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Evaluation of a fog cooling system for applying plant-protection products in a greenhouse tomato crop

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A B S T R A C T

The hand-held high-volume spray techniques used to apply plant-protection products in glasshouses in south-eastern Spain have poor efficiency due to heavy losses to the soil and to high risks of worker exposure. Therefore, it is necessary to develop alternative techniques to reduce these problems. The main objective of fog cooling systems is to control the climate inside the greenhouse, but the possibility of adding the extra function of plant protection without the presence of an operator inside the greenhouse, thereby accelerating the payback on the investment in equipment, has stirred interest among farmers. In the present study, the capabilities of fog cooling system were investigated in comparison with con-ventional spray guns. The results show that the deposition values on the crop were very low, far below the values reached with spray guns. Also, losses increased, due mainly to evaporation of droplets, despite saturating the atmosphere of the greenhouse before applications. The need to saturate the atmosphere implying an expense in water that is not necessary with spray guns.

1. Introduction

The greenhouse production system in south-eastern Spain is characterized by high planting density, which together with unfavourable environmental conditions (high temperatures, high relative humidity) provokes a high incidence of pests and diseases. In these greenhouses, plant-protection control relies primarily on the use of spray guns working at high pressures (>20 bar) to distribute large volumes of water. This spraying technique has poor efficiency because of extensive losses of plant-protection products (PPP) to the soil as well as an uneven distribution on the plant canopy (Derksen et al., 2008a, 2008b; Sánchez-Hermosilla et al., 2011, 2012), in addition to high exposure of the operator to the chemical applied (Nuyttens et al., 2004b, 2009).

The need for agricultural practices that are more environmentally friendly and healthier for greenhouse workers and consumers of products has led to the development of new techniques to apply PPP. Recently, as an alternative to the use of spray guns, machinery equipped with vertical booms have been developed for better control of variables such as spray pressure and volume, achieving more uniform coverage with greater deposition on the plant canopy (Langenakens et al., 2002; Nuyttens et al., 2004a) while reducing losses to the soil (Sánchez-Hermosilla et al., 2011, 2012). Also, fog cooling systems have begun to be used for application of PPP. The aim is to control the climate inside the greenhouse to prevent thermal stress, which in Mediterranean greenhouses can appear in crops cultivated during the summer, reducing crop yield and quality (Katsoulas et al., 2009; García et al., 2011). The system is based on very fine water droplets sprayed in the interior of the greenhouse over the vegetation, which evaporate during their fall, cooling temperatures and raising humidity. Currently, three different fogging systems are used (Arbel et al., 1999; Li and Willits, 2008): high-pressure, low-pressure, and air—water systems. The most appropriate for applying PPP are air—water systems. Using twin fluid nozzles that combine an air jet with a water stream under appropriate pressure and flow rates inside the nozzle chamber, these systems require a double network of pipes with a compressor that raises the cost of the installation as well as the energy consumption for operation. The main advantage of these fogging systems is to use nozzles with large emitter orifices that are not easily obstructed, allowing the use of low-quality water and even PPP. The air current also helps to clean the nozzle and avoid dripping.

The high cost of the fog cooling system and its limited utility (only certain days of summer) has also led to their use for applying PPP in order to increase the use time of the system and thereby improve the payback on the investment. According to Giles et al. (1995), the reasons for fogging are the potential to

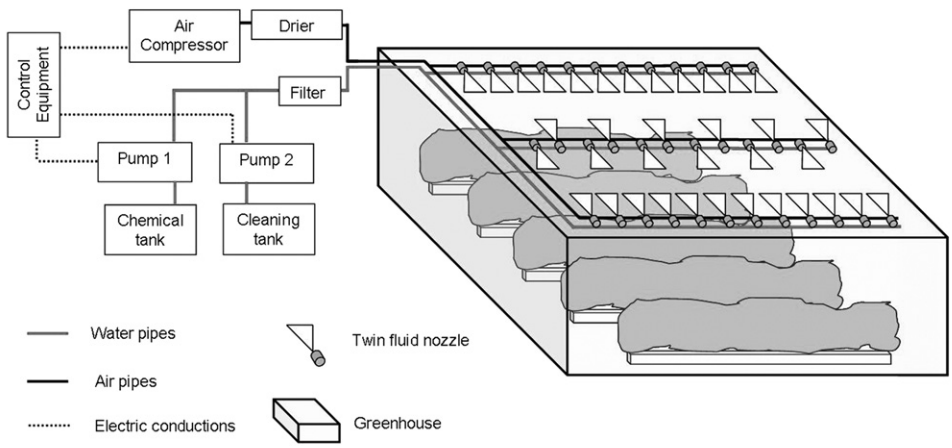

Fig. 1. Scheme of the greenhouse fog system installation.

