Influence of air-assistance on spray application for tomato plants in greenhouses

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Abstract

Protected horticulture production represents one of the most important agricultural businesses in Southern Europe. However, many problems related to the lack of mechanisation, intensive use of pesticides, and, in some cases, undesirable residues on food, have not been solved yet. In this context, application technology is a key factor for the improvement of the efficacy and efficiency of plant protection products. Spray guns and knapsack sprayers are the most common technologies that have been used for this purpose. However, several studies have demonstrated that, compared with spray guns, the use of vertical boom sprayers in greenhouses improves spray

Abbreviations: PPP – plant protection products; DISAFA – *Dipartimento di Scienze Agrarie, Forestali e Alimentari*; LAI – leaf area index; LWA – leaf wall area; TRV – tree row volume; LAD – leaf area density; ANOVA – analysis of variance; HSD – honest significant difference; SEM – standard error of the mean.

distribution and reduces labour costs and operator exposure. The main objective of this study was to evaluate the influence of air-assistance on spray application in conventional tomato greenhouses. For this purpose three different spray conceptions were evaluated: 1) a modified commercial handheld trolley sprayer with two air assistance concepts; 2) a self-propelled sprayer; and 3) an autonomous self-propelled sprayer with remote control. All the sprayers considered were evaluated in terms of absolute and normalised canopy deposition, uniformity of distribution, and losses to the ground. In addition, the vertical liquid and air velocity distributions of the sprayers were assessed and compared with the canopy profiles and spray depositions. Yellow tartrazine (E-102 yellow) was used as a tracer for deposition evaluation. The results indicated that increasing the air velocity does not increase the efficiency of a spray application. In general, the modified handheld trolley sprayer showed the best results in terms of deposition and uniformity of distribution, especially at the lowest air assistance rate. These results were confirmed with evaluation of the uniformity of the air and liquid distribution.

Keywords: Handheld trolley sprayer, air assistance, vertical pattern, air velocity, spray deposition

1. Introduction

One of the most hazardous factors affecting the economic, environmental and productivity parameters in protected horticultural production involves the use of plant protection products (PPP) for pest/disease control. Operator safety, residues on produced food, environmental contamination and economic investment are the problems related to this specifically as well as labour requirements, and most of them are directly linked to the technology used during the process (Nilsson and Balsari, 2012). At the same time, covered horticulture production represents one of the most important agricultural businesses in Southern Europe, focused mainly in Spain, Italy, and France (EFSA, 2010). However, many unsolved problems exist related to the lack of mechanisation, intensive use of PPPs (Nuyttens et al., 2004a; Céspedes et al., 2009), and undesirable residues on food (van Os et al., 2005).

In recent years, there have been important improvements in spray technology, with considerable differences depending on the target crops. Manufacturers of field crop and orchard sprayers have progressively introduced new and improved devices, taking advantage of the latest developments in computers, electronics, and global positioning systems. Those improvements have led to a safer and more effective use of pesticides, reducing the risk of contamination, adapting the proper dose to the canopy structure (Gil et al., 2007, 2011; Siegfried et al., 2007; Zhou et al., 2012) and improving traceability. However, the improvements have not been implemented as quickly in the case of spray application techniques used in greenhouses, where handheld sprayers or knapsack sprayers are still very popular (Nuyttens et al., 2004b; Balloni et al., 2008; Nilsson and Balsari, 2012; Sánchez-Hermosilla et al., 2013). The use of such primary technologies leads to limited efficacy and efficiency of pesticide application, with high risk of operator exposure (Nuyttens et al., 2009).

