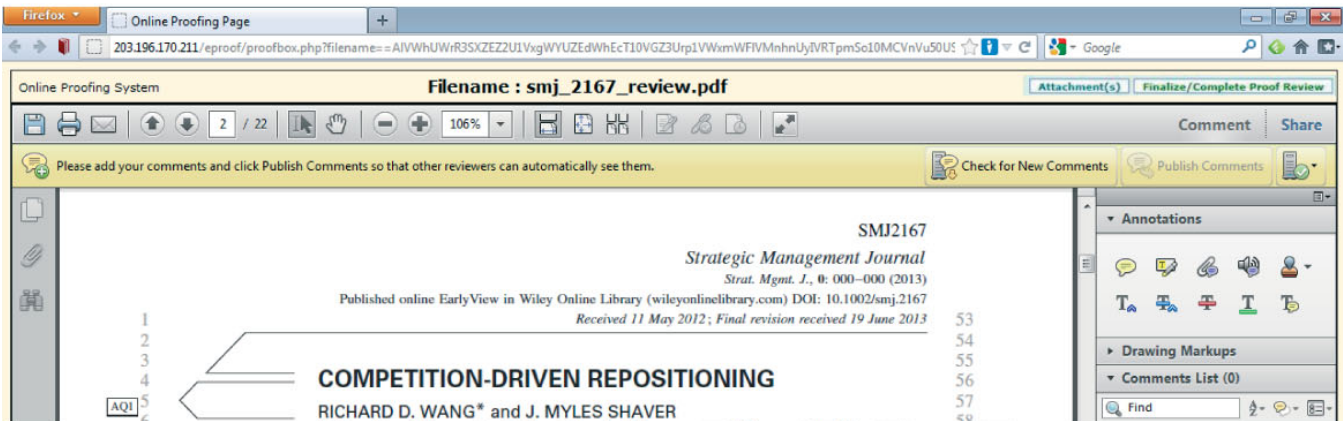


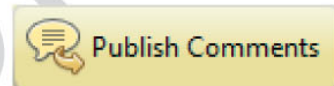
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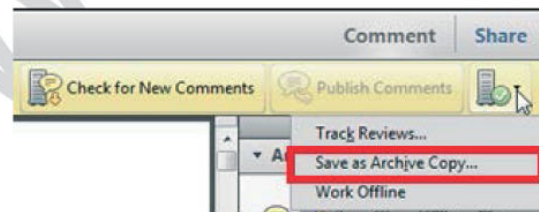
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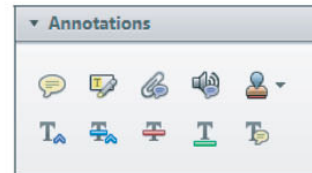
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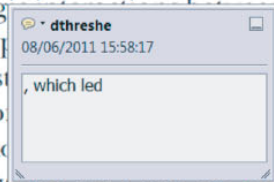


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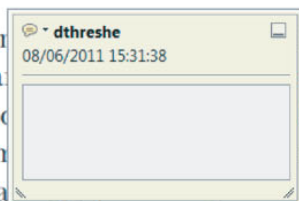
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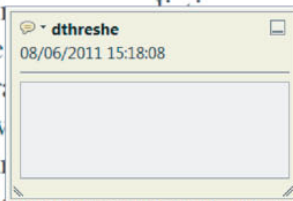


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land and supply shocks. Most of the administrative data used in this study is from the standard framework. Nevertheless, the number of competitors and the impact is that the structure of the sector





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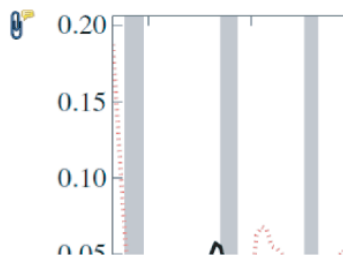


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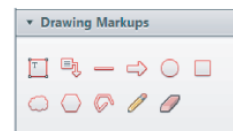
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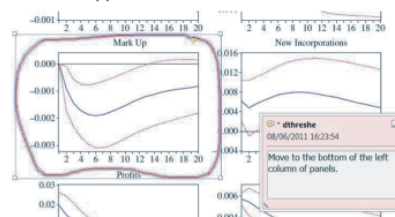
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Spray distribution evaluation of different settings of a hand-held-trolley sprayer used in greenhouse tomato crops

Jordi Llop,^a Emilio Gil,^{a*} Montserrat Gallart,^a Felipe Contador^b and Mireia Ercilla^a

Abstract

BACKGROUND: Hand-held-trolley sprayers have recently been promoted to improve spray application techniques in greenhouses in south-eastern Spain. However, certain aspects remain to be improved. A modified hand-held-trolley sprayer was evaluated under two different canopy conditions (high and low canopy density) and with several sprayer settings (nozzle type, air assistance and spray volume). In this study, the deposition, coverage and uniformity of distribution of the spray on the canopy have been assessed.

RESULTS: The deposition on leaves was significantly higher when flat-fan nozzles and air assistance were used at both high and low spray volumes. No differences were detected between the reference system at a high spray volume and the modified trolley at a low spray volume. Flat-fan nozzles with air assistance increased penetrability into the canopy.

CONCLUSIONS: Air assistance and flat-fan nozzles allow volume rates to be reduced while maintaining or improving spray quality distribution. The working parameters of hand-held sprayers must be considered to reduce environmental risk and increase the efficacy of the spraying process.

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Keywords: greenhouse; hand-held trolley; air assistance; deposition; coverage; nozzle type

1 INTRODUCTION

Producing high-quality food in a safer manner is one of the most important objectives in modern agriculture. This is especially important in intensive horticultural production, where the agriculture and food industry is seeking to produce high-quality foods by safe and sustainable procedures.¹ Fresh vegetable production represents one of the most important agricultural businesses in southern Europe in general and in the south of Spain in particular, with many unsolved problems related to the lack of mechanisation, intensive use of plant protection products (PPPs)^{2,3} and in some cases undesirable episodes related to the residues on food.⁴

According to Eurostat statistics (<http://epp.eurostat.ec.europa.eu>), the area devoted to protected crop cultivation in the European Community member states (MSs) is roughly 150 000 ha. The countries with the highest areas under protected cultivation are Spain (66 000 ha), Italy (34 600 ha), France (11 400 ha), the Netherlands (10 200 ha), Poland (6300 ha) and Greece (4900 ha).⁵

One of the greatest risk factors affecting the economic, environmental and productive parameters in covered horticulture production is directly related to the use of PPPs during pest/disease control. Aspects of operator safety, residues on the produced food, environmental contamination and economic investment are problems linked to this specific and necessary labour; most of these are directly linked to the technology used during the process.^{6–13}

Hand-held spray guns and lances are the most widely used methods of crop protection in greenhouses, in spite of the heavy workload and high risk of operator exposure associated with these techniques.¹⁴ These spray application techniques have also proved to be less effective than spray boom equipment under many conditions.¹⁵ Hand-held spraying techniques are less expensive; however, they are less specific in practical use. Many growers also erroneously believe that high spray volumes and pressures are needed to assure good plant protection,^{16,17} achieving in some cases values of over 4000 L ha⁻¹.^{18,19} Given the high number of treatments per year, this constitutes a great risk of contamination and a considerable economic factor that deserves to be considered.