increase the spray deposition, to improve the effectiveness of pest control and reduce the application time and spray exposure. Numerous works in the literature examine the performance of fog cooling systems for the control of environmental conditions inside greenhouses (Arbel et al., 1999; Abdel-Ghany and Kozai, 2006; Perdigones et al., 2008; Li and Willits, 2008; Katsoulas et al., 2009; García et al., 2011). Rincón et al. (2010), using this system to apply PPP in a greenhouse, have reported that the deposition on canopy and the uniformity were lower for a fog system than for a spray gun.

Scientific studies analysing the capacity of a cold fogger in a single location in the greenhouse (Austerweil and Grinstein, 1997; Olivet et al., 2011) have used equipment in which the liquid was distributed in the greenhouse by the effect of draw caused by the air current generated by the ventilator. The droplets generated are not homogeneous, larger ones being deposited close to the equipment (Olivet et al., 2011). The use of auxiliary ventilators in the application area improves the distribution of the fog generated (Austerweil et al., 2000).

The aim of the present work was to evaluate the spray deposition and losses to the soil caused by the air–water fog cooling system with twin fluid nozzles used to spray PPP, in comparison with a spray treatment with a manual spray gun (reference treatment).

2. Materials and methods

2.1. Application equipment

For this study, a spray gun and an air–water fog system with twin fluid nozzles were used. The spray gun is widely used by local farmers and therefore was considered as reference equipment. The gun used had two twin flat fan nozzles (Novi-Fan S.L., Almería, Spain), with a 25 m long hose (17 mm in diameter) connected to a wheel barrow holding a 100 l tank and a membrane pump (M-30, Inmovilli Pompe S.R.L., Reggio Emilia, Italy) that provided a maximum pressure of 3000 kPa and maximum flow of 33 l min^{-1}.

The fogging system was composed of two parts (Fig. 1), the air and hydraulic system, which joined in the twin fluid nozzles used inside the greenhouse, and a climate-control system (Himarcan S.L., El Ejido, Spain) that regulated the functioning of the equipment. The air system had a compressor (Rand ML 5.5, Ingersoll-Rand Co. Ltd., Wigan, UK) that expelled the pressurized air through a network of pipes located in the upper part of the greenhouse and an air-drying unit (ThermoStar, Ingersoll-Rand Co. Ltd., Wigan, UK). The hydraulic system was composed of an electric pump (2CDX/A 70/12, EBARA Pumps Europe S.P.A., Trento, Italy) to drive the liquid content of a 200 l tank through a network of pipes parallel to air-pipe network. Also, it had a cleaning system equipped with an electric pump (Múltiplo M, ESPA Bombas Eléctricas S.A., Girona, Spain) and a 100 l tank of clean water used for rinsing the system after the PPP.

The air and water pipes joined the twin fluid nozzles. The fogging system had a total of 36 twin fluid nozzles (FICFOG, Fíclaho S.L., Alicante, Spain) distributed in three lines of 12 nozzles set 2 m apart. The lines were located over the crop canopy (3 m from the soil). Two lines were located on opposite sides of the test greenhouse module with the nozzles aimed towards the central part, and the other line along the centre of the module with the nozzles pointed alternating in opposite directions.

For the assays with the spray gun, working conditions were established according to the routine practices of local farmers (Table 1), consisting of spraying at high pressures while using high volumes of water. The spraying distance was approximately 0.30 m to the outermost part of the crop, spraying both sides of the test row. The data on pressure and flow rate were recorded with 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).

Table 1
Working conditions of the equipment.

Spraying equipment	Nozzle type	N° nozzles	Spray pressure (kPa)	Flow (l min^{-1})	Test	Operation time (min)	Travelling speed (m s^{-1})	Application rate (l ha^{-1})
Fog system	Twin fluid	36	Water: 300	2.125	1	22.47	–	994.63
			Air: 250		2	34.10	–	1509.62
Spray gun[a]	Twin flat fan	2	2116	3.188	1	–	0.57	932.28
			2109	3.183	2	–	0.35	1515.87

[a] Reference application (routinely used by local farmers).

Table 2
Environmental conditions inside the greenhouse.

