximum flow position. As the handle is turned, the depth of

the turbulence chamber is modified, changing the spray pattern from a hollow-coned spray to a straight stream.

3. Flat-fan spray lance (Novi Fan S.L., Almería, Spain): this spray lance (Figure 2a) is equipped with two steel flat-fan nozzles, which form angles of 40° and 70° from the outlet tube axis (Figure 2b).

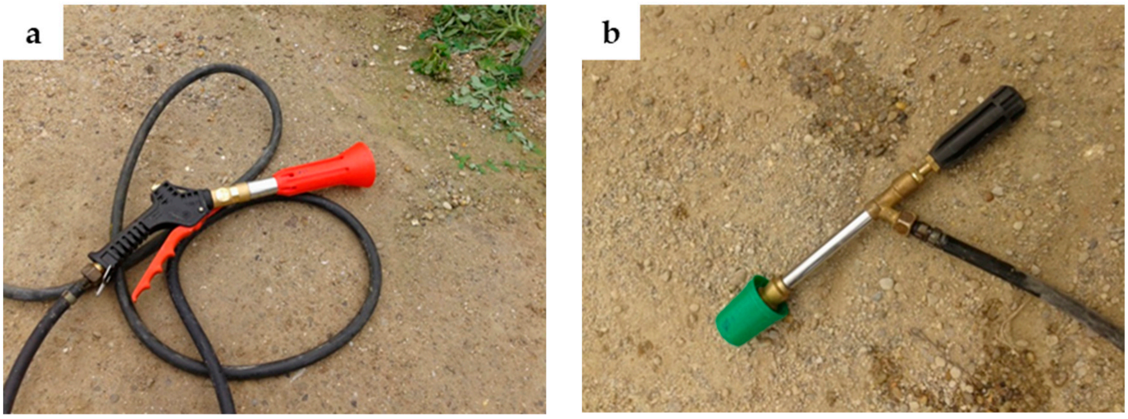

Figure 1. Trigger spray gun (**a**). Rotating-handle spray gun (**b**).

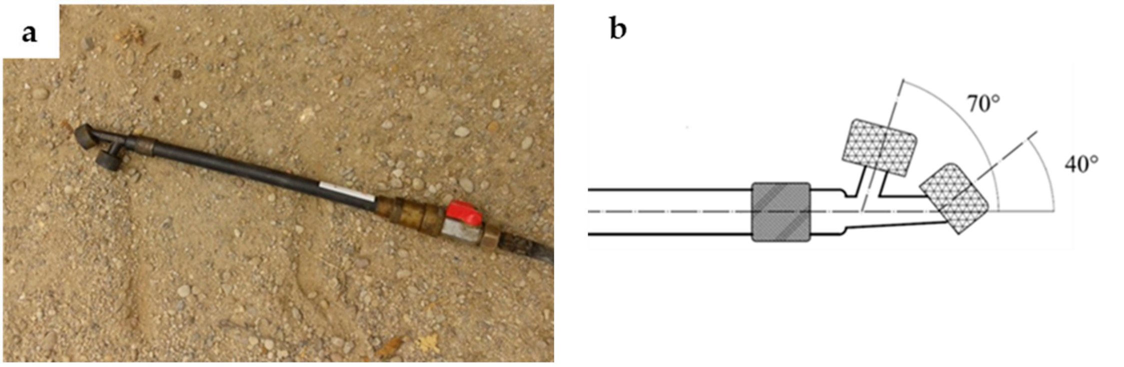

Figure 2. Flat-fan spray lance (**a**). Position of the twin flat-fan nozzles (**b**).

The hand-held sprayers were connected to a forklift carrying a 100 L tank and a membrane pump (M-30, Imovilli Pompe S.R.L., Reggio Emilia, Italy) by means of a 25 m long hose (17mm in diameter). The pressure and flow data were recorded at the pump outlet using a datalogger (DataChart 1250, Monarch Instrument, Amherst, NH, USA) equipped with a pressure sensor (ARAG s.r.l., Reggio Emilia, Italy) and a flow sensor (ORION Visual Flow, ARAG s.r.l., Reggio Emilia, Italy).