Alternative spraying techniques to handheld sprayers have been developed and tested in the past few years. Several studies have already demonstrated that the use of vertical boom sprayers in greenhouses improves spray distribution (Nuyttens et al., 2004a; Sánchez-Hermosilla et al., 2012) and reduces labour costs and operator exposure (Nuyttens et al., 2004b, 2009) in comparison with spray guns. Other researchers have investigated automatic spraying on PPP using new technologies such as navigation systems and autonomous vehicles with ultrasonic sensors or machine vision (Mandow et al., 1996; Sammons et al., 2005; Subramanian et al., 2005; González et al., 2009; Balsari et al., 2012; Sánchez-Hermosilla et al., 2013). However, according to Sánchez-Hermosilla et al. (2012), the use of such vehicles is very limited because of the high costs involved.

Air assistance has been considered one of the key elements for improving the efficiency of the spray application process in greenhouses, especially for dense crops (Llop et al., 2015). Derksen et al. (2007) achieved higher spray coverage on lower surfaces of bell pepper leaves using air-assisted delivery with single-fan nozzles than when using conventional delivery with either twin-fan or air induction nozzles. Similar results were obtained by Braekman et al. (2010) and Abdelbagi and Adams (1987). However, although air assistance has proven to be important for improving deposition on the canopy, it is still necessary to investigate the air distribution according to the canopy structure and the optimal relationship between the vertical distributions of the three factors affecting deposition, namely canopy surface, air velocity profile, and liquid distribution. Improvements in the uniformity of deposition have been achieved through optimum relationships between those parameters in several vertical crops such as vineyards (Pergher and Gubiani, 1995; Gil et al., 2013), citrus (Pai et al., 2009; Khot et al., 2012), and orchards (Landers et al., 2012).

Along with the new and improved technologies, the working parameters selected for the spray application processes (mainly volume rate and pressure) are also important factors affecting the final success. A survey of greenhouse farmers in the Netherlands (Goossens et al., 2004) showed that 90% of growers used high-pressure spray equipment (i.e. spray guns or lances) to apply PPPs, even though spray boom equipment has become increasingly popular. Braekman et al.

(2009) confirmed that growers were convinced that high application rates and spray pressures are indispensable for obtaining satisfactory coverage and sufficient penetration. Moreover, van Zuydam and van de Zande (1996) reported that the condition of the average spraying equipment used in daily practice is variable and usually not of a high standard.

The main objective of this research was to investigate the effect of air-assistance on different spray application techniques, ranging from manually pulled trolley sprayers to autonomous sprayers, on the spray deposition on tomato plants grown in greenhouses. Additionally, the effect of air velocity and nozzle pattern on canopy deposition, uniformity, and losses to the soil were also assessed.

2. Materials and methods

2.1. Spraying equipment

Three air-assisted sprayers adapted to greenhouse conditions were tested (Fig. 1). These three sprayers were used for four independent treatments as the first sprayer, a research prototype derived from a commercial handheld trolley sprayer, was converted into two different versions equipped with different blower units. Consequently, four different treatments (T1 to T4) were tested.

[insert Fig.1]

Fig. 1. Sprayers tested during trials: a) modified sprayer – T1; b) modified sprayer – T2; c) Sagevi sprayer – T3; d) Unigreen sprayer – T4

2.1.1. Modified prototype of handheld trolley sprayer (used for treatments T1 and T2)

The modified prototype T1 was a modification of a commercial handheld trolley sprayer (Carretillas Amate, Almería, Spain) with two vertical booms that could be adjusted to the canopy width and had six nozzles per side spaced at 0.35 m intervals. This modified sprayer (Fig. 1a) was fitted with an air-assistance device (average air velocity of 19.3 m s^{-1}) composed of an air generator (Nuvola 5HP, Cifarelli S.P.A., Voghera, Italy) activated by a 3.68 kW engine, a central air collector, and six individual spouts fitted parallel to each nozzle.

The modified prototype T2 (Fig. 1b) consisted of the same handheld sprayer as previously mentioned, but equipped with a different blower (B&D 3000W, Stanley Black & Decker Inc., New Britain, UK) with an air velocity of 14.0 m s^{-1} (average of values measured at each air outlet surface). This blower had an electric engine connected to a cable attached to the feeding pipe following the specifications described by Llop et al. (2015).

