Research Article

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Characterization of irrigator emitter to be used as solid set canopy delivery system: which is best for which role in the vineyard?

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Abstract

Background: The timely and flexible treatment of solid set canopy delivery systems (SSCDS) is expanding. Laboratory and field trials were conducted to evaluate the performance of three different irrigators (Pulsar™ system and nozzle combination), typically used in anti-frost and irrigation in vineyards/apple orchards, for plant protection product (PPP) delivery in a Guyot-trained trellised vineyard.

Results: Results showed that irrigator setups perform best when matched to the task—flat fan emitters for horizontal spray application (canopy top) and circular emitters for middle and low canopy application. A combination configuration of a double-sided flat fan and circular emitter system was indicated as the best option for homogenous coverage and minimal ground losses.

Conclusion: The tested emitters hold promise for SSCDS delivery of PPPs in vineyards. Further validation of the alternative use of this technology is warranted.

Keywords: environmental impact; SSCDS; PPP application; multipurpose system; fix spray system; irrigator

INTRODUCTION

Plant protection product (PPP) application is optimal when it delivers the precise amount of product to the target, minimizes in-field ground losses and spray drift, and avoids environmental and human harm. An expanding understanding of such products and their effects has led European Union (EU) policymakers to introduce the Farm to Fork Strategy[1,2], which aims to halve the overall use and risk of chemical and hazardous PPPs by 2030. To attain this goal in bush/tree crops, where spray drift represents a larger risk than in arable crops, research has focused on spray application. In particular, precision agriculture principles have advanced sideways and upwards air-assisted application and sprayer efficiency for 3D crops (vineyards and orchards).

Generally, spray application improvements have come from two research paths. One path tailors sprayed volume to target size and density through variable-rate application (VRA). The most recent and advanced VRA technologies use pulse width modulation (PWM) nozzle systems, which permit changes in the flow rate by varying the PWM duty cycle. In this way, spray pressure is held constant and droplet size spectrum remains unchanged throughout the spraying process.[3-5] The other path reduces spray drift in one of three ways: using air inclusion nozzles in hydraulic atomization,[6] employing adjuvants to increase droplet size,[7,8] and correctly aligning active nozzles, air flow and spray direction.[9,10] Air-assisted sprayers have undergone many upgrades, yet still fall short for spraying the steep-sloped, niche vineyards that predominate in Europe.[11–13] Replacing the knapsack sprayers commonly adopted in these areas is needed to limit farm labour costs[14,15] and operator risk.[16]

Delivering PPPs in commercial orchards and vineyards via a solid set canopy delivery system (SSCDS) represents a modern version of fixed spray methods promoting sustainability. A SSCDS typically consists of micro-emitters (or agricultural nozzles) positioned directly within the plant canopy and fed from a common pumping station.[17] The system represents an advantage for farmers because it makes it possible to spray at the time when the best environmental conditions exist (low wind speed, right temperature and after a rain). Moreover, such systems reduce human/operator presence in PPP delivery areas to mitigate worker health and safety risks.[18,19] This apple orchard- and vineyard-tested innovation has demonstrated its capability to equal (or better) air blast sprayer performance for plant pest[17,20,21] [17,20,21] and off-field drift control.[22,23] However, until now, only a

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few prototype anti-frost and irrigation orchard systems have been considered for PPP application through SSCDSs.[24]

Development of a new or alternative application for an existing technology (SSCDS) requires that it at least equal the standards and efficiencies provided in its original use. Before considering investment cost, long-term system reliability and regulatory compliance, the actual performance of the technology (emitter) is most important. Although many emitter type and mounting configuration studies have been conducted in vineyards and orchards,[18,25–28] there is a dearth of research on emitter type and positioning as a function of different canopy morphologies (e.g. variability resulting from the varieties) and plant training systems (trellised-, pergola- or tendone-trained vineyards). To this end, this study has five objectives: (i) to evaluate the flow rate variability of three emitters/irrigators, (ii) investigate their spray patterns, (iii) to measure and characterize the droplet size spectra generated by the emitters in the laboratory, and (iv) to evaluate the potential canopy spray coverage in field tests in a Guyot-trained trellised vineyard.

MATERIALS AND METHODS

The feasibility of using bush/tree crop irrigation and frost/heat damage mitigation emitters as part of a SSCDS in a Guyot-trained trellised vineyard for PPP application was investigated at DiSAFA facilities of the University of Turin, Italy (45° 3′ 54.6′ N, 7° 35′ 28.9′ E). To answer this question required that we characterize the emitters under consideration for this alternative use. First, flow rate variability, horizontal spray pattern and droplet size spectra were measured in the laboratory to identify the best configuration of each emitter system to be field tested. Second, potential canopy spray coverage and potential ground losses were measured for each emitter system type in the field. The field-test dataset of emitter positions inside vine canopies and their relative distance and density along vine rows then were used to determine the emitter network configuration that would provide maximum homogenous spray coverage in a trellised vineyard.

Emitter components and functioning

The emitters used in this study had two components—a Pulsar™ system (Netafim Ltd Co., Tel Aviv, Israel) and a nozzle mounted atop the system. Several subcomponents comprise the Pulsar™ system: (i) a fuchsia-coloured pressure compensating dripper (colour not referred to ISO 10625:2018[29]) [Fig. 1(a)] installed on the main hose feeding the emitter, (ii) a micro-tube [Fig. 1(b)] connecting the pressure compensating dripper to (iii) the Pulsar™ tube [Fig. 1(c)] with an airbag-accommodating chamber that acts like a pressure compensator, and (iv) a calibrated blue-pin, anti-drip valve (AD Valve™) positioned at the Pulsar™ tube outlet [Fig. 1(d)]. Nozzles are installed downstream of the Pulsar™ system [Fig. 1(e)].

A pulse emitter operates on basic mechanical principles. According to the manufacturer, pure water (0.30 MPa) supplied via the feeding hose to the inlet of the Pulsar™ system maintains a 0.20 L min^{-1} flow rate so long as the pressure remains within a range of 0.25–0.40 MPa. Colour-coded pressure compensating drippers determine specific flow rates and eliminate flow rate variation. A diaphragm and labyrinth inside the compensating dripper work in combination to sense and stabilize flow rate at the outlet, regardless of the water pressure at its inlet. The micro-tube conducts liquid to the Pulsar™ tube chamber where an airbag is compressed as water fills the chamber. Rising pressure inside the chamber triggers the blue-pin calibrated anti-drip valve (0.25 MPa) (Netafim Ltd Co.) to open, at which point the liquid is atomized and the spray is released through the nozzle in a single pulse. The opposite action—a falling chamber pressure—causes the anti-drip valve to close and the liquid atomization pulse stops. Upon closure of the anti-drip valve, chamber pressure begins to build for a sequential pulse. The Pulsar™ system ensures a stable pressure at the inlet of the emitter regardless of its field location and overcomes any feeding hose pressure variations related to distance to the pump or field topography.