2.2. Experimental Design

The tests were conducted in the southern half (45 × 20 m^2) of an 1800 m^2 greenhouse located at the Foundation ANECOOP-UAL experimental facilities at the University of Almería (36°52′ N, 2°17′ W).

A pepper crop was used in the tests (*Capsicum annuum*, cv. Melchor), planted in a twin-row system, with a 2 m separation between the lines and 0.5 m between each pair of plants (2 plants/m^{-2}). The spray equipment tests were carried out at two different crop stages. The crop characteristics in the 2 tests carried out are listed in Table 1. The leaf area index (LAI) was measured from 6 plants taken at random in the greenhouse. The plants were completely stripped of their leaves and the surface area of each leaf was measured with an electronic planimeter (WinDias, Delta-T Devices Ltd., Cambridge, UK).

Table 1. Crop Characteristics.

Test	LAI	Crop Height (m)	Crop Depth (m)
1	3.20	1.44	1.13
2	4.75	1.75	1.08

The test area consisted of 25 crop lines, each of which was 18 m long with a north–south orientation, divided into 3 blocks. Each block contained 6 crop lines, 3 of which were used for Test 1 and the other 3 for Test 2, located alternately to avoid possible contamination between applications in the same test (Figure 3).

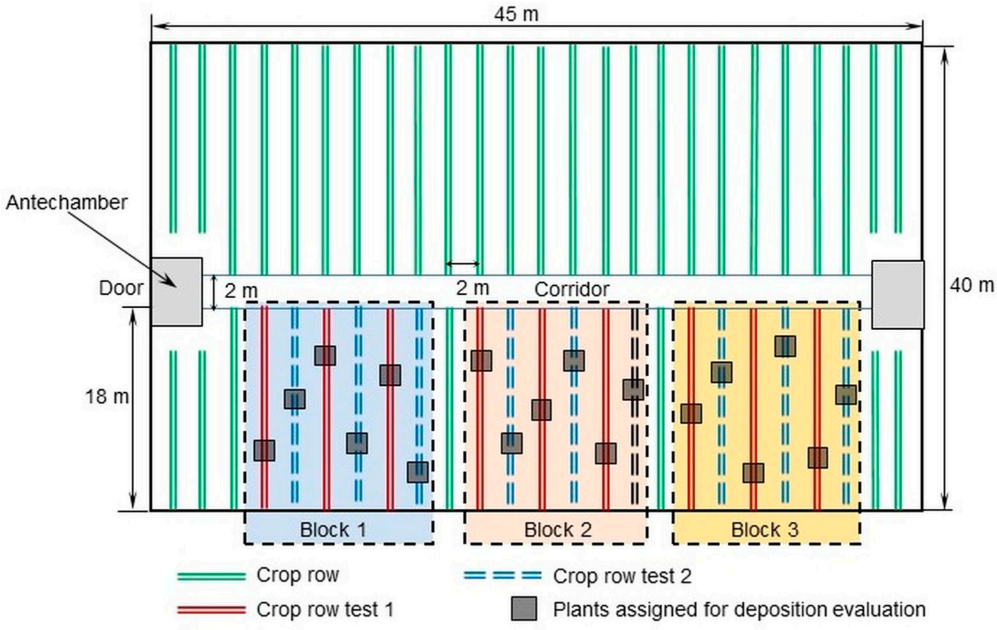

Figure 3. Floor plan of the greenhouse indicating the sampling blocks for the experimental plants.

In each block, and for each test, 3 applications were carried out, one for each hand-held sprayer on a different randomly assigned crop line. In each test line, a pair of plants was randomly selected for sampling; this was conducted in 12 different zones (at 4 depths and 3 heights; Figure 4). On the ground, coincident with the external layer (P1 and P4) and at the centre of each plant pair (Figure 4), artificial collectors were placed; these consisted of 30 × 80 mm filter paper strips (Filter-Lab Ref 1238, Filtros Anoia S.A., Barcelona, Spain). A total of 135 samples were taken in each trial ((12 zones + 3 soil samples) × 9 pairs of plants).