Both sprayers (T1 and T2) were fed using a pipe connected to an external sprayer through a piston pump with a tank of 100 L capacity.

2.1.2 Sagevi sprayer (used for treatment T3)

A self-propelled sprayer Atom 120 (Sagevi, Vilassar de Dalt, Spain), with air assistance, 120 L tank capacity, and four nozzles per side mounted in pairs, was also tested (Fig. 1c). The first pair of nozzles was located 0.59 m from the ground, and the second one was on an adjustable mast with a height range of 1 – 2 m that could be varied using a hydraulic piston activated by the operator. The distance between the two pairs of nozzles was 0.7 m, and the nozzles were fitted inside individual air outlets.

2.1.3 Self-propelled sprayer (used for treatment T4)

A Unigreen self-propelled sprayer mounted on a platform with remote control, developed in collaboration with Unigreen (Maschio Gaspardo S.p.A., Campodarsego, Italy) and DISAFA (Dipartimento di Scienze Agrarie, Forestali e Alimentari) (University of Turin, Italy), was also selected for the field trials. The prototype (Fig. 1d), described in detail in Balsari et al. (2012), has a 150 L capacity tank with two vertical booms and four nozzles on each side located at 0.45 m intervals. The air-assistance device consisted of an electric axial fan blower connected to a vertical air sleeve with several outputs per side.

2.2. Canopy characterisation

The experiments were conducted at Viladecans (Barcelona, NE Spain) in a commercial tomato (*Solanum lycopersicum* L. cv. Barbastro) greenhouse of 1265 m^2 (composed of a main corridor with several aisles on each side) located in a typical field farming area of this region.

The tomato plants had an average canopy height of 1.96 m and average width of 1.07 m. The plants were dispersed in a twin row system (two plants close together) with 2 m aisle width, 0.4 m distance between plants in a row, and 0.8 m between twin plants. The canopy was characterised by measuring the whole leaf area of three pairs of randomly selected plants. The values of leaf area index (LAI) were determined by adapting the area/weight ratio protocol, as described in previous work (Cross et al., 2001; Gil et al., 2007; Llorens et al., 2010; Llop et al., 2015). Geometric parameters (canopy height and canopy width) and derived parameters (leaf wall area (LWA), tree row volume (TRV), and leaf area density (LAD)) were also calculated.

2.3. Experimental setup

The sprayers were evaluated in terms of absolute and normalised canopy deposition, uniformity of distribution over the whole canopy, and losses to the ground. In order to quantify the amount of tracer deposited on the canopy, four masts were mounted, two in between the twin plants and two outside (Fig. 2). Each mast was divided into three vertical areas (top, middle, and bottom) covering the total height of the canopy and resulting in 12 sampling zones for each replication. Filter paper pieces of 24 cm^2 surface (3 x 8 cm) (Filtros Anoia S.A., Barcelona, Spain) were used as collectors and placed on dedicated paper clips previously fixed on the masts. The collectors were positioned horizontally. To evaluate the losses to the ground, four filter strip pieces were placed on wooden supports, two in the middle of the row (one per side) and two under the canopy. Due to the difficulty of completely randomising the sampling zones, nine replicates containing all the sampling protocol were settled along the same canopy row of 23.4 m, with a minimum distance of 2 m between replicates. Gil (2001), Llorens et al. (2010) and Llop et al. (2015) used similar arrangements. The sprayers passed along the row spraying the canopy from both sides. After every test, all the samples (filter papers) were carefully collected, placed in tagged plastic bags, and stored in a dark container. During the trials, the recorded values of temperature and humidity ranged from 25ºC to 30ºC and from 60% to 70%.