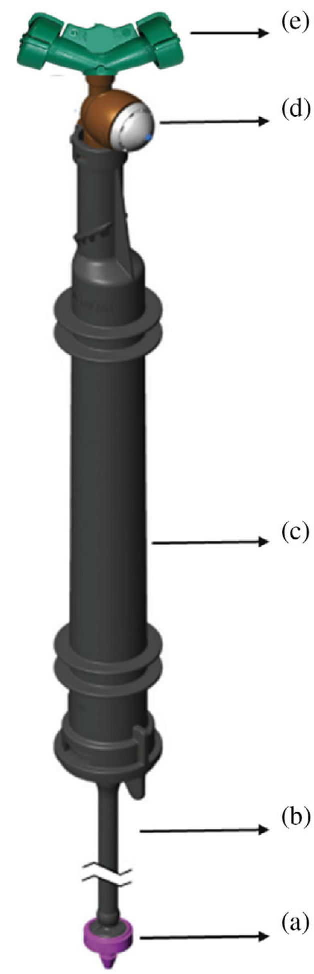

Figure 1. Schematic of the emitter used in the experiment by assembling the Pulsar™ system and nozzle. The Pulsar™ system has several pieces: (a) pressure compensating dripper, (b) micro-tube connecting the compensating dripper to the (c) Pulsar™ tube with an internal airbag that acts like a pressure compensator, and (d) a calibrated anti-drip valve. (e) Nozzles are installed downstream of the Pulsar™ system.

Laboratory trials: experimental design

The laboratory setting was used to test the characteristics of the different emitters. Three plastic nozzle types were installed and tested with the Pulsar™ system: single-sided flat fan (StripNet™ model STR31 1AN), double-sided flat fan (StripNet™ model STR31 2AN) and circular (VibroNet SD™ model50) nozzle (Netafim Ltd Co.) (Fig. 2).

Flow rate measurements

The flow rates of the three 'emitter systems' (Pulsar™ system + nozzle) were determined using ISO:5682 (2017) standardized

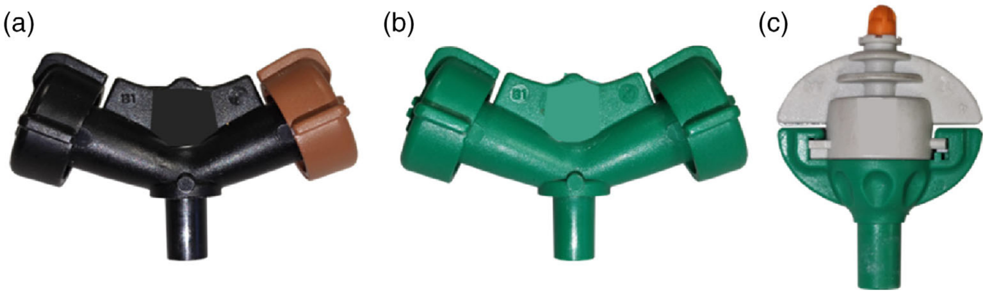

Figure 2. Nozzles combined with the Pulsar™ system determines the different emitter systems tested: (a) single-sided flat fan (StripNet™ model STR31), (b) double-sided flat fan (StripNet™ modelSTR31 AN) and (c) circular (VibroNet SD™ model 50) nozzles.

methodologies.[30] In total, 60 emitter systems were tested by randomly selecting 20 nozzles from each nozzle type. The emitter systems were connected by a polyethylene hose to a portable pumping station. The station included an electric membrane pump (AR252 BlueFlex™; Annovi Reverberi S.p.a., Modena, Italy) for moving the liquid through the main hose, a manual pressure regulator (GR 30 – code 879; Annovi Reverberi S.p.A.) installed upstream of the main hose for adjusting the pressure of the liquid, and a pressure gauge (WIKA; Alexander Wiegand SE & Co. KG, Klingenberg-am-Rhein, Germany) for monitoring a constant liquid pressure throughout the trials (set to 0.30 MPa).

The liquid sprayed by each emitter for 120 s (measured with a Delta E200 field chronometer; Hanhart 1882 Gmbh, Gütenbach, Germany) was collected using a plastic cylinder. The total amount of liquid was measured using an electronic analytical balance (precision level of 0.01 g - BCE4200; Orma S.R.L., Trofarello, Italy). Nominal flow rate was calculated and expressed as L min^{-1}. Three replicates were performed for a total of 180 flow rate.

Next, from each batch of 20 tested nozzle per type, the five nozzles characterized by flow rate closest to the flow rate averaged over the 20 batch nozzles (0.30 MPa) were selected. Using the same procedure described above, the flow rates of the five selected emitters were measured in triplicate at several liquid pressures (0.20, 0.40 and 0.50 MPa) for a total of 45 measurements. These liquid pressures were tested to investigate flow rate variation when the pressure-compensating dripper operates out of its optimal pressure range (0.25–0.40 MPa).

Data were analyzed using Spss Statistic (v28; IBM, Armonk, NY, USA) predictive software for Windows™. Data were tested for normality using the Shapiro–Wilk test. Residual analyses also were performed and the data derived from the emitter system types were analyzed separately. One-way ANOVA was used to test the effects of the independent variable pressure (0.20, 0.30, 0.40 and 0.50 MPa) on the dependent variable flow rate (L min^{-1}). In all cases, the means were compared using a Duncan *post hoc* test for multiple comparison ($p < 0.05$).

Horizontal spray pattern

Horizontal spray patterns were assessed using an *ad hoc* indoor spray collecting system. A total ground area of 11.88 m^2 was covered with 20 rows of plastic Petri dishes (diameter 90 mm; APTACA S.p.a., Canelli, Italy). Each row was spaced 0.30 m apart and consisted of 23 Petri dishes for a total of 460 units analyzed per each emitter system type (three replicates) (Fig. 3). Petri dishes were weighed individually with an analytical balance (model BCE4200; Orma S.R.L.) before and after spraying pure water. The five single- and double-sided flat fan emitter systems were positioned with their nozzle orifices parallel and 0.50 m aboveground at 0.30 m from the first Petri dish row (1 L) (Fig. 3). The five circular emitters were positioned parallel and 1.10 m aboveground over the Petri dishes (11P) (Fig. 3). An identical amount of liquid was sprayed from each emitter system for 5 (single-sided flat fan), 10 (double-sided flat fan) and 5 min (circular). The emitter systems were connected to the portable pumping station set to 0.30 MPa pressure. Three replicates per system type yielded 45 total measurements.

We calculated three variables for each horizontal spray pattern: (i) percentage (%) of volume recovered at each sampling point; (ii) percentage (%) of total volume recovered at each sampling distance from the spray source to obtain the horizontal spray pattern; and (iii) maximum length and width (m). Spray distribution homogeneity was calculated based on the horizontal spray pattern per each emitter system type. Adopting similar procedure to that used by Zwertvaegher *et al*.,[31] multiple spray patterns for the same emitter type was graphed one next to each other and areas superimposed. Based on the superimposition area analysis the homogeneity of spray distribution was defined. Two variables describing spray distribution homogeneity were used—total average spray volume (%) and coefficient of variation (*CV*, %) of the spray distribution in the target zone. They were guided by two criteria—average spray volume ≥ 3% of the total target zone volume sprayed and $CV < 10\%$. If both criteria were met, then the layout was considered field-test suitable. The thresholds were selected such that at least one layout per emitter system type met both criteria. Thus, the optimal emitters network layout able to provide homogeneous spray coverage above the canopy (single- and double-sided flat fan emitter systems) and into the canopy (circular emitters) were identified. The information obtained then was used to define the position of different systems inside the vine canopies and their relative distances along the row.