The working conditions (Table 2) were established in accordance with the common farming practices in the area; these consist of spraying at high pressures (approximately 2500 kPa) using high water volumes—for Test 1 and Test 2, these amounted to approximately 1100 L ha^{-1} and 1500 L ha^{-1}, respectively. The flow rates for each of the hand-held sprayers under these conditions are shown in Table 2—in Test 1, it was 4.53 L min^{-1} for the trigger spray gun, 4.38 L min^{-1} for the rotating-handle spray lance and 4.19 L min^{-1} for the flat-fan spray lance; in Test 2, the flow rates were 4.67, 4.35 and 4.21 L min^{-1} for the trigger spray gun, the rotating-handle spray lance and the flat-fan spray lance, respectively. The hand-held sprayers were tested on a horizontal test bench complying with the ISO 5682-1 standard [37] to determine the actual spray angle (Figure 5). The test bench was equipped with 36 grooves, each 50 mm wide and 1500 mm long.

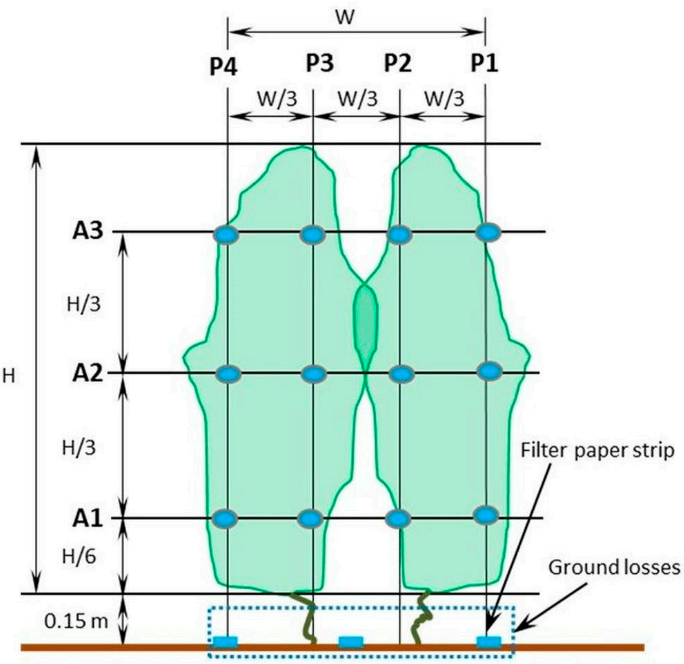

Figure 4. Sampling position (depth and height) for assessing the spray deposition on the canopy and the losses to the ground.

Table 2. Spray application parameters for the tests.

Applications		Nozzle No.	Spray Pressure (kPa)	Actual Spray Angle (Degrees)	Flow (L min^{-1})	Travel Speed (m s^{-1})	Application Rate (L ha^{-1})
Test 1	TSG	1	2440	60	4.53	0.63	1188.25
	RHSL	1	2565	46	4.38	0.68	1075.35
	FFSL	2	2559	90	4.19	0.62	1128.08
Test 2	TSG	1	2492	60	4.67	0.51	1517.12
	RHSL	1	2548	46	4.35	0.48	1498.45
	FFSL	2	2576	90	4.21	0.46	1511.16

TSG: trigger spray gun, RHSL: rotating-handle spray lance, FFSL: flat-fan spray lance.