[insert Fig. 2]

Fig. 2. Sampling protocol. Positions of collectors on the canopy by height (top, middle, and bottom), by depth (external and internal), and on the ground (AL: aisle left, CL: canopy left, CR: canopy right, AR: aisle right)

2.4. Adjustment of working parameters of sprayers

The spray conditions selected for the three sprayers in the four tests are shown in Table 1. The sprayers were adjusted for an application rate of 800 L ha^{-1} following grower recommendations. It is worth noting that, with the self-propelled sprayer (Unigreen), problems relating to the efficiency of the electric batteries made it difficult to reach a pressure up to 1.5 bar during the trial and, consequently, it was not possible to reach the intended volume rate, resulting on an applied volume of 613 L ha^{-1}.

All the sprayers were fitted with the conventional flat fan nozzles XR11003 (Spraying Systems Co., TeeJet Technologies, Illinois, USA). The working pressure (in the range 1.5 – 3.0 $\times 10^2$ kPa) was established following the recommendations of the nozzle manufacturer, and the forward speed (3.5 km h^{-1}) was selected and measured to be a comfortable speed for the operator. The forward speed was measured recording the time used to travel a known distance. Prior to each test, the flow rate of the nozzles was measured using a mechanical nozzle flow meter (A.A.M.S. NV, Meldegem, Belgium) and the pressure was measured with a tested manometer at the entrance of the section.

The configuration of each sprayer (nozzle number, nozzle orientation, and boom height) was individually adjusted according to the canopy characteristics in order to match the whole canopy as much as possible, while avoiding losses to the soil or over the top of the canopy. In the case of the handheld modified sprayers (T1 and T2), the lowest nozzle, placed at 0.3 m from the ground, was closed to adjust the spray pattern to the canopy profile. In the case of the Sagevi sprayer (T3), the height of the top pair of nozzles was adjusted to 1.8 m. It was not possible to close the lowest pair of nozzles because of the characteristics of the particular sprayer. The nozzle setting on the Unigreen (T4) sprayer was also adjusted considering the canopy structure and the sprayer characteristics. The bottom nozzle was placed at 0.46 m from the ground, and the highest nozzle was at a height of 1.66 m from the ground.

2.5. Characterisation of sprayers

Before the spray tests, each sprayer was characterised in terms of air velocity and liquid spray pattern distribution. To evaluate the air velocity profile, a 3D ultrasonic anemometer (Gill instruments, Hampshire, United Kingdom) was used. The air speed was assessed perpendicular to the main air direction, simulating the canopy position in relation to the pass of the sprayer. Measurements for the modified sprayer (T1 and T2) were obtained at vertical intervals of 0.1 m at distances of 0.14 m, 0.2 m, 0.3 m and 0.4 m from the air outlet. This methodology is an adaptation of the method described by García-Ramos et al. (2012). In the case of the Sagevi and Unigreen sprayers, measurements were obtained at vertical intervals of 0.1 m at the distances of 0.2 m, 0.3 m, and 0.4 m from the air outlet; the distance of 0.14 m was not possible because of the dimensions of the anemometer and the design of air outlet. For all the sprayers, three replicates were performed for each measurement position. Data from the anemometer were interpolated to obtain the air distribution map using the *filled.contour* function of the software R (Murrell, 2005). Additionally, the air velocity at each outlet surface was measured using a portable impeller anemometer (Lambrecht Meteodigit I 14163, Lambrecht meteo GmbH, Göttingen, Germany).

The spray pattern liquid distribution was evaluated using a vertical patternator (A.A.M.S. NV, Meldegem, Belgium), which was placed at 0.3 m distance from the sprayer. The spray collectors on the vertical patternator were placed at vertical intervals of 0.2 m. Three repetitions were carried out for each sprayer. Results have been expressed as a percentage of total liquid recovered at each collector by height position following the models purposed by (Pergher et al., 2002; Balsari et al., 2007; Gil et al., 2013).