Droplet size spectrum

The droplet size spectra were characterized using a Malvern Spraytec™ laser diffraction system (model STP5342; Malvern Instruments Ltd., Worcestershire, UK) as other have described.[32,33] When the sprayed liquid passes through the laser beam, the scattering of the light intensity is measured. Droplet size spectra were obtained from an analysis of the spray streamed. Single-, double-sided flat fan and circular emitter systems were positioned to ensure that the spray streamed perpendicular to the laser beam, with the nozzle orifice placed at 0.50 m from the beam. Before each trial, the reliability and repeatability of the laser diffraction system was tested with the British Crop Protection Council (BCPC) reference nozzle[34] (flat fan 11 003) at 0.30 MPa. Emitters always were

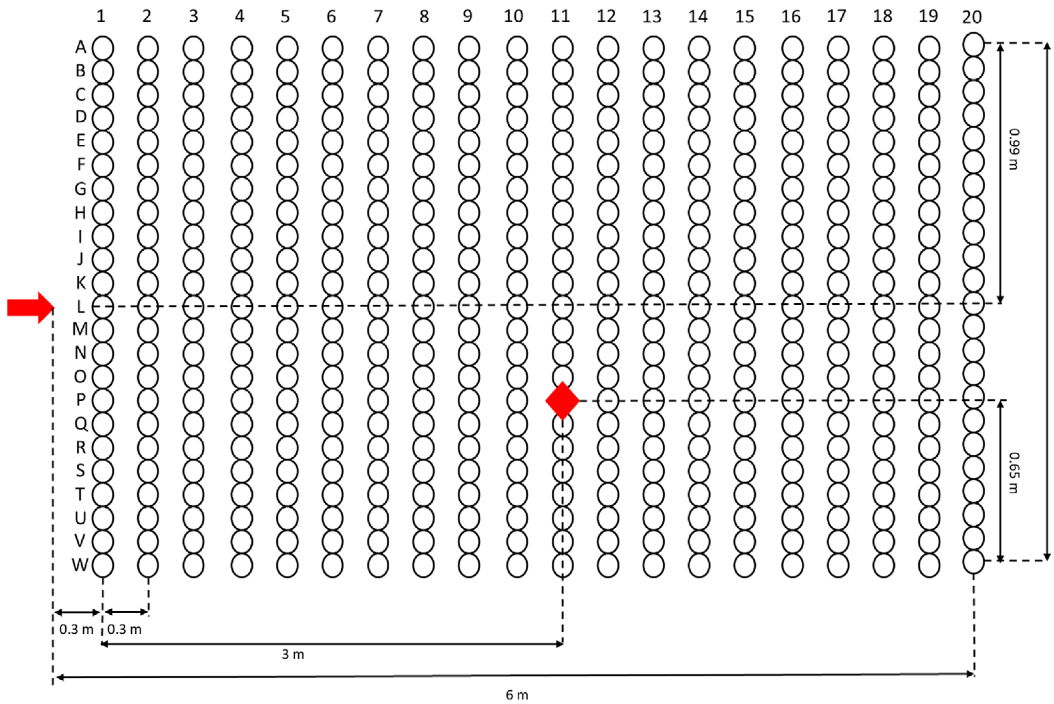

Figure 3. Spray pattern design used for emitter horizontal spray pattern investigation using plastic Petri dishes covering a total ground area of 11.88 m^2. Red arrow indicates the location and the spray jet direction considered for the sampling of both single- and double-sided emitter systems. Red diamond indicates circular emitter system location.

connected to the portable pumping station set at 0.30 MPa pressure (see section 2.2.1). Three replicates per emitter system type resulting in a total of 45 measurements. The measurements were carried out at 1 kHz and ≥10 000 droplets were recorded per each trial. Room temperature and relative humidity (RH, %) conditions were monitored with a thermo-hygrometer (model Testo 625;Testo S.p.a., Settimo Milanese, MI, Italy) and found to average 20 (±2) °C and range in RH from 60% to 80%.

For each emitter system, the Malvern Spraytec™ system determines that the specific droplet diameter of 10 ($D_{V0.1}$), 50 ($D_{V0.5}$), and 90% ($D_{V0.9}$) of the total spray volume is of a specific droplet diameter.[6] Relative span (*RS*) measures the spread/homogeneity of the droplet size distribution within the sprayed volume, calculated according to Eqn (1)[35,36]

$$RS = \frac{(D_{v0.9} - D_{v0.1})}{D_{v0.5}} \quad (1)$$

where *RS* is dimensionless, and $D_{V0.9}$, $D_{V0.1}$ and $D_{V0.5}$ are expressed in μm.

The lower the *RS* value, the more homogeneous is the droplet size distribution.

The value V_{100} is used to express spray driftability. It represents the amount of total spray volume with droplets <100 μm in diameter, expressed in %.[35,37,38]

The coefficient of variation ($CV_{DV0.5}$, %) for the volume median diameter (*VMD*) of each system type was calculated; it was found to be acceptable at values <10%.[35] The cumulative sprayed volume curves for each emitter system type were compared with nozzle standard classifications from the American Society of Agricultural and Biological Engineers (ASABE).[39]

Field trials: experimental design

Preparing for field trials

The number of emitter systems for field testing was honed following the laboratory trials. We selected one system per nozzle type based on its ability to perform close to the prescribed 0.20 L min^{-1} flow rate at 0.3 Mpa. The horizontal spray applications delivered by the narrow and long-range spray jets of flat fan emitter systems were tested from vertical positions 0.50 m above the canopy top in the middle of the row width [Fig. 4(a)]. We also tested the middle and low canopy spray coverage delivered from the side and parallel to the ground by the rounded spray jet of the circular system [Fig. 4(b)].

Experimental area, vineyard characteristics and environmental conditions

All field trials were performed at DiSAFA facilities in Grugliasco, Turin, Italy (45° 3′ 54.6′ N, 7° 35′ 28.9′ E) in a Guyot-trained trellised vineyard (*Vitis vinifera* cv. Barbera). As has been done for other 3D crops,[4,40] the inclined point quadrant technique (PQT)[41] was used to characterize the vine canopies pre-trial. The PQT measurements were taken in the vegetative strip at points between 0.40 and 2.20 m aboveground. The vineyard had an average height of 2.08 m and a canopy width of 0.52 m; the average height of the vegetative strip was 1.54 m. The following averages characterize the vegetation: 1.95 leaf layers, 13.54% gaps, 1.20 leaf area index (LAI) and 3.75 leaf area density (LAD), calculated[42] at the BBCH 89 'Berries ripe for harvest' growth[43] stage.