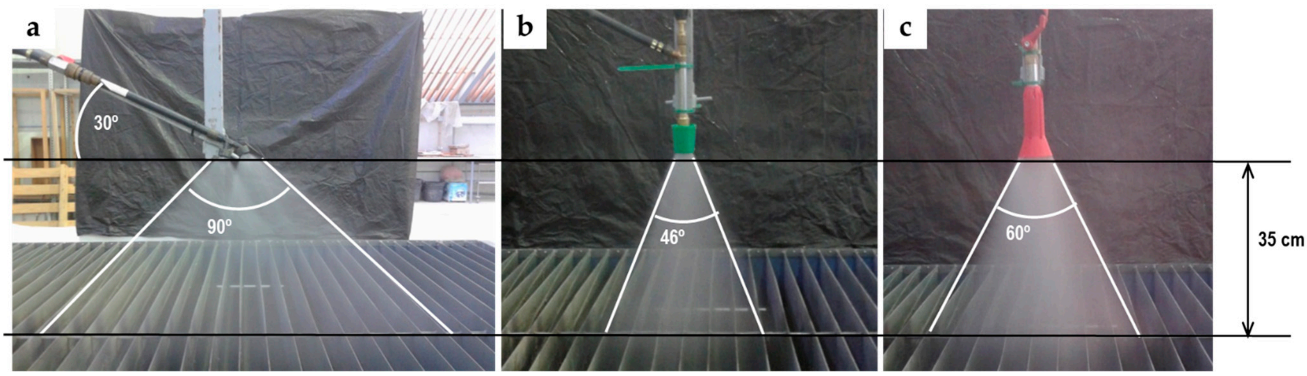

Figure 5. Testing the hand-held sprayers on a horizontal test bench (ISO 5682-1-compliant) to determine the actual spray angle: the flat-fan spray lance (**a**), rotating-handle spray lance (**b**) and trigger spray gun (**c**).

2.3. Measuring the Spray Deposition and Losses to the Ground

Tartrazine (Roha Europe, S.L.U., Torrent, Spain) was used as a tracer to quantify the deposition, using a tank concentration of approximately 10 g L^{-1}. After the tests were carried out in the greenhouse, 3 or 4 leaves were taken from each of the sampling areas listed above (Figure 4), depending on their size, to ensure that the total surface area sampled in each zone was approximately the same. These leaves were placed in 200 × 320 mm self-sealing bags. Likewise, the filter paper strips were placed in 120 × 180 mm self-sealing bags.

In the laboratory, the leaves were washed with 50 mL of distilled water in the same self-sealing bags, and after stirring for 1 min, they were stored in the dark for 30 min to prevent degradation by ambient light. Once the washing process was complete, the sheets were carefully removed from the bags, dried slightly by placing them on filter paper and then the surface was measured using an electronic planimeter (WinDias, Delta-T Devices Ltd., Cambridge, UK).

To extract the dye from the filter paper strips, a procedure similar to that used for the leaves was followed, but using 25 mL of distilled water to wash the sample in the same self-sealing bags.

The amount of tartrazine in the washing solution was determined at a wavelength of 425.5 nm using a dual-beam, UV-visible spectrophotometer (Helios Zeta, Thermospectronic, Cambridge, UK). As a baseline, the solution from washing the blank samples was used following the procedure described above.

To ascertain the actual tracer concentration in the tank, samples of the applied solution were taken at the outlet of the hand-held sprayers, recording a concentration of 8.21 g L^{-1} in Test 1 and 9.81g L^{-1} in Test 2. To compare the applications made with the different hand-held sprayers, the measured depositions were normalised, taking a reference application volume rate of 1100 L ha^{-1} in Test 1 and 1500 L ha^{-1} in Test 2, according to Equation (1).

$$d_n = \frac{d \cdot V_n}{C_T \cdot V} \quad (1)$$

where d_n is the normalised deposit (μL cm^{-2}), d is the tracer concentration per unit sample surface (μg cm^{-2}), V_n is the reference volume rate application (L ha^{-1}), V is the volume rate application (L ha^{-1}) and C_T is the tracer concentration of the tank for each treatment (g L^{-1}).

2.4. Statistical Analysis

The statistical analysis of the data was performed using SPSS v26.0 software (SPSS Inc., an IBM Company, Chicago, IL, USA). An analysis of variance (Anova) was performed, and the significant differences were evaluated using Duncan's test. Before the statistical analysis, the normality of the data was checked using the Kolmogorov–Smirnov test ($p < 0.05$), and the equality of variances by means of the Levene test.

3. Results and Discussion

3.1. Crop Deposition

There were no significant differences in canopy depositions made by the different hand-held sprayers used in the tests (Table 3), although the flat-fan spray lance deposited the most in both tests, followed by the trigger spray gun and the rotating-handle spray lance. Cerruto et al. [22] compared two spray lances similar to those used in this study on a tomato crop, obtaining comparable results. Likewise, Rincón et al. [27] obtained similar deposition results for the flat-fan spray lance on a greenhouse pepper crop.

Table 3. Normalised deposition on the canopy and losses to the ground (mean ± SD) in μL cm^{-2}.