For these reasons, several improvements and new developments have appeared in the last 10 years with the aim of improving the spray application technology for use in greenhouses. The developments range from newly designed hand-held trolleys equipped

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with vertical booms, either with or without air assistance,^{3,15,18} to the most sophisticated and expensive self-propelled and autonomous vehicles.^{19–22} The advantages of using vertical boom sprayers compared with using hand-held sprayers or lances have been widely reported^{12,15,23–25} in terms of coverage and uniformity of spray distribution. Self-propelled and autonomous sprayers have also attracted interest because of reduced operator exposure,^{19,26,27} improved work capacity^{19,22} and in some cases reduced application of PPPs while maintaining the efficacy of pest/disease control.^{28,29} However, problems have also been reported: poor penetration capacity exhibited by vertical boom sprayers without air assistance;^{28,30} management of hand-held trolleys depending on the soil type and sprayer design; difficulties of identifying accurate conditions for safe and efficient use of self-propelled sprayers, including aspects related to the high level of investment required.¹⁶

The objective of this study was to improve the spray application process in Spanish greenhouses by modifying and improving an existing spray technology. A commercial hand-held-trolley sprayer (Carretillas Amate, Almería, Spain) was selected, and its technical characteristics (incorporation of air assistance, different nozzle types, nozzle distance reduced from 50 to 30 cm, operation system) were modified. The modified sprayer was then compared with the original reference sprayer in two different tomato crop (*Solanum lycopersicum* L. cv. Velasco) greenhouses in El Ejido (Almería, south of Spain). The specific objectives of this work were: (a) to evaluate the effects of air assistance on spray distribution quality; (b) to determine the most suitable nozzle type and nozzle distribution along the boom; (c) to quantify the influence of canopy characteristics on the spray distribution quality; (d) to analyse the effect of applied spray volume on the efficiency of spray distribution quality and leaf deposition.

2 MATERIALS AND METHODS

2.1 Sprayers tested and working conditions

Two types of spraying equipment (a reference sprayer and a modified sprayer) with two nozzle spray types (flat-fan and hollow-cone nozzles) and an optional air assistance system were tested in two different greenhouses (high and low canopy densities of 2.98 and 1.4 m² m⁻³ respectively) at two different application volumes (600 and 1000 L ha⁻¹). The technical specifications of the trials are shown in Table 1.

The reference spraying equipment was equipped with two vertical spray booms 1.5 m long with four nozzles per side (0.5 m between nozzles), mounted on a manually pulled trolley (Carretillas Amate, Viator, Spain).

On the modified sprayer, the spray booms were replaced with two new stainless steel profiles where six nozzles per side were mounted, resulting in an internozzle distance of 0.30 m. The total height of the modified boom was 1.8 m. Additionally, an air assistance system was added, with six individual and adjustable outputs per side, each corresponding to a nozzle; each outlet was placed after its corresponding nozzle according to the spraying direction. An electrical blower (B&D 3000 W; Stanley Black and Decker, New Britain, CT) was installed in the central part of the trolley. A plastic box of 0.037 m³ (0.5 × 0.25 × 0.30 m) was placed in the trolley to collect the air generated by the blower and distribute it among the individual outlets. Twelve individual flexible plastic pipes were connected to the air distribution box, and air flow was conducted to every nozzle. The modified sprayer was converted into a hydropneumatic sprayer with an air assistance system of ca 13 m s⁻¹ measured at each output. Six individual outlets (only one side) of 0.0015 m² section (total air outlet section 0.009 m²) were placed along the boom, giving a total air flow rate of 435.24 m³ h⁻¹. The highest air speed (14.7 m s⁻¹) was measured in output 4 placed 1.0 m over the ground. The lowest air speed

Table 1. Technical data of field trials

Trial	Canopy density	Spray equipment	Applied volume rate (L ha ⁻¹) ^a	Air assistance	Nozzle characteristics					Pressure (bar)
					Pattern ^b	Type	VMD ^c (μm)	Distance ^d (m)	Flow rate (L min ⁻¹)	
T1	High	Modified sprayer	1000	No	FF	XR 110 02	163.6	0.3	1.03	5.2
T2	High	Modified sprayer	1000	Yes	FF	XR 110 02	163.6	0.3	1.03	5.2
T3	High	Modified sprayer	600	No	FF	XR 110 015	163.6	0.3	0.63	3.8
T4	High	Modified sprayer	600	Yes	FF	XR 110 015	163.6	0.3	0.63	3.8
T5	High	Modified sprayer	1000	Yes	HC	ATR Yellow	143	0.3	1.03	10.0
T6	High	Modified sprayer	600	Yes	HC	ATR Brown	147	0.3	0.63	9.0
T7	High	Reference sprayer	1000	No	FF	XR 110 02	99.9	0.5	1.60	13.0
T8	High	Reference sprayer	600	No	FF	XR 110 015	99.9	0.5	0.92	8.0
T9	Low	Modified sprayer	1000	No	FF	XR 110 02	163.6	0.3	1.03	5.2
T10	Low	Modified sprayer	1000	Yes	FF	XR 110 02	163.6	0.3	1.03	5.2
T11	Low	Modified sprayer	600	No	FF	XR 110 015	163.6	0.3	0.63	3.8
T12	Low	Modified sprayer	600	Yes	FF	XR 110 015	163.6	0.3	0.63	3.8
T13	Low	Modified sprayer	1000	Yes	HC	ATR Yellow	143	0.3	1.03	10.0
T14	Low	Modified sprayer	600	Yes	HC	ATR Brown	147	0.3	0.63	9.0
T15	Low	Reference sprayer	1000	No	FF	XR 110 02	99.9	0.5	1.60	13.0
T16	Low	Reference sprayer	600	No	FF	XR 110 015	99.9	0.5	0.92	8.0

^a For an intended forward speed of 3 km h⁻¹ and a row distance of 2.5 m for high canopy density and 2.8 m for low canopy density.

^b Spray angle 110° for flat-fan nozzles (FF) and 80° for hollow-cone nozzles (HC).

^c Volume median diameter (information provided by the nozzle manufacturers).

^d Six nozzles for 0.3 m nozzle distance and four nozzles for 0.5 m nozzle distance.



Figure 1. Reference hand-held-trolley sprayer (left) and modified sprayer with air assistance (right).

(12.0 m s⁻¹) was detected at the highest output placed 1.8 m over the ground. Great uniformity among air velocities was observed (5.8% CV). Figure 1 shows the details of the two evaluated sprayers.

The two sprayers were tested with two different spray application volumes: 600 and 1000 L ha⁻¹. The high volume was first established following standard application practices according to the canopy characteristics. The low volume was then established by a 40% reduction on the basis of best results from previous practical experience in greenhouses (Syngenta, unpublished data).

The intended calibration of the sprayer for accomplishing the volume application rate was performed by establishing a fixed forward speed and selecting the appropriate nozzle size and pressure according to the required flow rate. However, the actual spray volume was calculated according to the real forward speed, row spacing and flow rate.

The working conditions for the reference sprayer were chosen following the recommendations of the Spanish Plant Protection Assessment Organisation.¹⁷ An extended-range flat-fan nozzle XR 110 (Spraying Systems Co., TeeJet Technologies, IL) was used at high pressure (13.0 bar).

The modified sprayer was tested with two different nozzle types: extended-range flat-fan (XR 110) nozzles and hollow-cone (ATR) nozzles (80°) (Albuz-CoorsTek, Evreux, France). In this case, the working pressure was adjusted according to the manufacturer's recommendations to obtain the intended volume rate. For all trials, the forward speed was measured and adjusted to remain as constant as possible around 3 km h⁻¹. This value was obtained after several previous tests made in order to find a comfortable forward speed for the operator.

Note that all trials with the modified sprayer were conducted with and without air assistance, except in the case of hollow-cone nozzles, which were only tested with air assistance according to their recommended use.^{11,24} The trial settings are summarised in Table 1. Both sprayers were connected via a 30 m long hose (0.025 m diameter) to a hand-held wheelbarrow with a tank capacity of 100 L, and a piston pump (37 L min⁻¹) and a petrol engine (3.5 kWA) (Honda, Slough, UK) were used for feeding the sprayers. This procedure simplified the feeding process with a more precise tank concentration while avoiding the difficulties of connecting the sprayers to the greenhouse installation.