Throughout the trials, a weather station located 5 m from the sampled rows monitored conditions. The station included a sonic anemometer 232 (Campbell Scientific, Logan, UT, USA) to measure wind speed (m s^{-1}) and direction, and two thermo-hygrometer HC2S3 probes (Campbell Scientific) placed at two different heights and spaced 1 m apart to measure air temperature (°C) and humidity (%). All measurements were made at 1 Hz and the data logger CR800 (Campbell Scientific) auto-recorded the readings. The mean air temperature ranged between 10.1 and 19.9°C and the mean RH ranged between 35.0% and 78.1%. All trials were conducted in 'light air' conditions[44]; thus, the wind speed averaged <1.5 m s^{-1}, which is an optimal parameter value for spray application, as defined by TOPPS BMPs.[45] Detailed weather data recorded during field trials are shown in Table 1.

Experimental layout and spraying parameters

A 6-m length of row was employed to evaluate spray coverage performance and ground losses for longer row lengths. For single- and double-sided flat fan emitter systems [Fig. 5(a)] we selected four sampling locations (at 0.75, 2.25, 3.75 and 5.25 m from the spray source) along the row. For the circular emitter system, we selected three different sampling distances: at 2.25 m from the spray source and in line with the emitter system, at 0.75 m (−1.50 m from the emitter system), and at 3.75 m (+1.50 m from the emitter system) [Fig. 5(b)]. Spray delivery time, for single- and double-sided flat fan emitter systems, was defined to keep the total delivered spray volume consistent to 0.2 L. It took 1 min to provide the test quantity of pure water using the single-sided emitter system; 2 min were needed to deliver an equal amount using the double-sided emitter system. Based on the experience conducted in preliminary trials, to avoid over-spraying, the circular emitter system was activated for 30 s to apply 0.1 L pure water.

Side spray to a row from a circular emitter system can affect spray coverage and ground losses according to its positioning aboveground and depth in the canopy. Therefore, the circular

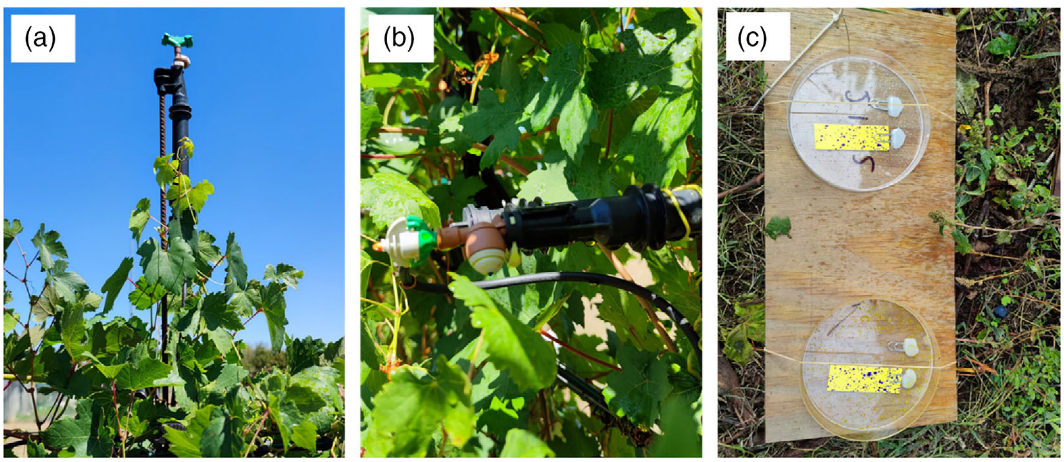

Figure 4. Examples of in-field collocations: (a) double-sided flat fan, (b) circular emitter systems and (c) water-sensitive paper (WSP) used for ground loss (*GL*, %) investigation.

Table 1. Weather conditions recorded during field trials for single- and double-sided flat fan and circular emitters. The circular emitter was tested at two emitter aboveground heights (1.10 m, 1.50 m) and two emitter row midpoint distances (0.18 m, 0.36 m)

Emitter configuration		Temperature [°C]		RH [%]		Wind speed [m s^{-1}]			Wind direction [azimuth]	
		Mean	Δ h_1–h_2	Mean	Δ h_1–h_2	Min	Max	Mean	Dominant	Mean [°]
Single-sided flat fan emitter	**R1**	16.11	0.23	46.27	−0.31	0.38	2.03	1.22	NE	142
	R2	16.29	0.22	46.94	−0.57	0.56	2.09	1.34	ESE	95
	R3	15.98	0.01	49.05	0.22	0.57	2.47	1.38	NW	237
Double-sided flat fan emitter	**R1**	19.75	0.16	35.98	−0.31	0.45	1.97	1.32	SW	343
	R2	18.71	0.01	38.35	0.03	0.27	2.32	1.45	NE	156
	R3	17.97	−0.05	36.15	0.21	0.54	2.66	1.23	NE	159
Circular emitter 1.10 m – 0.18 m	**R1**	13.20	0.27	57.69	−0.55	0.20	2.30	1.41	NE	148
	R2	14.09	0.26	55.01	−0.63	0.01	2.71	1.05	ESE	92
	R3	14.51	0.37	52.12	−0.67	0.68	1.90	1.41	NNE	190
Circular emitter 1.10 m – 0.36 m	**R1**	10.96	0.17	73.32	−0.12	0.36	1.72	0.99	ESE	125
	R2	12.05	0.21	67.38	−0.36	0.28	1.97	1.07	NE	159
	R3	12.62	0.24	64.77	−0.41	0.03	2.05	0.78	N	185
Circular emitter 1.50 m – 0.18 m	**R1**	16.06	0.15	47.36	−0.55	0.13	2.07	1.11	ESE	85
	R2	16.65	0.14	47.72	−0.34	0.12	2.25	0.95	NW	223
	R3	16.58	0.12	47.28	−0.12	0.12	2.17	0.12	NE	157
Circular emitter 1.50 m – 0.36 m	**R1**	15.96	0.01	49.17	0.28	0.57	2.47	1.40	NW	237
	R2	15.72	0.02	51.30	0.06	0.27	2.35	1.26	NNW	220
	R3	10.19	0.17	77.73	−0.13	0.12	2.02	1.20	ENE	135

emitter system was tested at two aboveground heights and at two row midpoint distances—1.10 and 1.50 m, and 0.18 and 0.36 m, respectively [Fig. 5(b)] Both the laboratory and field trials utilized the same portable pumping station to feed the emitter systems (0.30 MPa pressure; section 2.2.1). Three test replicates per each emitter system were performed for 18 total measurements.

Spray coverage and ground losses

In order to measure the canopy spray coverage (*SC*, %) of a single emitter system relative to its row and canopy position (section 2.3.3), water-sensitive papers (WSPs) (76 mm × 26 mm; Syngenta Crop Protection AG, Basel, Switzerland) were placed at different canopy heights and depths at each sampling distance (section2.3.3). The WSPs were stapled to the adaxial (up) and abaxial (down) sides of vine leaves at nine sampling positions (canopy depths A, B, C; canopy heights low, middle, high aboveground).[4,5,46] Where and when possible, the WSPs were clipped to the same leaves throughout all trials and replicates; if not possible, then the nearest leaves were selected.