Hand-Held Sprayer	Test 1		Test 2	
	Canopy	**Ground**	**Canopy**	**Ground**
TSG	0.97 ± 0.53a	7.39 ± 3.03a	0.97 ± 0.59a	8.69 ± 3.38a
RHSL	0.90 ± 0.54a	9.70 ± 5.460a	0.84 ± 0.68a	11.77 ± 6.61a
FFSL	1.06 ± 0.51a	3.76 ± 1.36b	1.09 ± 0.65a	4.28 ± 1.50b

TSG: trigger spray gun, RHSL: rotating-handle spray lance, FFSL: flat-fan spray lance. Means in the same column with the same letter do not differ significantly ($p < 0.05$; Duncan's test).

Furthermore, the flat-fan spray lance resulted in more uniform applications in the two tests, with coefficient variation (CV) values of 48.75% and 59.63% for Tests 1 and 2, respectively. The least uniform applications occurred with the rotating-handle spray lance, with variation coefficients of 60.27% and 79.76% in Tests 1 and 2, respectively. Similar results were obtained by Sánchez-Hermosilla et al. [21] in a greenhouse tomato crop. This may be due to the lower spray angle that this spray lance has, concentrating the droplets within a smaller spray width, which forces the operator to have good coordination between the arm movement and the feed to achieve adequate overlap and good distribution uniformity. This aspect is less limiting in the other devices tested, especially in the flat-fan spray lance, which, with a 90° spray angle, distributes the droplets in a wider arc (approximately 80 cm for applications made 35 cm from the vegetation), hence the higher application uniformity.

For the rotating-handle spray lance, both the closing and the adjustment of the output flow is performed using the rotating handle, which makes it difficult to keep the same handle position once the spray lance has been closed. Normally, the operator shuts off the spray lance when reaching the end of the crop line and opens it when starting a new line. All of this can also cause lower application uniformity for the rotating-handle spray lance than for the other equipment.

Another aspect contributing to the lack of application uniformity is the difficulty in reaching the internal areas of the plant canopy. As indicated by Braekman et al. [16], this is because only the finest droplets reach the inner part of the canopy. For all the hand-held sprayers tested, more than 69% of the quantified deposition occurred in the outer planes of the plant canopy (planes P1 and P4, Figure 4). The deposition in the interior planes (planes P2 and P3, Figure 4) was very low for all the devices, although in both tests it was somewhat higher for the flat-fan spray lance, with significant differences in the test on the more developed crop (Test 2) compared to the rotating-handle spray lance (Figure 6).