To quantify the leaf deposit and coverage at different parts of the canopy, a fluorescent tracer (Helios SC 500; Syngenta Crop Protection AG, Basel, Switzerland) was used at 0.1% v/v. The

Table 2. Canopy characterisation of the greenhouses

	Greenhouse 1	Greenhouse 2
Canopy density	High	Low
Row width (m)	2.50	2.80
Canopy height (m)	2.19	2.49
Canopy width (m)	1.24	0.85
LAI ^a	5.96	2.53
LWA ^b (m ² vegetation ha ⁻¹)	17 520	17 714
TRV ^c (m ³ vegetation ha ⁻¹)	10 868	7514
LAD ^d (m ² leaves m ⁻³ canopy)	2.98	1.42

^a Leaf area index.

^b Leaf wall area.

^c Tree row volume.

^d Leaf area density.

calculated amount of tracer was added to the external tank and mixed thoroughly.

2.2 Canopy characterisation

Field tests were carried out at El Ejido (Almería, south-eastern Spain) on a representative commercial tomato (*Solanum lycopersicum* L. cv. Velasco) production system (plastic greenhouse) of this zone. The two sprayers were tested in two different greenhouses, each with different canopy characteristics. Greenhouse 1 had a plantation pattern of 0.4 m between plants and a row spacing of 2.5 m (2 plants m⁻²) in a twin-row system (two rows growing close together and separated by 0.4 m). The greenhouse had a typical configuration for south-eastern Spain, consisting of a main corridor and several aisles coming from this corridor. The average aisle length was 30 m.

Greenhouse 2 had a plantation pattern of 0.4 m between plants and a row spacing of 2.8 m (1.8 plants m⁻²) in a twin-row system with 0.3 m separation. This greenhouse had the same configuration as greenhouse 1 (30 m).

In both cases, the canopy was completely characterised. Geometric parameters (canopy height, canopy width) and derived parameters (leaf wall area,³¹ tree row volume^{32–34} and leaf area density^{35,36}) were calculated after the field measurements (Table 2). For leaf area measurements, four plants were randomly selected along the row. The leaf area and the corresponding leaf area index were determined by estimating the area/weight ratio.^{37–39} The total weight of each plant (only leaves) was measured in the laboratory immediately after cutting it, and an 80 g sample of tomato leaflets picked randomly was measured with a LI-COR LI 3100C electronic planimeter (LI-COR, Lincoln, NE). Equations (1) and (2) indicate the area/weight ratios obtained for greenhouses 1 and 2 respectively:

$$A = 1.9502 \cdot g + 0.0095 \quad (1)$$

$$A = 1.5613 \cdot g + 0.0084 \quad (2)$$

where A is the leaf surface (m²) and g is the leaf weight (g).

2.3 Layout of trials in greenhouses

Different rows of tomato plants were strategically selected in each greenhouse to avoid cross-spraying between the different tests, leaving a boundary zone for this purpose. For every test, one

complete row was sprayed from both sides, following the normal procedure concerning the direction during two-sided sprayings (Fig. 2). The trials were arranged to maintain practical management of both tests and sprayer equipment.

Sampling zones were defined by the height (top, middle and bottom) and depth (peripheral edge and centre or internal edge) of the canopy. In total, six different positions were distinguished. For each zone, ten samples composed of five tomato leaflets each were collected after the spraying process, placed into hermetically sealed plastic bags, and stored until analysis in the laboratory. Samples were randomly collected along the canopy row.

Environmental conditions (temperature and relative humidity) during the trials were recorded. For greenhouse 1, temperature ranged from 14.4 to 19.5 °C, and relative humidity (RH) from 55 to 83.9%. For greenhouse 2, temperature ranged from 16.0 to 22.0 °C, and RH from 55.0 to 60.0%.

2.4 Procedure for spray distribution evaluation

The spray distribution was evaluated by analysing three parameters: (1) spray deposit on leaves, expressed by the amount of tracer per unit leaf area (ng cm^{-2}); (2) spray coverage, which represents the percentage of leaf surface covered by the fluorescent tracer used as the active ingredient; (3) penetration index (PI), which enables the spray deposit measured in the external parts of the canopy to be compared with that in the internal part.

Immediately after the collection, all the samples were weighed individually, and the data were transformed to leaf area per bag (cm^2 of leaf surface per sample) by applying the previously determined surface-weight factor. This value together with the tracer concentration made it possible to determine the deposition per unit leaf surface. Samples were then washed by adding 200 mL of diethyleneglycol-monoethylether solution into each plastic bag and shaking every sample for 20 s. A liquid sample from each plastic bag was poured through a filter paper into a test tube for fluorescence measurements. Tracer concentration was determined using the fluorimetry technique at an excitation wavelength of

375 nm and a measurement wavelength of 435 nm (Fluorimeter 96; Syngenta).

Tank samples were collected directly from the nozzle prior to and after the spraying of each individual trial to measure the tracer concentration in the tank. The results were normalised to ng cm^{-2} leaf/ g ha^{-1} ground, depending on the concentration, following the procedure of Gil *et al.*,³⁸ according to the equation

$$d_n = \frac{d \cdot 10^5}{V \cdot T_{cs}} \quad (3)$$

where d_n is the normalised tracer deposit rate per unit leaf surface (ng cm^{-2}), d is the actual deposit per unit of leaf surface (ng cm^{-2}), V is the spray volume dose (L ha^{-1}) and T_{cs} is the tracer concentration of the spray mixture in the tank (mg L^{-1}).

The degrees of leaf coverage on the upper and lower sides were also measured. Sample leaves collected on each trial at each position were photographed using ultraviolet light with a Canon 450D camera (Canon Europa NV, Amstelveen, The Netherlands). The obtained pictures (Fig. 3) were evaluated with *FluorSoft*, a software program dedicated to image analysis (Syngenta image analysis). The results were expressed as the percentage of the leaf surface covered by the tracer in relation to the total leaf surface. This procedure was executed for both sides of the leaves to obtain separate coverage information for the upper and lower sides of the leaves.

PI (%) was defined in order to analyse the relative deposition between the internal and external parts of the canopy according to the equation

$$PI = \frac{I}{E} \cdot 100 \quad (4)$$

where I and E are the average coverages at the internal and external parts of the canopy respectively.

Parameter E was calculated by taking into consideration the deposition levels measured at the two external parts of the canopy, because the sprayer circulation was arranged to spray the canopy completely from both sides.