2.6. Analysis of samples

Yellow Tartrazine (E-102 yellow) mixed in the tank was used as a tracer in all the trials. Tartrazine was selected for the easy sample methodology in the laboratory, the high recovery rate of the tracer and the reasonable low photodegradation (Pergher, 2001). In addition, this product has been used as a tracer by several researchers (Sánchez-Hermosilla et al., 2011; Balsari et al., 2012; Gil et al., 2014). For the extraction of the tracer, 20 mL of deionised water was added in the plastic bag, and after 1 min of mixing, a sample was extracted and measured with a colorimeter (Thermo Scientific Genesys 20, Thermo Fisher Scientific Inc., Waltham, USA) at a wavelength of 427 nm. At the beginning and end of each trial, a sample from the tank (Table 3) was obtained at the output of the nozzle in order to normalise the deposit.

The amount of tracer deposited on the sample (canopy and soil) was calculated considering the water solution volume to extract the tracer and the area of the collector according Llorens et al. (2010) and Gil et al. (2007) as it shows equation 1:

$$d = \frac{T_{cl} \times w}{S_a} \qquad (1)$$

where d is the tracer concentration per unit sample surface (µg cm^{-2}), T_{cl} is the tracer concentration of the sample (mg L^{-1}), w is the amount of water used to extract the tracer from the sample (mL) and S_a is the area exposed of the sample (cm^2).

Since the tracer application rates (T_{cs}) were not the same for all treatments, a normalised deposit, d_n (µg cm^{-2} $_{sample}$/µg cm^{-2} $_{ground}$), was calculated according to Eq. (2) by dividing the deposit d by the amount of tracer applied per unit ground area, following similar previously described procedures (Cross et al., 2001; Gil et al., 2011; Siegfried et al., 2007; Viret et al., 2003). The normalised deposit enables comparisons between the different sprayers and it is represented by equation 2:

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

where d_n is the normalised deposit (µg cm^{-2}$_{sample}$/ µg cm^{-2}$_{ground}$), d is the tracer concentration per unit sample surface (µg cm^{-2}), V is the volume rate application (L ha^{-1}) and T_{cs} is the tracer concentration of the tank for each treatment (mg L^{-1}). Table 3 show the main values of absolute and normalized deposition of every test.

2.7. Statistical analysis

Statistical analysis was performed using the statistical software R (R Development Core Team, 2013). The effects of the different sprayers on canopy and soil deposition were examined using one-way analyses of variance (ANOVA), followed by the Tukey HSD (honest significant difference) post-hoc test for multiple comparisons. Before statistical analysis, the assumptions of ANOVA were checked.

3. Results and discussion

3.1 Canopy characterisation

The results of canopy characterisation are summarised in Table 2. High values of the calculated parameters (e.g. high crop density) indicated particular difficulties regarding pesticide application on this type of crop. In addition, from the ground to a height of 0.34 m, the tomato crop had no leaves.

3.2. Air velocity distribution on vertical profile

The results of air velocity measured at each outlet (Table 1) provide a general overview of the air performance. The highest value was obtained for the Sagevi sprayer (31.3 m s^{-1}), and the lowest for the Unigreen sprayer (10.08 m s^{-1}). The air velocities of the modified sprayers T1 and T2 were 19.3 ms^{-1} and 14.0 ms^{-1}, respectively.