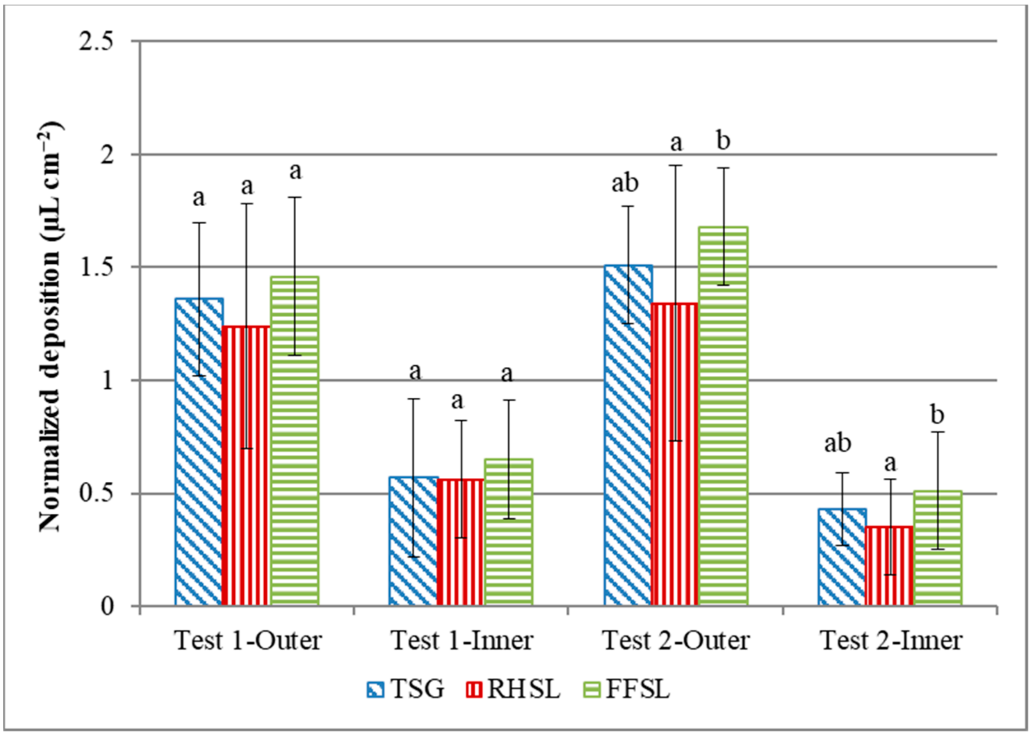

Figure 6. Normalised deposition (µL cm^{-2}) in the outer and inner zones of the canopy. The same letter means no significant differences (Duncan's test, $p < 0.05$). Bars signify the means ± SD of the data. TSG: trigger spray gun, RHSL: rotating-handle spray lance, FFSL: flat-fan spray lance.

3.2. Losses to the Ground

Ground loss values are shown in Table 3. One can observe that lower losses occurred with the flat-fan spray lance, while significant differences existed with regard to the losses caused by the other hand-held sprayers in the two tests. Cerruto et al. [22] also found lower ground losses when using a flat-fan spray gun on a greenhouse tomato crop.

The flat-fan spray lance results in ground losses 2 to 2.75 times less than for the other devices. This may be due to the orientation of the nozzles towards the vegetation. When the operator works with the flat-fan spray lance, the nozzles generate a flat jet which is approximately perpendicular to the vegetable canopy, moving from top to bottom; thus, the direct projection of droplets to the ground is very low, so most losses are due to the lower number of droplets that do not reach the vegetation or are due to runoff. This fact is confirmed when looking at the quantified losses in the internal and external zone, which are similar for this equipment in each of the tests (Table 4).

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

Application	Test 1		Test 2	
	Outer	Inner	Outer	Inner
TSG	8.59 ± 2.99a	4.98 ± 1.13a	10.03 ± 3.34a	6.02 ± 1.31ab
RHSL	12.57 ± 4.24b	3.97 ± 0.63a	15.19 ± 5.25b	4.93 ± 0.54bc
FFSL	3.80 ± 1.71c	3.66 ± 0.27a	4.36 ± 1.87c	4.11 ± 0.35c

TSG: trigger spray gun, RHSL: rotating-handle spray lance, FFSL: flat-fan spray lance. Means in the same column with the same letter do not differ significantly ($p < 0.05$; Duncan's test).

In contrast, for the other hand-held sprayers, the nozzles are located at the end of the devices, generating a tapered jet, the shaft of which forms an angle of approximately 20–25° to the crop line. This results in a direct projection of droplets towards the ground during the downward movement of the operator's arm, leading to high ground losses, which were greater in the external area than in the internal area for the two tests carried out (Table 4). In the external area, as well as the droplets received by direct spraying, we also quantified the losses caused by droplets not reaching the vegetation and falling as runoff. However, most of the quantified losses in the internal area were due to the falling of droplets that did not reach the vegetation or to the runoff; thus, their values are very similar to those obtained with the flat-fan spray lance.

4. Conclusions

The tests have shown that the plant canopy depositions do not present statistically significant differences for the different hand-held sprayers used, although they were somewhat higher for the flat-fan spray lance.

In general, there is a uniform distribution of spray in the plant canopy, with coefficients of variation greater than 48% for all the hand-held sprayers, mainly due to the arrangement of the nozzles and the opening of the spray jet, as well as the difficulty in reaching the internal vegetation areas. However, the increased spray angle of the flat-fan spray lance's opening allows for more uniform distributions, with coefficients of variation of less than 60% in the tests carried out.

As far as ground losses are concerned, these were between 2 and 2.75 times lower for the flat-fan spray lance than for the other hand-held sprayers tested, amongst which there were no statistically significant differences. This is due to the flat-fan spray lance's nozzle arrangement, which generates a flat jet during spraying which is approximately perpendicular to the vegetation.

In general, one can conclude that the flat-fan spray lance results in more uniform application with less ground losses than the other hand-held sprayers.

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