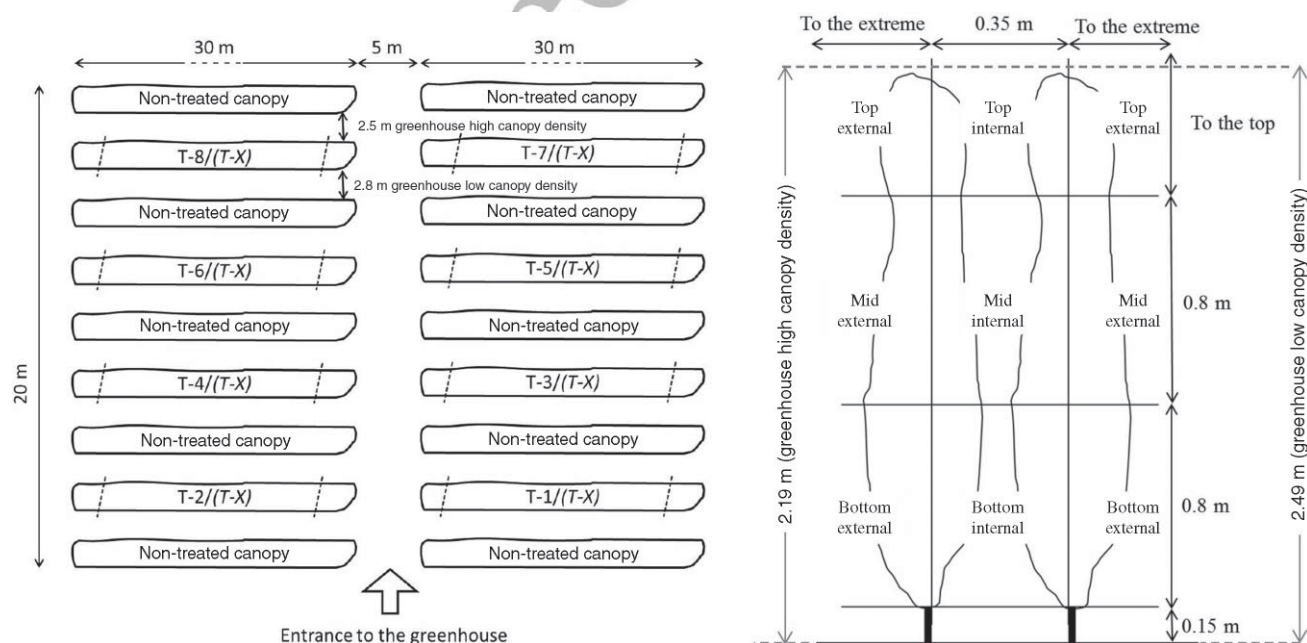


Figure 2. Schematic diagram of field trial distribution in greenhouses (code in italics refers to trials conducted in greenhouse 2). Schematic diagram of canopy sampling areas.

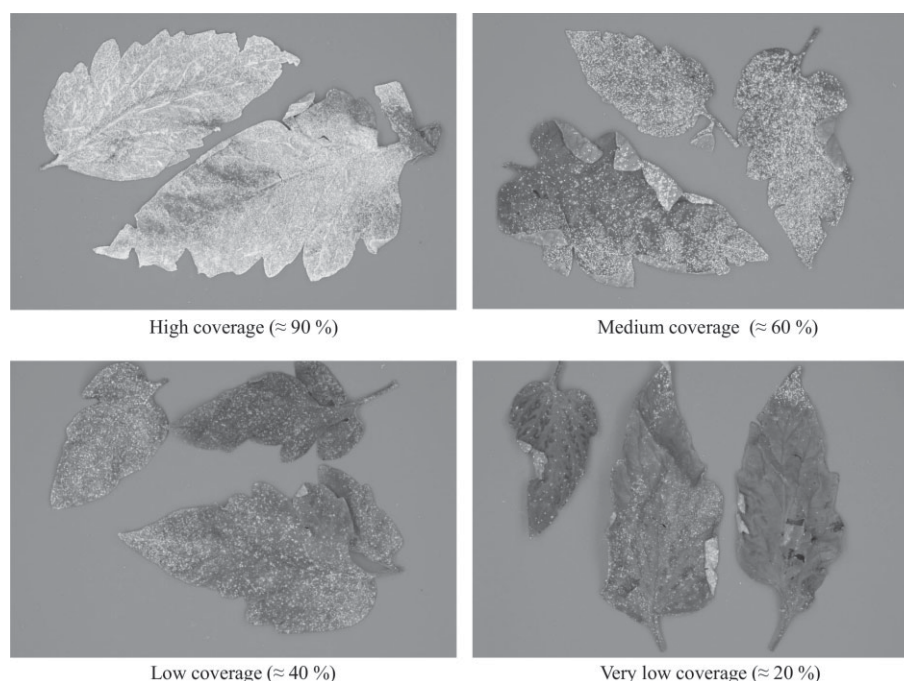


Figure 3. Examples of images used to assess leaf coverage.

2.5 Data analysis

The effects of the different parameters evaluated (application volume, nozzle type, canopy density, nozzle distance, air assistance, sample position) on spray deposition and spray coverage were examined by analysis of variance (ANOVA), with the treatment as a source of variation, followed by the Student–Newman–Keuls *post hoc* test.

Prior to statistical analysis, the data were transformed (square root for deposition data and arcsine for coverage data) to homogenise variances.⁴⁰ In addition, residual analyses were also performed. All statistical analyses were performed with R software (R Development Core Team, Vienna, Austria, 2012).

3 RESULTS

An overview of the data collected shows the influence of the canopy and spray volume on the deposition and coverage on the leaves (Table 3). A significantly high deposition level was obtained in the greenhouse with a low canopy density and a high volume rate; conversely, the opposite was observed with a high canopy density and a low application rate. Coverage was also affected by canopy characteristics, and the combination of low canopy density and low application rate yielded the lowest average coverage on both sides of the leaves.

Considering leaf deposition and coverage as principal factors for evaluating spray quality, Figs 4 and 5 show the average levels of deposition and coverage, respectively, obtained for all tests, canopy characteristics and applied volume rates. Significant differences were found between tests, with the combination of flat-fan nozzles and air assistance yielding the highest deposition levels. In general, flat-fan nozzles yielded higher levels of deposition than hollow-cone nozzles, irrespective of other parameters. The effects of nozzle type and air assistance were unclear in terms of coverage. However, coverage levels tended to increase with hollow-cone nozzles. Importantly, the influence of canopy characteristics on coverage was notable, resulting in the highest levels on

Table 3. Average values of deposition (ng cm^{-2}) and coverage (%) by canopy density and spray volume^a

	High canopy density		Low canopy density	
	1000 L ha ⁻¹	600 L ha ⁻¹	1000 L ha ⁻¹	600 L ha ⁻¹
Deposition	2.51 bc	2.38 c	3.18 a	2.83 ab
Coverage	38.33 a	31.19 b	31.64 b	21.03 c

^a Values followed by the same letter (in rows) indicate no significant difference.

high-density canopies. The following section includes a detailed analysis of the results, with a particular focus on canopy characteristics, following the same procedure carried out in previous studies.^{29,41}

3.1 High-canopy-density greenhouse

3.1.1 Spray deposition

Table 4 shows the results of average deposition and coverage for each test in the case of a high canopy density. For each value, the uniformity in the whole canopy volume was measured by calculating the coefficient of variation (CV) in every case. Deposition levels show significant differences among treatments, with tests T2 and T4 (flat-fan nozzles with air assistance) yielding the highest values. In contrast, the same nozzles without air assistance and the reference sprayer yielded the poorest results in terms of coverage. Notably, the lowest CV values, indicative of the most uniform deposition for the whole canopy, were also obtained in tests T2 and T4. This effect was opposite to that found in the case of hollow-cone nozzles, indicating great variability among the different sampling zones in the canopy.