Parameter		Test 1	Test 2
Before saturation	Temperature (°C)	24	27
	Relative humidity (%)	54	58
	Wet Temperature[a] (°C)	30.37	33.19
After saturation	Temperature (°C)	22	25
	Relative humidity (%)	90	92
	Wet Temperature[a] (°C)	23.21	26.03
Water to saturate (l ha^{-1})		4006	3958

[a] Determined using a psychometric chart (http://www.sc.ehu.es/nmwmigaj/CartaPsy.htm).

The trials with the fog system were made with the greenhouse completely closed and with the atmosphere previously saturated with water, to reduce the evaporation of the fog droplets and achieve better distribution of the PPP. To saturate the atmosphere, water was sprayed until reaching a relative humidity higher than 90%. Table 2 shows the environmental conditions before and after the saturation of the atmosphere. With the fog system, application rates similar to those applied with the spray gun were used, with an air pressure of 250 kPa and liquid pressure of 300 kPa, regulating the operating time of the system (Table 1).

2.2. Experimental design

The trials were undertaken in a multi-gabled greenhouse located in the IFAPA Center La Mojonera (Almería, Spain, latitude 36°48′N, longitude 2°41′W, altitude 142 m). The greenhouse, oriented east-west, had an area of 960 m^2 (24 m × 40 m), with a height of 6 m to the ridge and 4.5 m to the end of the column. The crop used was tomato (*Lycopersicon esculentum* Mill. cv. Deni Sen), grown in con-tainers filled with perlite and planted in a twin-row system (two rows planted close together). The twin rows were 2 m apart and had 50 pairs of plants spaced on 0.4 m (2.5 plants m^{-2}).

The tomato seedlings were transplanted on 15 March 2011 and two trials were made with spray equipment, the first at 69 and the second at 111 days after transplanting. The characteristics of the crop in the two trials are listed in Table 3. 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).

The greenhouse was divided into two modules, separated by a plastic partition, each of 20 m × 24 m containing 9 rows of crop. One module was for the spray-gun application and the other for the fogging system (Fig. 2). With the spray gun, each trial was made on a different crop row assigned at random, and in each row, 6 plant pairs were taken at random at least 2 m apart to evaluate deposition. For the trials with the fogging system, 6 plant pairs were designated at random for evaluation among the 9 rows of the test module, making sure that at least one pair of plants was taken in each quadrant of the test module. In this way, samples were taken throughout the area sprayed by the fogging system.

Each plant pair was considered a replicate and was fitted with artificial collectors consisting of filter-paper strips 30 mm × 80 mm (Filter-Lab Ref. 1238, Filtros Anoia, S.A., Barcelona, Spain). The collectors were placed in 12 zones (3 heights and 4 depths; Fig. 3). In

Table 3
Crop characteristics.

Test	dat[a]	Leaf-area index	Crop height (m)	Crop depth (m)
1	69	1.68	1.53	0.75
2	111	3.34	2.53	0.80

[a] Days after transplanting.

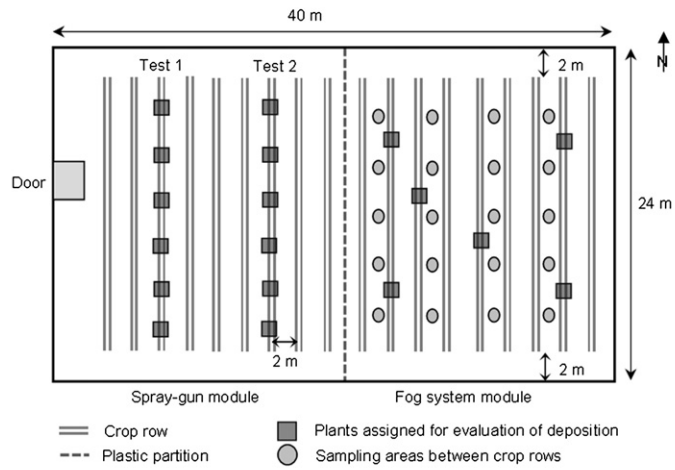

Fig. 2. Distribution of the sampling zones.

each zone, a leaf was assigned at random to be fitted with the collector on the upper sides and undersides of the blade (two positions). Collectors were also placed on the soil coinciding with the four depths defined in the plant pairs (Fig. 3). In this way, the deposition on the plant canopy could be quantified, differentiating between the upper sides and undersides of the blade, as well as measuring losses to the soil. For each trial, a total of 168 samples were taken: (12 zones × 2 positions + 4 soil samples) × 6 plant pairs. In addition, to characterize the functioning of the fog cooling system, samples were also taken in the lanes between crop rows at three heights: at soil level, at 1 m and at 2 m above the soil (Fig. 3). For this, 4 lanes were taken at random and in each case 5 sampling zones were delineated (Fig. 2). Therefore, between the crop rows, 60 samples were taken in each trial: (soil sample + 1 m sample + 2 m sample) × 5 points per lane × 4 lanes.