Ground losses (*GL*, %) generated by each emitter type also were evaluated using WSPs (76 mm × 26 mm; Syngenta Crop Protection AG). Petri dishes of 140-mm diameter (APTACA S.p.a., Canelli, Italy), modified with glued clips to hold one WSP each, were

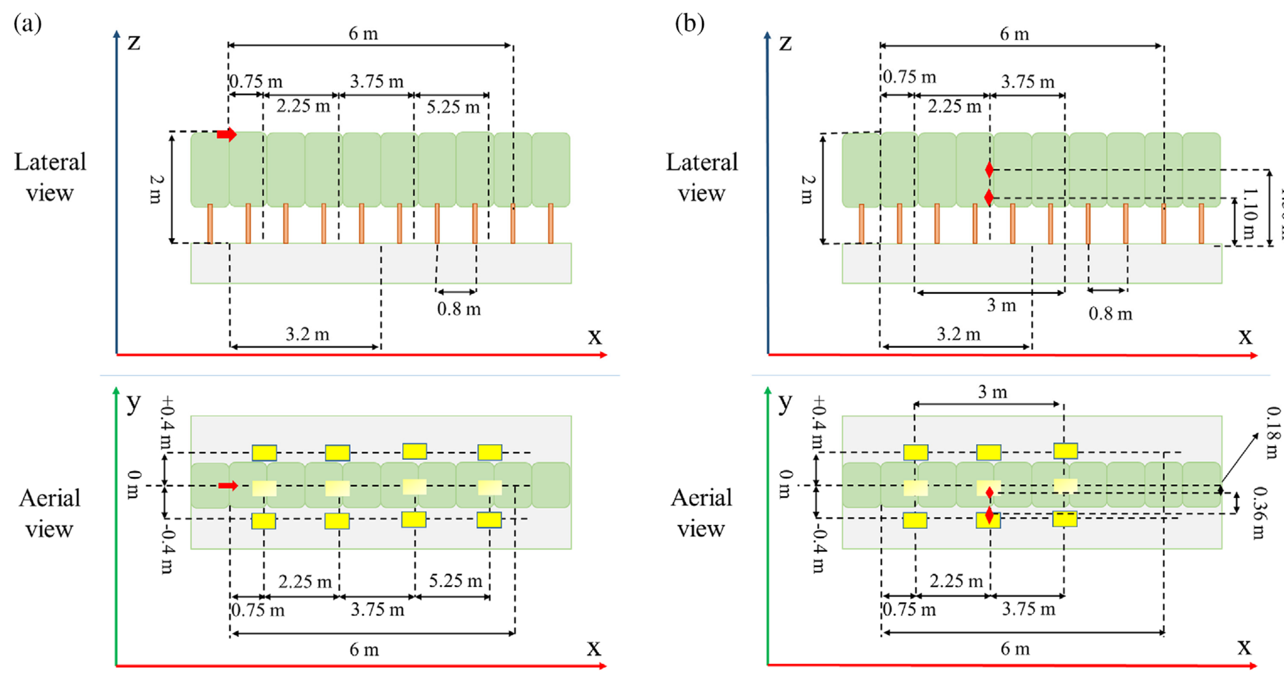

Figure 5. Schematic of emitters positions and sampling distances used for spray coverage evaluation (*SC*, %) for the (a) single- and double-sided flat fan (0.75 m, 2.25 m, 3.75, 5.25 m) and for the (b) circular emitter systems (0.75 m, 2.25 m, 3.75 m). The circular system was tested at two different aboveground heights (1.10 m, 1.50 m) and at two different row midpoint distances (0.18 m, 0.36 m). Red arrows indicate the location and the spray jet direction considered for the sampling of both single- and double-sided emitter systems. Red diamonds indicate the location of the circular emitter system. For all systems tested, ground losses (*GL*, %) were evaluated at three ground sampling positions per each sampling distance from the row midpoint (– 0.40 m, 0 m, + 0.40 m). Yellow rectangles indicate the locations of the *GL* samplers.

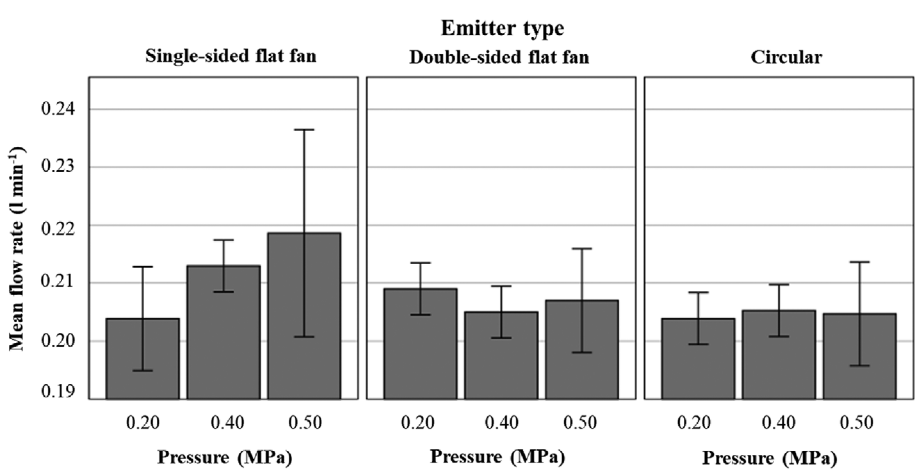

Figure 6. Mean flow rate (l min^{-1}) measured three liquid pipeline pressures (0.20, 0.40 and 0.50 MPa) for the five set-ups selected for each single- and double-sided flat fan and circular emitters. Bars show emitter mean flow rate ± SEM.

placed on the ground [Fig. 4(c)]. At each selected distance from the spray source, an array of two Petri dishes was placed at 0 m (row midpoint) and at −0.40 and +0.40 m distance from the row midpoint to sample the GL beneath the canopy.

WSPs sample processing

The WSPs were dried, collected and affixed to a rigid support. An HP Color Laser Jet Pro MPF M479dw printer with integrated scanner (HP, Palo Alto, CA, USA) scanned the WSPs and obtained 600-dpi resolution images. Image processing software (ImageJ, v1.52n; Wayne Rasband, National Institutes of Health, Bethesda, MD, USA) converted the image to greyscale and used the intensity value of each pixel to determine the areas of the stains generated by the liquid droplets reacting with the WSP surface coating.[47-49] Spray coverage and *GL* (%) were calculated as the ratio between the spray deposit area (stained area) and total area analyzed on the WSP[50] (WSP total area analyzed ranged between 82% and 97%).

Statistical analysis

Statistical analyses were performed using IBM Spss Statistic (v28) predictive analytical software for Windows™. Data were tested for normality using Shapiro–Wilk test and by visual assessment of the Q-Q plots of *Z*-scores for both *SC* and *GL* (%). Residual analyses also were performed. An Arcsin transformation was used to achieve residual normality and homoscedasticity of data, expressed as a percentage. Data derived from single- and double-side flat fan emitters and circular emitters were analyzed separately. Data were analyzed separately also for *SC* and *GL* (%) dependent variables.