A detailed analysis of coverage levels indicates no significant differences ($P < 0.05$) among treatments. Interestingly, however, a tendency for coverage levels to decrease was observed when

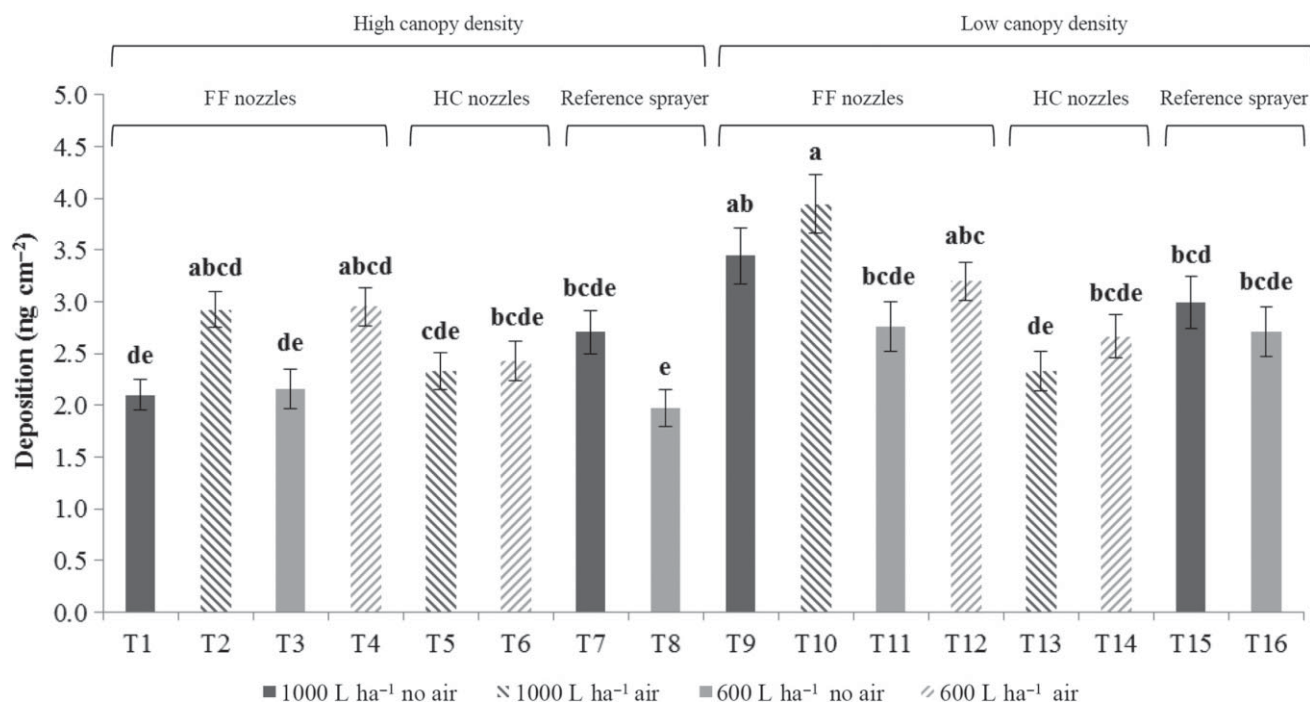


Figure 4. Average deposition levels on leaves for all tests. Black series corresponds to 1000 L ha⁻¹ without air assistance, black-striped series corresponds to 1000 L ha⁻¹ with air assistance, grey series corresponds to 600 L ha⁻¹ without air assistance and grey-striped series corresponds to 600 L ha⁻¹ with air assistance. Values with the same letter indicate no significant differences ($P < 0.05$).

canopy density was reduced. Considering the volume application rate, flat-fan nozzles with air assistance generated the best results in terms of deposition, with no significant differences relative to the reference test (T7). The same combination of nozzle and air assistance also yielded the best results in terms of deposition in the case of a low application rate, albeit with significant differences compared with the rest of treatments. In this case, the lowest deposition levels were obtained in the reference test (T8).

Figure 6 shows the levels of leaf deposition obtained in every sample zone of the canopy, arranged separately by test and volume rate. Application of 1000 L ha⁻¹ led to spray deposition on the external part of the canopy becoming highest at medium height in all treatments, with the top centre position of the canopy being the most difficult area to spray. This tendency was similarly maintained at 600 L ha⁻¹, except in the case of hollow-cone nozzles with air assistance, where the deposition in different canopy zones was highly uniform. Interestingly, low deposition levels were obtained in all cases on the internal part of the canopy, especially on the highest part of the crop profile. In general, no run-off episodes were detected visually at the two spray volumes selected.

3.1.2 Leaf coverage

Figure 7 shows the coverage levels on different parts of the canopy and sides of the leaves, generated after the image analysis procedure developed for this experiment. The results indicate a similar pattern among the tests, regardless of the spray volume applied. In all cases, coverage levels for the upper sides of leaves were higher than those for their undersides, on both the external and internal parts of the canopy. The lowest coverage levels were always obtained on the undersides of the leaves located in the internal part of the canopy. In general, the combination of low coverage levels on the internal part of the canopy and on the

undersides of the external leaves led to a reduction in average coverage for the low spray volume rate (Table 3).

3.1.3 Spray penetration into the canopy

The PI was defined and calculated with the aim of evaluating the amount of product that arrives at the internal part of the canopy in relation to the amount of product deposited in the external zones of the crop (Fig. 8). At a high spray volume (1000 L ha⁻¹), the joint effect of air assistance and flat-fan nozzles increased penetration capability, with PI values near 60%. In contrast, hollow-cone nozzles yielded the worst results in terms of penetration. The highest PI values obtained with the reference sprayer (T7) could be related to the excessive working pressure (13 bar), which differed substantially from the recommended values for this type of nozzle. In the case of a low spray volume (600 L ha⁻¹), the highest PI was obtained with hollow-cone nozzles (56.2%), always with air assistance, owing to the high deposition levels measured in the internal part of the canopy. This result agrees exceptionally well with the deposition obtained in other sampling zones in the internal part of the canopy. Similar PI values were obtained with the reference sprayer technology (T8) and with the combination of flat-fan nozzles and air assistance (T4).

3.2 Low-canopy-density greenhouse

3.2.1 Spray deposition

An overall analysis of the obtained results in the case of low canopy density also reveals significant differences ($P < 0.05$) among treatments, both in terms of deposition and leaf coverage (Table 5). As observed in the case of high canopy density, the combination of air assistance and flat-fan nozzles (T10) yielded the highest deposition levels and the lowest CV values. Hollow-cone nozzles at both spray volume rates (T13 and T14) yielded the lowest levels of leaf deposition.