2.3. Deposition measurement

In all the tests, Tartrazine (Roha Europe, S.L.U., Torrent, Spain) was used as the tracer at a tank concentration of approximately 10 g l^{-1}. After the fog had disappeared from the greenhouse, the filter-paper strips were collected, and individually placed in zip-lock bags 120 mm × 180 mm. The bags were stored in an opaque box to protect them from sunlight, until processed in the laboratory.

In the laboratory, the filter-paper strips were washed for 60 min with 25 ml of distilled Mili Q Quality water in the same zip-lock bags. During the washing time, the bags were stored in darkness. After the washing, the quantity of tartrazine in the washing solution was quantified by spectrophotometry at a wavelength of 425.5 nm. A double-beam UV—visible spectrophotometer was used (Helios Zeta, Thermo Fisher Scientific, MA, USA). As the baseline, the solution resulting from washing the blank samples (filter-paper strips not exposed to the spray) was used following the procedure described above.

During the trials, samples from the spray tanks were taken to determine the exact concentration of the tracer (Table 4). To compare the treatment equipment used, the tracer concentration measured in the collectors was corrected with respect to the concentration and volume used in the reference application (spray gun).

2.4. Statistical analysis

Once normalized, the data were processed for the statistical study. First, it was determined whether they followed a normal

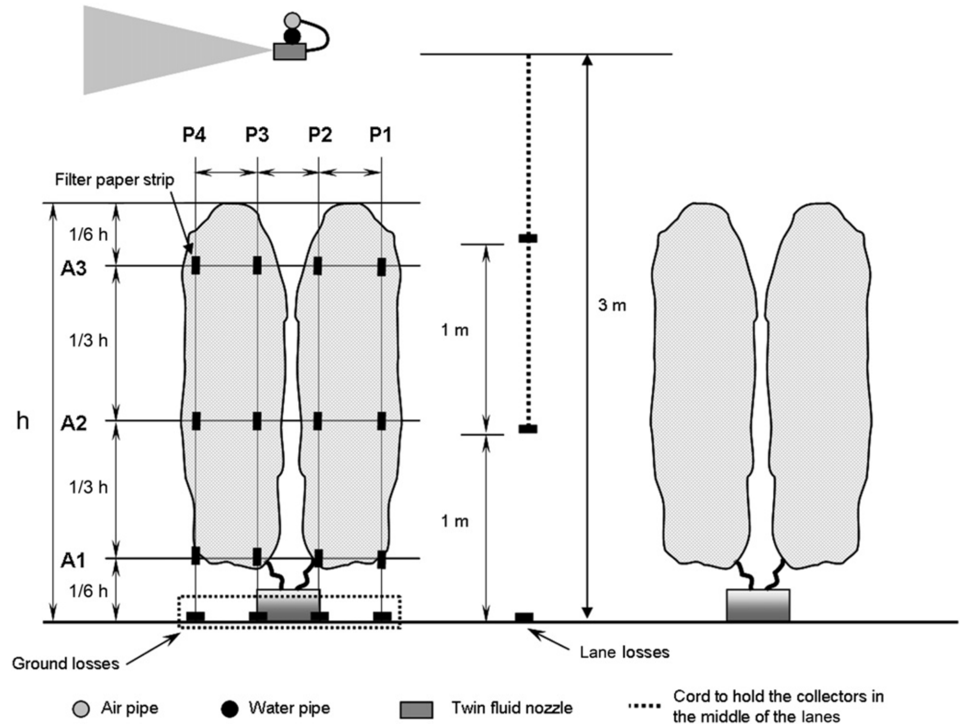

Fig. 3. Positions of the filter papers within the crop canopy.

distribution by the Kolmogorov—Smirnov test ($p < 0.05$). The distribution of the data proved non-normal and therefore a non-parametric test was used (Kruscall—Wallis), analysing significant differences by Dunn's test with a significance level of 95%. The statistical analysis was made by using the software SPSS v19.0 (SPSS Inc., an IBM Company, Chicago, IL, USA).