The detailed air velocity distribution obtained for each sprayer is shown in Fig. 3. In general, the modified sprayers (T1 and T2) produced similar air distributions, although the air velocities measured with the ultrasonic anemometer were lower for T2 (~3.5 m s^{-1}) than for T1 (~5.5 m s^{-1}) because of the difference in the air blower unit. In both cases, the plume of air was almost perpendicular to the vertical plane of the canopy, making it possible to identify the directions of individual jets, similar to the case in Dekeyser et al. (2013) for orchard sprayers. Moreover, the air velocity measurements at the top and bottom air jets were lower than those measured at the other four jets. This behaviour was similar for both sprayers (T1 and T2) but with different air velocity values. For the Sagevi sprayer (T3), three air areas could be clearly distinguished. At the bottom part of the sprayer, the highest values of air velocity were obtained (~6 m s^{-1}), whereas at the central zone of the sprayer, the air velocity was almost zero. At the top of the sprayer, the air velocities generated were lower than those measured at the bottom and had a crosswise direction, whereas the bottom air direction was perpendicular to the canopy. The air distribution of the Unigreen sprayer (T4) was more homogeneous than the rest, but the velocity values were lower (always less than 3 m s^{-1}). Differences observed in the zones were probably caused by the spraying system performance.

[insert Fig. 3]

Fig. 3. Air velocity (m s^{-1}) distributions of the sprayers tested: a) modified sprayer – T1; b) modified sprayer – T2; c) Sagevi sprayer – T3; d) Unigreen sprayer – T4. Arrow size and background colours represent air velocity. Arrows also indicate the main air direction

3.3. Spray liquid vertical distribution

The spray liquid profile distributions of the four tested sprayers obtained from the vertical patternator are presented in Fig. 4. The modified sprayers (T1 and T2) generated similar profile distributions because they had the same nozzle distribution on the vertical boom. In this case, the aforementioned differences in air velocity did not affect the liquid distribution. However, these results are not in accordance with those obtained by Khot et al. (2012), which indicated that, at higher air velocities, more liquid was retained by the vertical patternator.

[insert Fig. 4]

Fig. 4. Liquid distribution represented as percentage of spray recovered of each sprayer: a) modified sprayer – T1; b) modified sprayer – T2; c) Sagevi sprayer – T3; d) Unigreen sprayer – T4. Mean ± standard error of the mean (SEM) are represented. Bars mean ±SEM of the data.

The Sagevi sprayer (T3) showed a deficit of spray liquid between 0.7 m and 0.11 m and an excess at the heights near the ground. The liquid distribution of the Unigreen sprayer (T4) only reached 1.8 m, because the last spraying nozzle was mounted at 1.66 m, and was almost continuous in the vertical profile. Overall, considering the spray liquid distributed to the canopy profile (from 0.34–2.3 m), T1 and T2 were found to be best adapted mostly due to the height position of the top nozzle. Other studies (Derksen and Gray, 1995; Gil et al., 2013) have emphasised the importance of adjusting the vertical spray profile to the canopy characteristics in order to achieve adequate spray application.

The high uniformity in vertical liquid distribution obtained for T1 and T2 can be linked to the number of nozzles placed on the boom and, consequently, to the shortest distance between them. This factor was also deduced by Llop et al. (2015).

3.4. Canopy deposition

A general overview of canopy deposition (Table 3) indicates that T2 provided the highest values of deposition and uniformity over the canopy. T4 presented the lowest canopy deposition but with no statistical difference compared with T3. These results are in accordance with those obtained by Dekeyser et al. (2013), who postulated that individual spouts result in higher deposits than axial sprayers.

A detailed analysis of the canopy deposition showed that, in general and for all the sprayers tested, the average of the deposition values measured at the external sides of the plants was at least 2.5 times higher than the deposition at the internal sides. Moreover, the deposit at the top level was lower than those measured at the middle and bottom sample level, for all the tested sprayers (Fig. 5). The relation between the average deposition values at the internal and external sides was similar for all the treatments. These results (40%) are similar to those obtained by Sánchez-Hermosilla et al. (2012) (44%), even though the applied volume rate was doubled in this study.