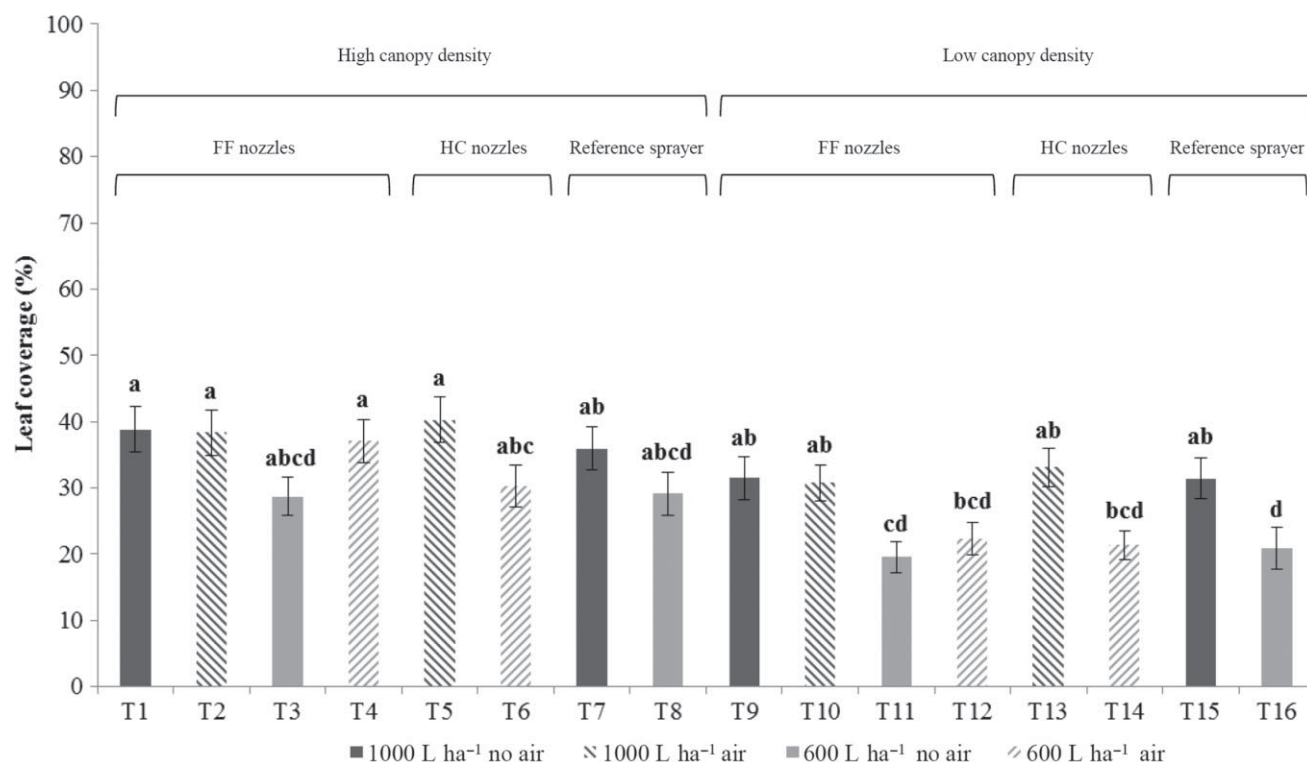


Figure 5. Average levels of leaf recovery for all tests. Black series corresponds to 1000 L ha⁻¹ and grey series corresponds to 600 L ha⁻¹. Values with the same letter indicate no significant differences ($P < 0.05$).

Table 4. High-canopy-density average deposition, with values of standard error of the mean (SEM), coefficient of variation (CV) of the deposition and coverage^a

Trial	Volume rate application (L ha ⁻¹)	Code	Deposition (ng cm ⁻²)	CV (%)	Coverage (%)	CV (%)
1	1000	T1 flat fan no air	2.10 ± 0.15 bc	57.9	38.8 ± 3.50 a	75.4
2	1000	T2 flat fan air	2.93 ± 0.17 a	48.3	38.3 ± 3.45 a	75.6
5	1000	T5 hollow cone air	2.33 ± 0.17 abc	62.8	40.2 ± 3.48 a	73.3
7	1000	T7 reference	2.71 ± 0.21 ab	56.7	35.9 ± 3.29 a	77.7
3	600	T3 flat fan no air	2.16 ± 0.19 bc	73.8	28.7 ± 2.95 a	93
4	600	T4 flat fan air	2.95 ± 0.18 a	48.8	37.1 ± 3.25 a	74.3
6	600	T6 hollow cone air	2.43 ± 0.19 abc	53.5	30.2 ± 3.13 a	87.8
8	600	T8 reference	1.98 ± 0.18 c	59.3	29.1 ± 3.32 a	96.8

^a Values followed by the same letter (in columns) indicate no significant difference.

A detailed analysis of the liquid distribution among the canopy sampling zones (Fig. 9) indicates diverse behaviour between treatments, depending on the spray volume. Whereas most treatments at a higher spray volume generated higher deposition levels on the external (rather than internal) part of the canopy, treatment with flat-fan nozzles and air assistance yielded no differences among canopy zones. For a low spray volume, no tests yielded significant differences ($P < 0.05$) among canopy zones, except at the top internal position where the zone was the most difficult to cover. Once again, flat-fan nozzles without air assistance yielded the poorest deposition results in the internal part of the canopy.

3.2.2 Leaf coverage

An overall evaluation of the leaf coverage results at a low canopy density shows no significant differences within treatments, either at high or low spray volumes (Table 5). A separate

analysis by leaf side and canopy position shows a similar distribution, regardless of the spray volume (Fig. 10), with generally less coverage in the case of 600 L ha⁻¹. Relative differences between the upper- and lower-side leaf zones were similar in all tests, regardless of the canopy sampling zone and spray volume rate.

3.2.3 Spray penetration into the canopy

The PI was also calculated separately according to the spray volume (Fig. 11). In both cases, flat-fan nozzles with air assistance yielded the highest PI values, with the value obtained at 1000 L ha⁻¹ (70% penetration) being the highest among all tests. This value confirms reports on evaluating the distribution across the canopy. Similar PI values were found for the rest of the treatments. This behaviour was repeated in the case of a low spray volume.

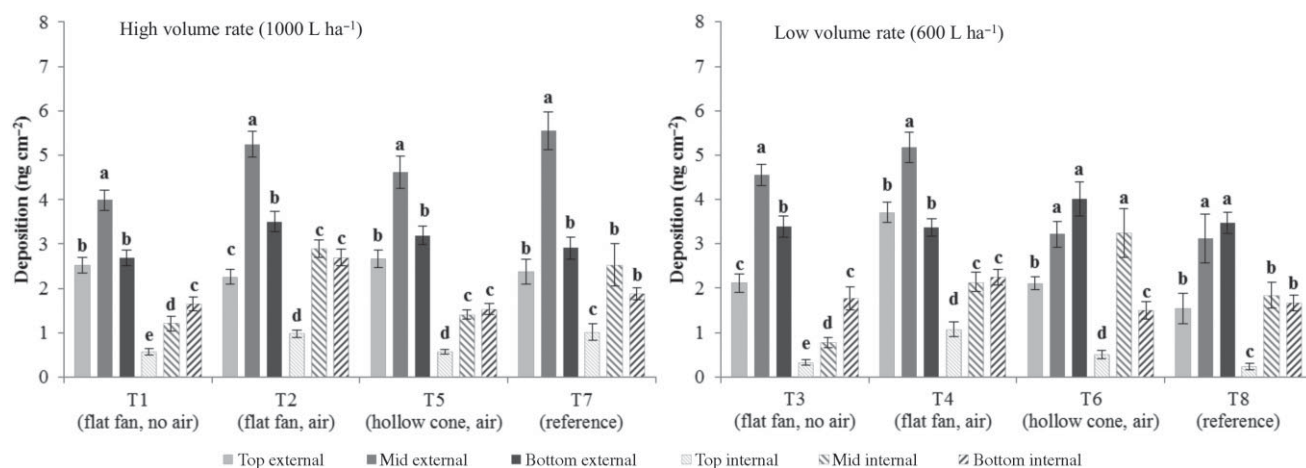


Figure 6. High-canopy-density average levels of deposition on leaves separated by test and sampling zone for a spray volume of 1000 L ha⁻¹ (left) or 600 L ha⁻¹ (right). Values with the same letter indicate no significant differences.

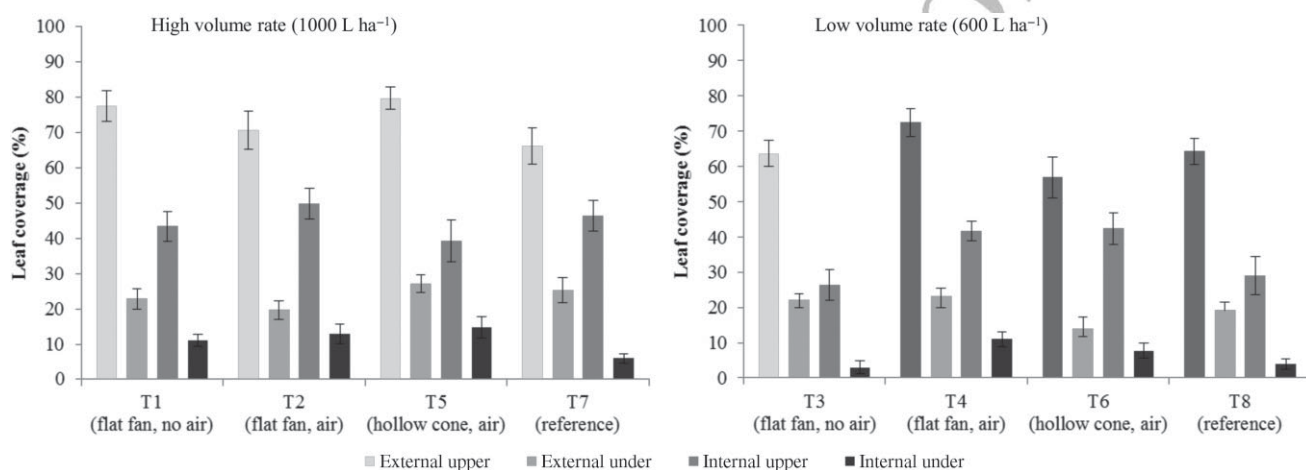


Figure 7. High-canopy-density average levels of leaf coverage separated by test and sampling zone for a spray volume of 1000 L ha⁻¹ (left) or 600 L ha⁻¹ (right). Values with the same letter indicate no significant differences.