3. Results and discussion

3.1. Deposition on the crop

The results corresponding to the deposition on the plant canopy are presented in Table 5. For the spray gun, regulated according to the criteria of the farmer, the values were similar to those reported by Sánchez-Hermosilla et al. (2011, 2012) for a tomato crop working with a similar spray gun. However, deposition with the fog system was very low, registering 76.5% and 58.5% lower than the spray gun in trials 1 and 2, respectively.

The light droplet deposition by the fog system was due to the distribution of the volume of the application throughout the entire greenhouse (zones with and without vegetation), implying major losses in the zones without vegetation, by evaporation, and by deposition on the ground. As the droplets from the fogging system fell, the distance that they travelled before evaporating depended on the droplet size and the environmental conditions within the greenhouse. The theoretical distance (D, in cm) a water droplet of diameter (d, in μm) will fall due to gravity before all the water has evaporated is given by equation (1) (Matthews, 2000).

$$D = \left(1.5 \times 10^{-3} \times d^4\right) \Big/ (80 \times \Delta T) \quad (1)$$

where ΔT is the difference in temperature (°C) between wet and dry temperature, which had values of 1.21 °C and 1.03 °C for tests 1 and 2, respectively. Taking into account that the nozzles were situated at 3 m from the ground and that all the droplets had a size smaller than 55 μm in test 1, and 40 μm in test 2, all the droplets evaporated before reaching the canopy. For this reason, the greater the space without vegetation, the greater the number of droplets lost by evaporation. This fact was confirmed on observing that the depo-sition increased notably with greater crop development (test 2). The deposition for the fogging system increased form test 1 to 2 by 131.3%, when the spray gun, which presented deposition values that increased by 28.6% between tests, because it was a technique that distributed the application volume only in the zones where there was vegetation.

On the other hand, if the atmosphere inside the greenhouse had not become saturated, the ΔT would have had a value of 6.37 °C for test 1 and 6.19 °C for test 2, so that the minimum size to reach the canopy was 84 μm and 62 μm for tests 1 and 2, respectively. Taking into account that fog systems produce populations of droplets with a VMD (Volume Median Diameter) of 2—60 μm (Arbel et al., 1999), with an unsaturated atmosphere, a high number of droplets did not reach the canopy. The saturation of the atmosphere implies a water expenditure of roughly 4000 l ha^{-1} in the tests made (Table 2), which was not necessary in the applications with the spray gun.

Analysis of the distribution of the deposition on the upper side and underside of the leaf (Table 6) indicated that the greatest

Table 4
Tracer concentration in the tank of the spray equipment.

	Test 1		Test 2	
	Fog system	Spray gun	Fog system	Spray gun
Application rate (l ha^{-1})	994.63	932.28[a]	1509.62	1515.87[a]
Tracer concentration (g l^{-1})	9.43	9.92	10.42	9.73
Rate correction factor	1.07	1.00	0.99	1.00
Concentration correction factor[b]	0.94	0.99	1.04	0.97
Common Correction factor	1.01	0.99	1.03	0.97

[a] Taken as reference application rate.
[b] Reference tracer concentration 10 g l^{-1}.

Table 5
Means and coefficients of variation (C.V.) of total deposition per unit of collector area in the canopy and losses to the soil.

Spraying equipment	Test 1				Test 2			
	Canopy		Soil		Canopy		Soil	
	Mean ($\mu g\ cm^{-2}$)	C.V. (%)	Mean ($\mu g\ cm^{-2}$)	C.V. (%)	Mean ($\mu g\ cm^{-2}$)	C.V. (%)	Mean ($\mu g\ cm^{-2}$)	C.V. (%)
Fog system	3.52b	56.79	5.92b	53.78	8.14b	59.91	13.55b	59.49
Spray gun	15.01a	66.41	23.88a	87.25	19.63a	63.89	38.87a	60.45

Means in the same column with the same letter do not differ significantly ($p < 0.05$; Dunn's test).

Table 6
Means and coefficients of variation (C.V.) of the deposition in the upper and underside of the leaf.