[insert Fig. 5]

Fig. 5. Normalized deposition on the canopy collectors (µg $cm^{-2}{}_{sample}$/ µg $cm^{-2}{}_{ground}$) for each sprayer: a) modified sprayer – T1; b) modified sprayer – T2; c) Sagevi sprayer – T3; d) Unigreen sprayer – T4. Same letter (by treatments) means no significant differences ($P < 0.05$). Bars means ±SEM of the data

The external depositions of the sprayers were found to be in the order: T2 > T1 ≥ T3 ≥ T4 with significant differences between T2 and the rest of the treatments (Table 4). In terms of internal deposition, no significant differences were detected between T1, T2, and T3 (mean of 0.10 µg cm^{-2}), whereas T4 presented a significantly lower value (0.05 µg cm^{-2}) respect T2.

A detailed evaluation of the results obtained for T1 and T2 indicated that higher air velocity does not imply higher spray deposition, and the sprayer with highest air velocity (T3) showed less deposition than sprayer T2. Furthermore, T1 and T2 presented more deposition at the top canopy level because of the position of the top nozzle, as shown in Fig. 4, which demonstrates that the high positions of those sprayers lead to more liquid recovery.

The importance of adjusting the vertical liquid distribution and air distribution according to the canopy structure has been widely demonstrated in previous studies (Derksen and Gray, 1995; Pergher et al., 1997). The results obtained in this research showed that T3 and T4, which delivered the most heterogeneous vertical liquid distribution and air distribution, also generated the greatest differences in canopy deposition between the sampling zones, especially in the external part of the canopy (Figs. 4 and 5). Treatments T1 and T2, which generated a more-homogeneous vertical distribution (air velocity and liquid), provided the most-uniform spray deposition on the canopy according to the coefficient of variation (Table 3). The obtained results also demonstrated that higher air velocity does not imply better liquid distribution or higher spray deposition, penetration, and uniformity. In general, T1 and T2, which had low air velocities but the most-uniform distributions, demonstrated the highest adaptabilities to the canopy. These results are in concordance with those obtained by Cross et al. (2003).

3.5. Losses to the soil

In terms of ground losses, measured as average deposition on the ground, there were no significant differences between the sprayers (Table 3).

The distribution of the losses to the soil was similar for all the treatments. The maximum deposition was measured on the samples placed under the crop (Fig. 6), whereas the losses detected in the middle aisle were less than 0.03 μg cm^{-2}, except for T3 for which the amount of deposition was significantly the highest (0.09 μg cm^{-2}). This tendency can be explained by the high air velocity of this sprayer (Fig. 3)., which could push the spray across the canopy, thereby increasing the losses to the soil In general, the tracer deposits under the canopy were high, sometimes similar to the deposits at the canopy collectors. This may be because there was no vegetation close to the ground (from ground level to 0.5 m). In the case of T4, the losses under the canopy were considerably higher, mainly because of the position of the lowest nozzle (0.45 m above the ground), which probably directed the spray pattern to the ground.

[insert Fig. 6]

Fig. 6. Normalized deposition on the ground collectors (μg cm^{-2}_{sample}/ μg cm^{-2}_{ground}) for each sprayer: a) modified sprayer – T1; b) modified sprayer – T2; c) Sagevi sprayer – T3; d) Unigreen sprayer – T4. AL: aisle left, CL: canopy left, CR: canopy right, AR: aisle right. Same letter (by treatments) means no significant differences ($P < 0.05$).

From the results, it was identified that losses to the soil are important compared with the deposition on the canopy for this particular case of tomato greenhouses with narrow layouts. Independent of the sprayer, nozzle configuration, and air velocity, the deposits on the soil under the canopy represent an important source of contamination. This fact could be attributed to the high-applied volume rate with respect to the canopy characteristics and density (see Table 1). However, this value was chosen according to the most representative value for the zone.