For the single- and double-sided flat fan emitters, a three-way ANOVA was used to test the effects of the independent variables: distance from the spray source (0.75, 2.25, 3.75, 5.25 m), emitter type (single-, double-sided flat fan) and sampling height aboveground (low, middle, high) on the dependent variable *SC*. A two-way ANOVA was used to test the effects of the emitter types used (single-, double-sided flat fan) and the distance from the spray source (0.75, 2.25, 3.75, 5.25 m) on the dependent variable *GL*. For the circular emitter, a four-way ANOVA was used to test the effects of the independent variables: emitter row midpoint distances (0.18, 0.36 m), emitter aboveground heights (1.10, 1.50 m), canopy depth level (A, B, C) and sampling height above the ground (low, middle, high) on the dependent variable *SC*. Effects of emitter row midpoint distances (0.18, 0.36 m) and emitter aboveground heights (1.10, 1.50 m) on the dependent variable *GL* were evaluated through a two-way ANOVA. In all cases, the means were compared using a Duncan *post hoc* test for multiple comparison ($p < 0.05$).

RESULTS AND DISCUSSION

Laboratory trials

Flow rate measurements

The ability of the various systems to deliver the prescribed flow rate of 0.20 L min^{-1} at 0.30 MPa suggests that the emitter types

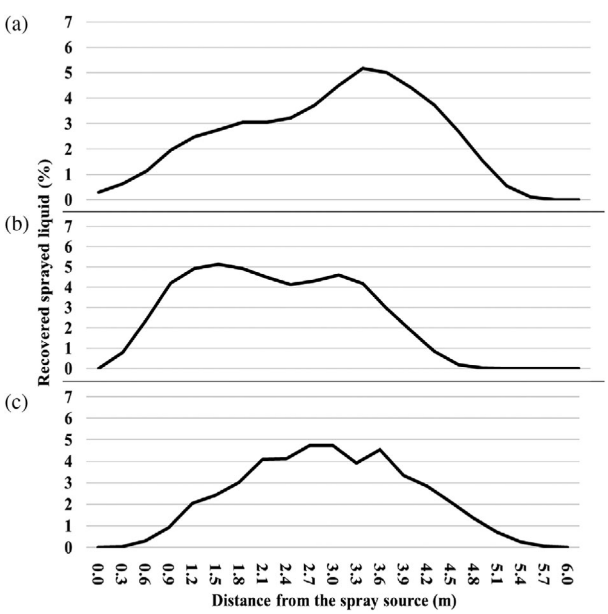

Figure 7. Lateral view of horizontal spray pattern profiles described by the amount of spray liquid (%) recovered at different distances (m) from the spray source for (a) single-sided flat fan (spray source at 0 m), (b) double-sided flat fan (spray source at 0 m) and (c) circular emitter systems (spray source at 3 m).

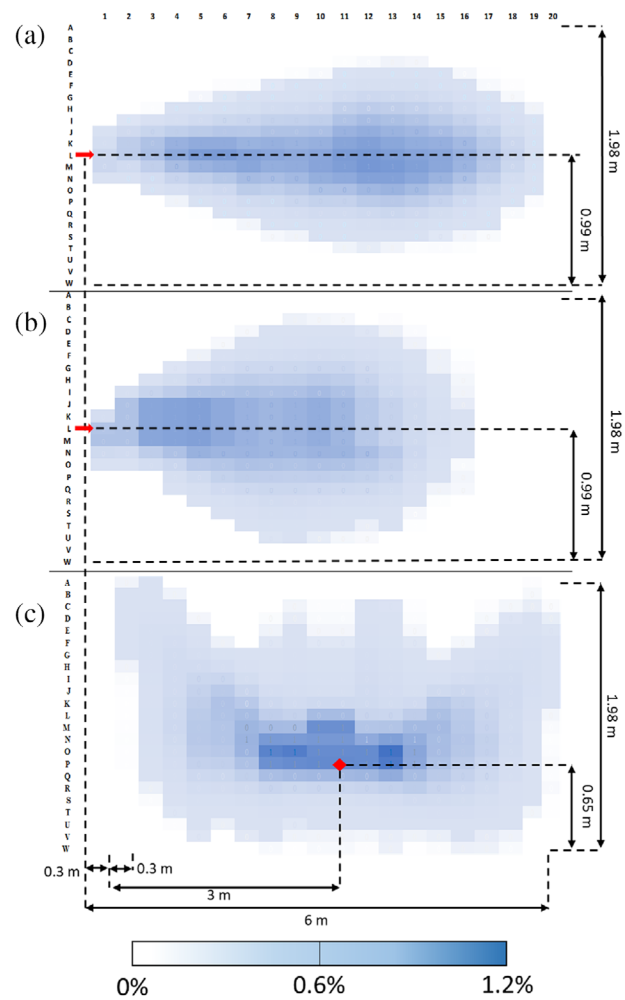

Figure 8. Aerial view of horizontal spray pattern profiles described by the amount of spray liquid (%) recovered at different sampling points (m) from the spray source for (a) single-sided flat fan emitter, (b) double-sided flat fan emitter and (c) circular emitter. Red arrows indicate the location and the spray jet direction considered for the sampling of both single- and double-sided emitter systems. Red diamond indicates the location of the circular emitter during the experiment. The amount of recovered liquid (%) increases as the colour changes from white (0%) to dark blue (1.2%).

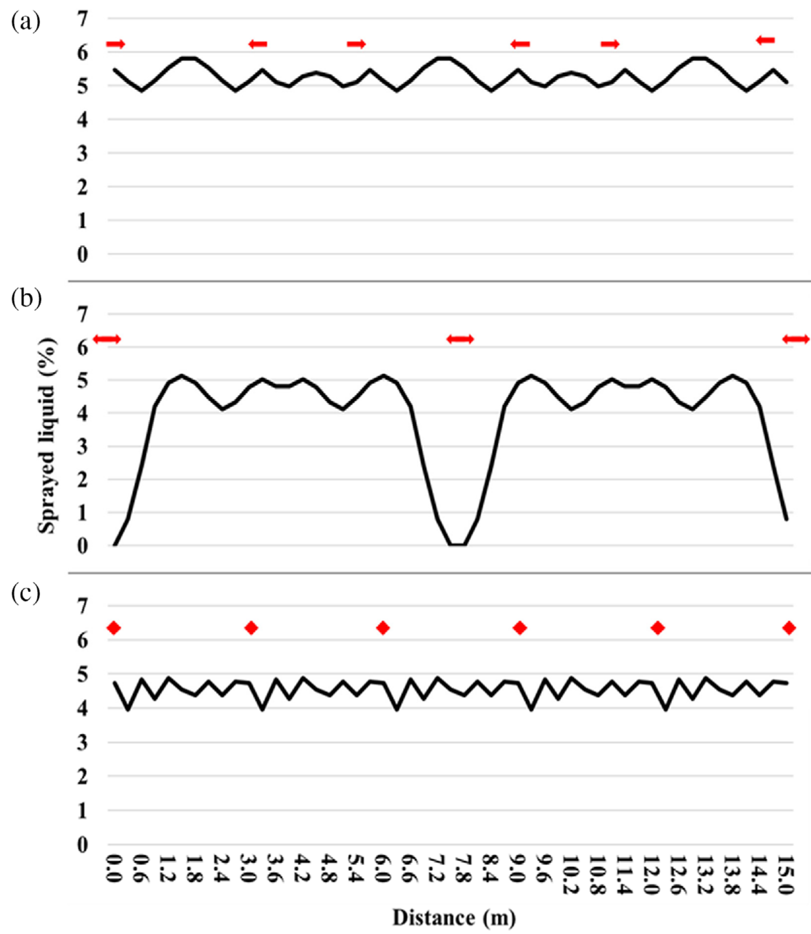

Figure 9. Spray distribution achieved with the horizontal spray pattern of single emitter systems (per each type). The graphs were built from variation in the spacing of emitters to the target area: (a) single-sided flat fan, (b) double-sided flat fan and (c) circular emitters. Red single arrows indicate the locations and directions of single-sided flat fan emitters. Red double arrows indicate the locations and directions of double-sided flat fan emitters. Red diamonds indicate the locations of circular emitter systems.