4 DISCUSSION

The research carried out here shows the important effects of canopy density, spray application rate and working parameters (mainly regarding nozzle settings and air assistance) on the final quality of spray distribution on tomato plants in greenhouses. In general, the highest leaf deposit levels are obtained at low canopy densities. This tendency is reversed in the case of leaf coverage, where a tendency for coverage to decrease is observed in the case of low canopy densities.

Air assistance has been demonstrated to be an interesting tool to improve the quality of spray application. In general, all treatments with air assistance yielded better results in terms of deposition in the internal canopy zones. However, no benefit was observed at the canopy periphery, a zone easily exposed to application. This trend was demonstrated at the two evaluated canopy densities, regardless of the spray application rate. This is especially marked in the case of flat-fan nozzles, with PI values ranging from 52.6 to 70.3%. Exceptionally, hollow-cone nozzles with air assistance yielded the highest PI value (52.6%) when a low spray volume was applied at a high canopy density. These results are in concordance with Foqué *et al.*,¹⁴ who reported a high effect of joint air support and flat-fan nozzles. Derksen *et al.*⁴² concluded that air assistance

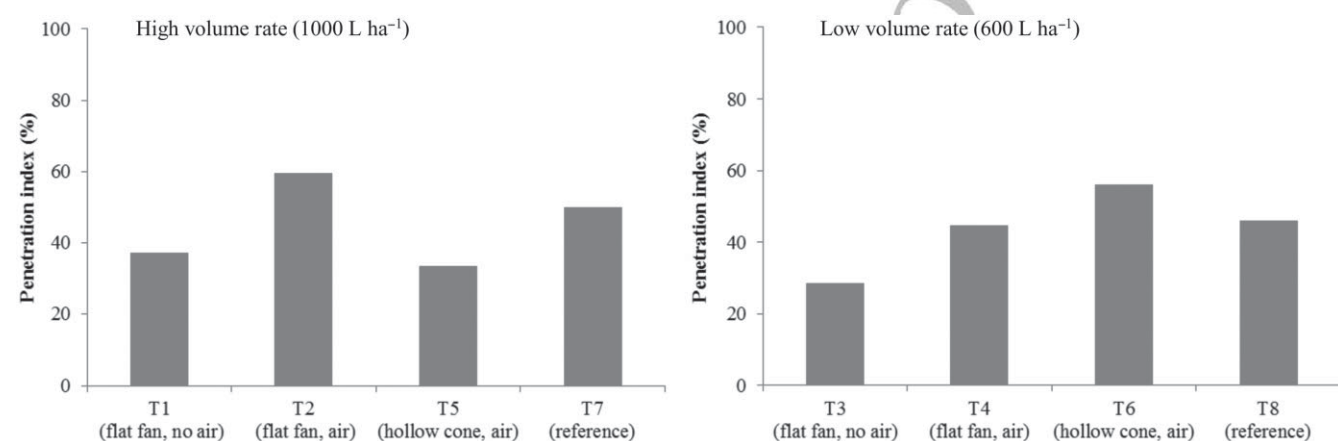
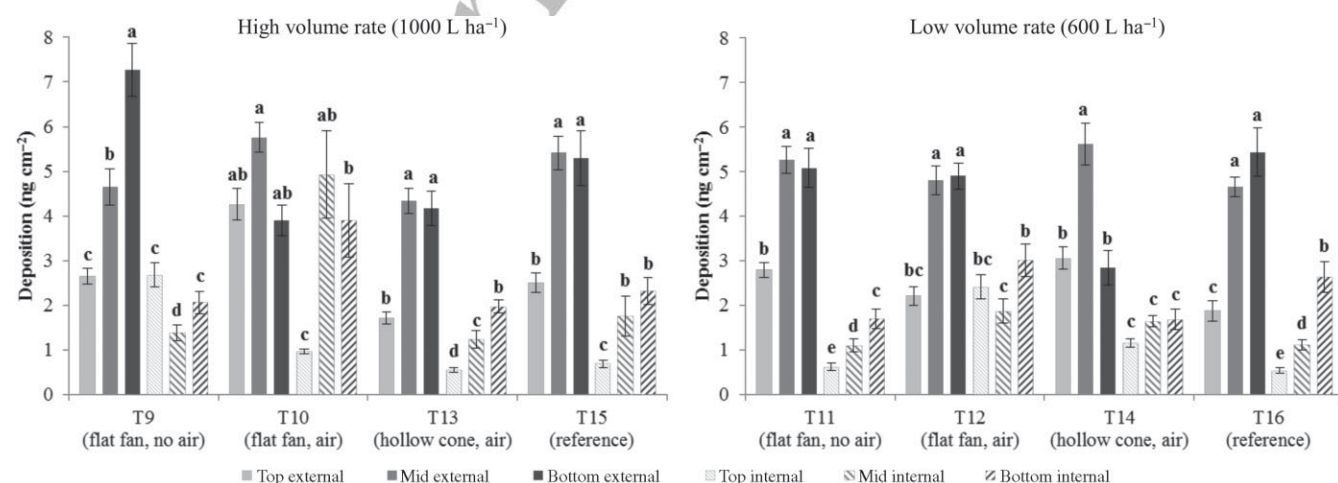
of 20 m s⁻¹ in spray trials in bell peppers provided no advantage in the amount of spray retained on the foliage, but it produced more desirable spray quality on foliage and resulted in more spray retained on the whole fruit. PI values of treatments with air assistance were higher than those obtained without air assistance. In this last case, PI values ranged from 26.1 to 50%; this indicates that in some part of the canopy the spray liquid retained by the leaves was only a quarter of the total deposited in the external part of the canopy. This fact directly relates to the efficacy of applying a certain spray, in terms of pest/disease control, as already reported by Sánchez-Hermosilla *et al.*¹⁶

The highest coverage levels obtained with air assistance, especially on the undersides of the leaves, agreed with the results of Lee *et al.*,¹⁸ who concluded that a sprayer equipped with flat-fan nozzles and air assistance improves the deposits on the upper and lower surfaces. Given the low canopy density, no clear effect of air assistance was found.

No clear effect of nozzle type was detected in the case of high canopy density. In contrast, tests carried out at low canopy density revealed a tendency for deposition to increase when flat-fan nozzles and air assistance were selected, yielding results superior to those obtained with hollow-cone nozzles. Considering the ability to penetrate into the internal parts of the canopy,

Table 5. Low-canopy-density average deposition, with values of standard error of the mean (SEM), coefficient of variation (CV) of the deposition and coverage^a

Trial	Volume rate application (L ha ⁻¹)	Code	Deposition (ng cm ⁻²)	CV (%)	Coverage (%)	CV (%)
9	1000	T9 flat fan no air	3.45 ± 0.27 ab	62.9	31.5 ± 3.20 ab	86.4
10	1000	T10 flat fan air	3.95 ± 0.28 a	41.3	30.7 ± 2.74 ab	75.9
13	1000	T13 hollow cone air	2.33 ± 0.19 c	67.3	33.1 ± 2.87 a	72.5
15	1000	T15 reference	3.00 ± 0.25 bc	64.5	31.4 ± 3.09 ab	83.5
11	600	T11 flat fan no air	2.76 ± 0.24 bc	72.6	19.5 ± 2.29 c	99.6
12	600	T12 flat fan air	3.20 ± 0.18 ab	41.6	22.4 ± 2.41 bc	92.7
14	600	T14 hollow cone air	2.67 ± 0.21 bc	60.9	21.3 ± 2.09 bc	83.2
16	600	T16 reference	2.71 ± 0.24 bc	72.2	20.9 ± 3.10 c	125.9

^a Values followed by the same letter (in columns) indicate no significant difference.**Figure 8.** High-canopy-density values of penetration index (PI) separated by high (left) and low (right) volume rates.**Figure 9.** Low-canopy-density average levels of deposition on leaves separated by test and sampling zone for a spray volume of 1000 L ha⁻¹ (left) or 600 L ha⁻¹ (right). Values with the same letter indicate no significant differences.