In conclusion, the results of the field tests conducted for the evaluation of different spray technologies in tomato greenhouses emphasise some important aspects:

- On sprayers T1 and T2, there was no effect of the air velocity on vertical liquid distribution made with vertical patternator.
- Even when air assistance was used, there was a great variability between external and internal deposition, considering the different canopy sections. The deposition at internal part of the canopy was at least 2.5 times lower than external side, highlighting the difficulty to penetrate at the internal side of the canopy.
- The modified spray hand held trolley T2 show the highest values in terms of deposition with an air speed of 14 m s^{-1}. However, increasing the air velocity did not increase the efficiency of the spray application.
- Air velocity and vertical spray pattern significantly affected the pesticide distribution on the canopy. The determination these parameters was a useful tool to assess the spray distribution on the canopy. In general the ground losses were relatively high even in some cases can be higher than the canopy deposition revealing the high risk of ground contamination. As concluded by some other researchers (Balsari et al., 2008; Khot et al.,

2012), there is a need to establish an appropriate relationship between the air characteristics (air velocity) and the canopy, even for greenhouse crops.

Considering the importance of greenhouse production in the area, there is a need to improve the pesticide application process, which is still hindered by a lack of advanced technologies, compared with other agricultural sectors.

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TABLES

Table 1. Selected working parameters for field trials

Treatment	Sprayer	Air velocity ($m\ s^{-1}$)*	Application rate ($L\ ha^{-1}$)	Forward speed ($km\ h^{-1}$)	Flow rate ($L\ min^{-1}$)	Number of nozzles	Pressure ($\times10^2$ kPa)
T1	Modified sprayer	19.34	819.2	3.57	0.97	10	2.0
T2	Modified sprayer	14.00	802.3	3.64	0.97	10	2.0
T3	Sagevi	31.3	784.8	3.66	1.20	8	3.0
T4	Unigreen	10.08	612.9	3.32	0.85	8	1.5

* mean of air velocities measured with a portable impeller anemometer at each sprayer outlet

Table 2. Canopy characterisation values

Parameter	Value
Row width (m)	2.00
Canopy height (m)	1.96
Canopy width (m)	1.07
LAI	5.46
LWA[a] ($m^2_{vegetation}\ ha^{-1}$)	19600
TRV[b] ($m^3_{vegetation}\ ha^{-1}$)	10486
LAD[c] ($m^2_{leaves}\ m^{-3}_{canopy}$)	5.21

[a]Leaf wall area; [b]Tree row volume; [c]Leaf area density

Table 3. Deposition and normalized deposition on canopy (mean ± SEM), uniformity (measured by coefficient of variation), and losses to the ground (mean ± SEM)

Treatment	Actual tracer concentration ($g\ L^{-1}$)	Canopy deposition ($\mu g\ cm^{-2}$)	Canopy normalized deposition ($\mu g\ cm^{-2}_{leaf}$/ $\mu g\ cm^{-2}_{ground}$),	Coefficient of variation of canopy deposits (%)	Ground losses ($\mu g\ cm^{-2}_{leaf}$/ $\mu g\ cm^{-2}_{ground}$)
T1	10.16	17.24±1.335	0.16±0.013 b	77.0	0.118±0.0330 a
T2	11.02	23.79±1.954	0.20±0.014 a	69.7	0.139±0.0360 a
T3	12.16	18.12±1.897	0.14±0.010 bc	78.1	0.158±0.0211 a
T4	13.42	12.28±1.250	0.11±0.010 c	91.4	0.207±0.0447 a

Different letters (in columns) represent significant differences ($P < 0.05$)

Table 4. Normalized deposition at external and internal side of the canopy (d_n)**.**

Treatment	d_n external side ($\mu g\ cm^{-2}_{leaf}$/ $\mu g\ cm^{-2}_{ground}$)	d_n internal side ($\mu g\ cm^{-2}_{leaf}$/ $\mu g\ cm^{-2}_{ground}$)
T1	0.24±0.018 b	0.08±0.010 ab
T2	0.32±0.026 a	0.11±0.012 a
T3	0.22±0.027 b	0.08±0.008 ab
T4	0.19±0.019 b	0.05±0.007 b

Different letters (in columns) represents significant differences ($p<0.05$)