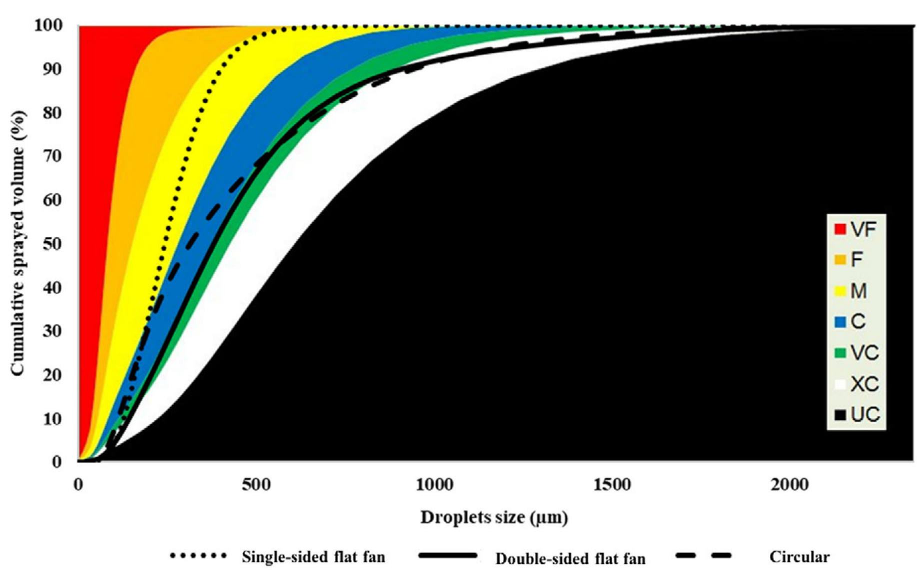

Figure 10. Cumulativee sprayed volume (%) curves as a function of droplet size (μm) per each emitter system type. VF, very fine; F, fine; M, medium; C, coarse; VC, very coarse; XC, extremely coarse; UC, ultra-coarse/unclassified (ASABE S572.1).

represent suitable options for large-scale SSCDS installation. Furthermore, flow rate mean values for all emitter systems varied to a similar low degree: 0.21 ± 0.03 (single-sided), 0.20 ± 0.03 (double-sided), and 0.21 ± 0.03 L min^{-1} (circular). The maximum standard deviation observed across all measurements was 0.04 for the single-sided emitter system at 0.50 Mpa. The flow rates for all emitter types also increased as pressures rose from 0.20 to 0.40 to 0.50 MPa (Fig. 6). The single-sided emitter system tested at 0.50 MPa produced the highest flow rate variation (0.219 ± 0.04 L min^{-1}), whereas the circular system varied the least when tested at 0.20 MPa (0.204 ± 0.01 L min^{-1}). These results indicate that overapplication can occur when the emitter system feeder hose exceeds a pressure of 0.40 MPa. Analysis confirmed that no statistical differences were found among the emitter systems tested at various pressures: single-sided flat fan [$F_{2,12} = 0.394$; $p = 0.683$], double-sided flat fan [$F_{2,12} = 0.100$; $p = 0.906$] and circular [$F_{2,12} = 0.012$; $p = 0.988$]. It is worth noting that pressures of 0.20 and 0.50 MPa represent testing values outside the manufacturer's recommended range of 0.25–0.40 MPa.

Horizontal spray pattern

Spray jet characteristics (range and shape, potential for *SC* and *GL*) are key for determining the best layout to minimize spray overlap and produce a homogeneous spray distribution. Based on laboratory measurements of 2D horizontal spray patterns (Fig. 8) and considering the 0.52 m row width (section 2.3.2), the single- and double-sided emitter systems can potentially deposit 90.70% and 85.70% of applied volume, respectively. By doing so, the canopy acted as an interceptor of the spray liquid resulting in potentially *GL* equal to 9.30% and 14.30% for single- and double-sided emitter systems, respectively. The flat fan emitter systems

Table 2. Results of two-way ANOVA ($p < 0.05$) for ground losses (*GL*, %) of single- and double-sided flat fan emitters. ANOVA is based on Arcsin-transformed data

Sources	DF	$p > (F)$	Significance[a]
	Average values (*GL*, %)		
Main effect			
Emitter (A)	1	1.65E-03	**
Sampling distance (B)	3	1.52E-07	***
Interactions			
A × B	3	0.8E-03	**

[a] Statistical significance codes: NS $p > 0.05$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