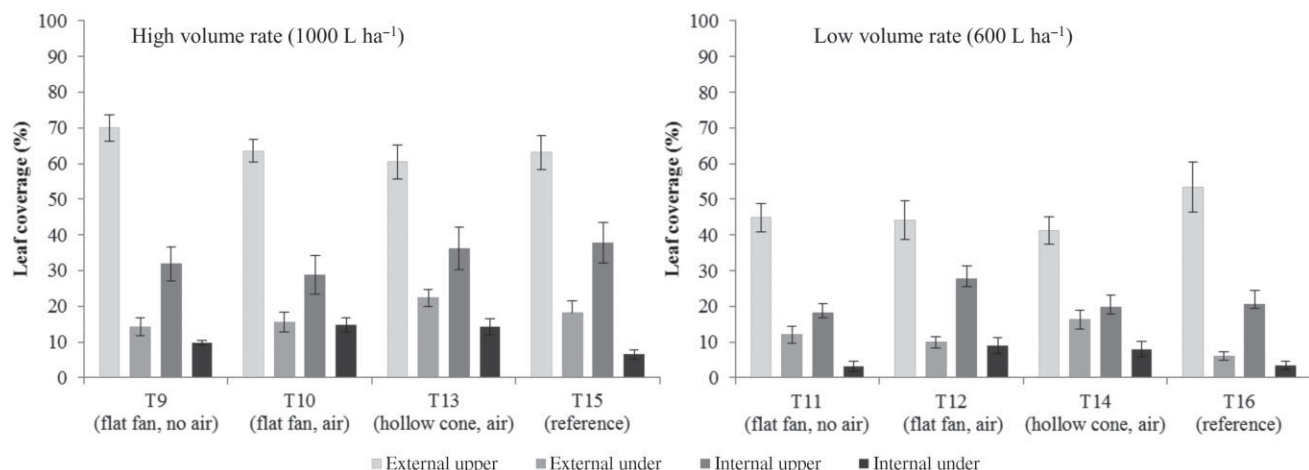


Figure 10. Low-canopy-density average levels of leaf coverage separated by test and sampling zone for a spray volume of 1000 L ha⁻¹ (left) or 600 L ha⁻¹ (right). Values with the same letter indicate no significant differences.

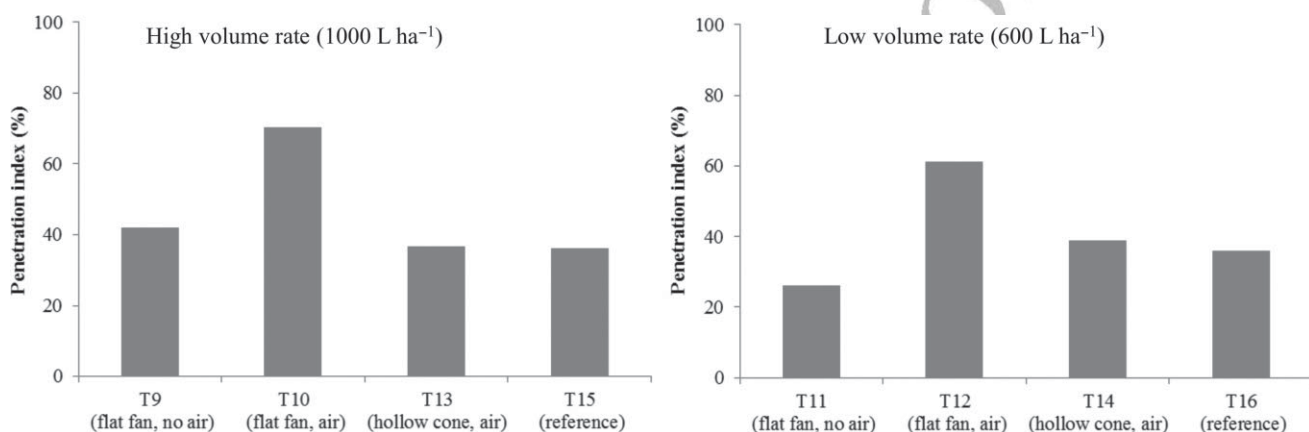


Figure 11. Low-canopy-density values of penetration index (PI) separated by high (left) and low (right) volume rates.

hollow-cone nozzles with air support yielded low deposition levels in the canopy. These results are in line with those reported by Foqué *et al.*,¹⁴ who found similar results for spray application to laurel crop. This fact may be explained by the results reported in previous studies, which stated that the small droplet generated by hollow-cone nozzles produced initial momentum dissipation and, as a consequence, a reduction in kinetic energy.³ Braekman *et al.*¹² and Foqué *et al.*⁴³ postulated that a coarse spray had higher momentum and therefore greater capacity to penetrate the canopy. Together with other important factors such as air assistance, this can explain why flat-fan nozzles at low pressure generally yield the highest deposition levels. These results also demonstrate the important influence of canopy characteristics (crop height and width) and air assistance in leaf deposition.

Other parameters, such as distance between nozzles and canopy, nozzle angling or spray direction, can affect the coverage inside the plants. A spray distance of 30 cm to the stem proved to be more effective when spraying conically shaped plants in a bay laurel crop.⁴³ Regarding nozzle angling, different results were obtained concerning its influence on deposition and coverage. Foqué *et al.*⁴³ concluded that angling the spray did not result in a higher deposition or penetration capacity compared with the standard vertical spray boom. However, later research carried out by the same authors³⁰ found a positive trend from using a forward spray angle.

In relation to leaf coverage, the results demonstrated that the differences among tests were lowest when the canopy density was highest. In contrast, in the case of low canopy density, the effect of spray application rate was greater than that of nozzle type. However, regardless of canopy density and spray application volume, similar results of coverage on both sides of the leaves were observed in all zones of the canopy. This suggests that the main factor affecting deposition and coverage is the presence of air assistance.

The average leaf deposition levels obtained at a low canopy density were higher than those obtained at a high canopy density. Moreover, clear differences in average deposition were shown between external and internal parts of the canopy. The sample height zone (top, middle and bottom) has been identified as an influential factor on spray distribution into the canopy. These results agree with those of Derksen *et al.*,²⁵ who reported that spray canopy position is also a significant factor for foliar deposition with artificial targets.

Generally, important differences between leaf coverage for the different parts of the leaf (upper and lower sides) were observed in all evaluated tests. These results were expected and agree with those obtained by Lee *et al.*¹⁸ and Sánchez-Hermosilla *et al.*¹⁵ The highest coverage levels were always found on the upper sides of the leaves in an external part of the canopy.



By considering the effect of applied volume rate on the quality of spray distribution, the sprayer settings were observed to have an influence far greater than that of the volume application rate. There were no clear benefits from increasing the water volume rate. The results are in accordance with the conclusions reported by Sánchez-Hermosilla *et al.*¹⁶ Notably, air assistance configurations allowed a reduction in the volume application rate without significant differences at either canopy density.

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