Spraying equipment	Test 1				Test 2			
	Upper side		Underside		Upper side		Underside	
	Mean ($\mu g\ cm^{-2}$)	C.V. (%)	Mean ($\mu g\ cm^{-2}$)	C.V. (%)	Mean ($\mu g\ cm^{-2}$)	C.V. (%)	Mean ($\mu g\ cm^{-2}$)	C.V. (%)
Fog system	3.19b	56.52	0.33a	143.27	6.95b	62.59	1.19b	84.12
Spray gun	12.28a	76.72	2.73a	182.77	16.38a	71.48	3.25a	79.84

Means in the same column with the same letter do not differ significantly ($p < 0.05$; Dunn test).

deposition was on the upper side with both application methods and in both trials. On the underside, the deposition with the spray gun proved very low and uneven, whereas deposition by fogging was even lower by 8-fold and 2.7-fold for tests 1 and 2, respectively.

Another noteworthy aspect to evaluate in an application technique is the capacity for the liquid spray to reach the inner areas of the crop canopy (planes P2 and P3, Fig. 3). As reflected in Table 7, the values in the case of fogging are far below the values of the spray gun, both on the exterior as well as in the interior of the canopy. However, the fogging system provided a more proportional distribution between the inner and outer parts (I/O), with values of between 86% and 105%, while for the spray gun these values were between 40 and 56%.

3.2. *Losses to the greenhouse soil and lanes*

The losses to the ground under the plants (Table 5) that resulted with the fogging system were less than with the spray gun, i.e. 75.2% and 65.1% lower in test 1 and 2, respectively, due fundamentally to the effect of shading of the plant mass. This fact was confirmed on observing that the deposition on the ground in the lanes (Table 8) was greater than quantified under the canopy.

The lower deposition on the canopy together with the lower losses to the soil under the plants under the fogging system indicated that this technique results in heavy losses by evaporation, despite saturating the atmosphere before fogging. As commented above, the fogging system is characterized by the distribution of the PPP throughout the entire greenhouse, while the spray gun directs the volume sprayed to the zones with vegetation. This results in heavy losses to evaporation and soil deposition in the areas unoccupied by vegetation. Table 8 shows the deposition values in the lanes between crop rows at three different heights. In test 1 the deposition on the soil of the lane was lower than that found at 1 and 2 m above the soil, i.e. 25.0% and 23.6% less, respectively. This trend may be due to the fact that on applying the reduced volume (test 1), a greater number of droplets evaporate and do not reach the ground. This effect was not noted in test 2, where no significant differences were found between the depositions recorded at different heights. In this case, the greater volume applied implies lower droplet evaporation, so that more droplets reach the soil.

In conclusion, the air–water spray system results in a deposition in the plant canopy that increases as the crop develops, given that there was a higher number of droplets that reached the vegetation before evaporating. However, in the two cases, we studied the deposition was far lower than that achieved by the spray gun. Therefore, fogging proved to be a technique that causes greater losses than did the spray gun.

Therefore, with respect to the losses to the soil, the losses that the fogging system caused to the soil under the lower crops were lower than in the spray-gun application because of the shading of the vegetation mass. This fact, together with the low deposition in the canopy, indicates that most of the losses caused by the fogging system were caused by evaporation. To reduce these losses by the fogging system, saturation of the air in the greenhouse becomes necessary, this representing a major loss of water that is not necessary with the spray gun.

In general, it can be concluded that the fogging air–water system caused a deposition over the crop that is lower than with conventional spray equipment used in greenhouses in southeastern Spain (spray guns) and therefore greater losses due fundamentally to droplet evaporation.

Table 7
Means (in $\mu g\ cm^{-2}$) of the deposition in the outer and inner zones of the canopy.

Spraying equipment	Test 1			Test 2		
	Outer	Inner	I/O (%)	Outer	Inner	I/O (%)
Fog system	3.40b	3.58b	105.29	8.4b	7.27b	86.55
Spray gun	19.02a	10.64a	55.94	27.24a	10.87b	39.90

Mean in the same column with the same letter do not differ significantly ($p < 0.05$; Dunn's test).

Table 8
Means and coefficients of variation (C.V.) of the deposition on the lanes with the fog system at three heights.

Height above the floor (m)	Test 1		Test 2	
	Mean ($\mu g\ cm^{-2}$)	C.V. (%)	Mean ($\mu g\ cm^{-2}$)	C.V. (%)
0	6.92a	40.39	20.40a	33.38
1	9.23b	25.67	17.91a	25.41
2	9.06b	25.73	21.36a	25.13
Mean	8.40	–	19.89	–

Means in the same column with the same letter do not differ significantly ($p < 0.05$; Dunn's test).

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