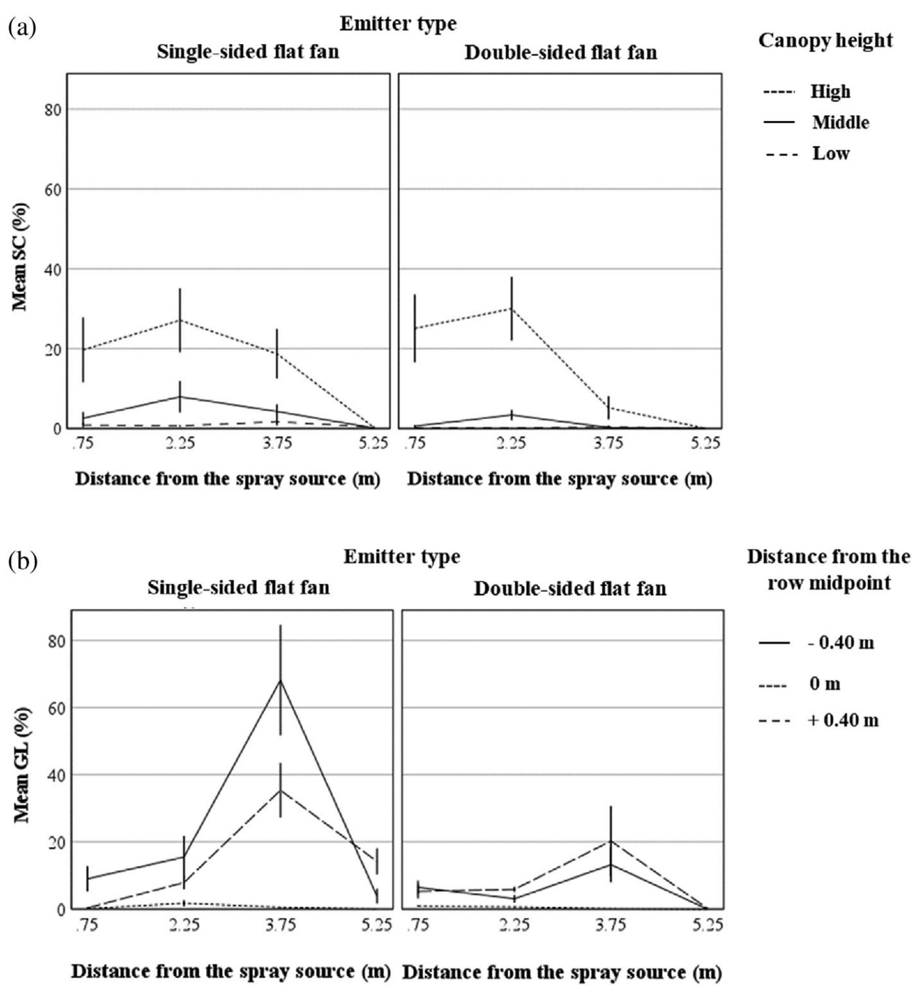

Figure 11. Single- and double-sided flat fan emitter field test results. The following measures were taken for each sampling distance from the spray. (a) mean spray coverage (*SC*, %) evaluated at three canopy heights (low, middle, high) above the ground and (b) mean ground losses (*GL*, %) evaluated at three ground sampling distances from the row midpoint (−0.40 m, 0 m, +0.40 m).

produced long-range jets (4.50 m for single-sided and 3.60 m for double-sided) [Fig. 7(a), (b)] of low amplitude (1.08 for single-sided and 1.26 m for double-sided) as viewed from above [Fig. 8 (a), (b)]. The circular emitter system placed deep within the canopy demonstrated how it could improve spray coverage. It produced an irregular shape with a maximum length of 1.35 m and width (potential canopy penetration) of 0.72 m from the spray source [Fig. 7(c), 8(c)].

Graphical representations show the peaks and troughs of spray liquid recovered at different distances for each emitter system type. A single peak is noted for the single-sided system at 3.30 m [Fig. 7(a)], whereas two peaks are noticed at 1.50 and 3.00 m from the spray source for the double-sided system [Fig. 7 (b)]. The *CV* value between the two peaks of the double-sided flat fan system (*CV* = 7.41%) showed that it was a better choice for a more homogenous spray distribution as opposed to the single-sided system (*CV* = 11.68%). Uniform spray jet distribution can increase the spacing needed between emitters in the field to minimize the number of emitters installed along the row.

Several different set-ups to spray the top, middle and low canopy homogeneously were tested to ascertain their theoretical optimal layouts.[31,51] The optimal density for single-sided emitter systems was found to be 40 emitter systems per 100 m length. The double-side flat fan emitters alone failed to meet the optimal criteria due to an inability to spray the area under its installation position [Fig. 9(b)], yet when they were combined with a circular emitter, they raised the level of coverage in undersprayed zones. Consequently, a combination layout of 20 double-sided flat fan and 20 circular emitter systems per 100 m achieved homogeneous coverage. For circular emitter systems, the optimal density resulted as 40 emitters per 100 m.

Spray direction also is important for coverage. Single-sided emitter systems are laid out to spray in two opposing directions. If spraying in the same direction, emitters must be spaced 5.7 m apart along the row; if spraying in different directions, emitters must be spaced 3.3 m apart [Fig. 9(a)]. The lowest variation within the target area represents the highest spray homogeneity. In the case of single-sided emitter systems, *CV* = 5.4% and total average spray volume = 5.0%. A double-sided flat fan combined with a circular emitter system placed every 7.5 m along the row achieved a *CV* = 7.3% and a total average spray volume = 4.7%. Circular emitters placed 3 m apart along the row [Fig. 9(c)] resulted in a *CV* = 6.3% and total average spray volume = 4.6%.

Table 3. Results of four-way ANOVA ($p < 0.05$) for spray coverage (*SC*, %) of circular emitter. ANOVA is based on Arcsin-transformed data

Sources	DF	$p > (F)$	Significance[a]
		Average values (*SC*, %)	
Main effect			
Emitter row midpoint distance (A)	1	0.478	NS
Emitter aboveground distance (B)	1	0.273	NS
Canopy depth level (C)	2	2.55E-09	***
Canopy height level (D)	2	1.76E-04	***
Interactions			
A× B	1	0.407	NS
A× C	2	0.065	NS
A× D	2	0.471	NS
B× C	2	0.011	*
B× D	2	0.468	NS
C × D	4	0.030	*
A× B × C	2	0.803	NS
A× B× D	2	0.089	NS
B× C × D	4	0.750	NS
A× C × D	4	0.836	NS
A× B × C × D	4	0.354	NS

[a] Statistical significance codes: NS $p > 0.05$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Droplet size spectrum

Droplet spectra parameters measured for double-sided and circular emitter systems aligned with those of air inclusion nozzles tested under field[9] and laboratory[6] conditions. In fact, they proved capable of significantly reducing spray drift and could be used as spray drift reducing technologies (SDRT).[6,35] The cumulative curves obtained (Fig. 10) moved between the 'coarse' and 'extra coarse' spray quality thresholds according to the ASABE classification.[39] However, the single-sided flat fan emitter cumulative curve was classified as in the 'medium' spray quality threshold.

The single-sided emitter system generated the finest droplet size spectrum compared to the others. It was characterized as having a $VMD = 266.3 \pm 40.6$ µm, $D_{V0.1} = 138.1 \pm 7.3$ µm and $D_{V0.9} = 416.8 \pm 52.5$ µm, whereas the double-sided flat fan emitter system had a $VMD = 453.1 \pm 37.9$ µm, $D_{V0.1} = 193.8 \pm 20.8$ µm and $D_{V0.9} = 879.8 \pm 42.5$ µm. The circular emitter system produced a $VMD = 338.1 \pm 6.8$ µm, $D_{V0.1} = 121.7 \pm 2.2$ µm and $D_{V0.9} = 1005.6 \pm 8.5$ µm. No significant differences were found for the mean V_{100} values of 4.5 ± 0.5 (single-sided flat fan), 4.6 ± 0.2 (double-sided flat fan) and 7.8 ± 0.3% (circular) emitter systems. However, a large difference was noticed in *VMD* variability among the systems in droplet size distribution. Indeed, even when the single-sided flat fan system had a *RS* factor equal to 1.1 ± 0.1, its *VMD* variance ($CV_{DV0.5}$ = 15.3%) exceeded the 10% acceptance threshold defined by Ferguson and co-authors.[35] However, double-sided flat fan and circular emitter systems reported *RS* values equal to 1.5 ± 0.1 and 2.6 ± 0.1 and $CV_{DV0.5}$ values equal to 8.4 and 4.8%, respectively.

Field trials

Spray coverage and ground losses: single- and double-side flat fan emitters

Field trial analysis indicated that a double-sided flat fan emitter system is preferable to a single-sided system for reducing *GL* and achieving adequate target *SC*. Three-way ANOVA indicated

Table 4. Results of two-way ANOVA ($p < 0.05$) for the ground losses (*GL*, %) of circular emitter. ANOVA is based on Arcsin-transformed data

Sources	DF	$p > (F)$	Significance[a]
		Average values (*GL*, %)	
Main effect			
Emitter row midpoint distance (A)	1	2.61E-06	***
Emitter aboveground height (B)	1	0.68	NS
Interactions			
A× B	1	0.98	NS

[a] Statistical significance codes: NS $p > 0.05$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

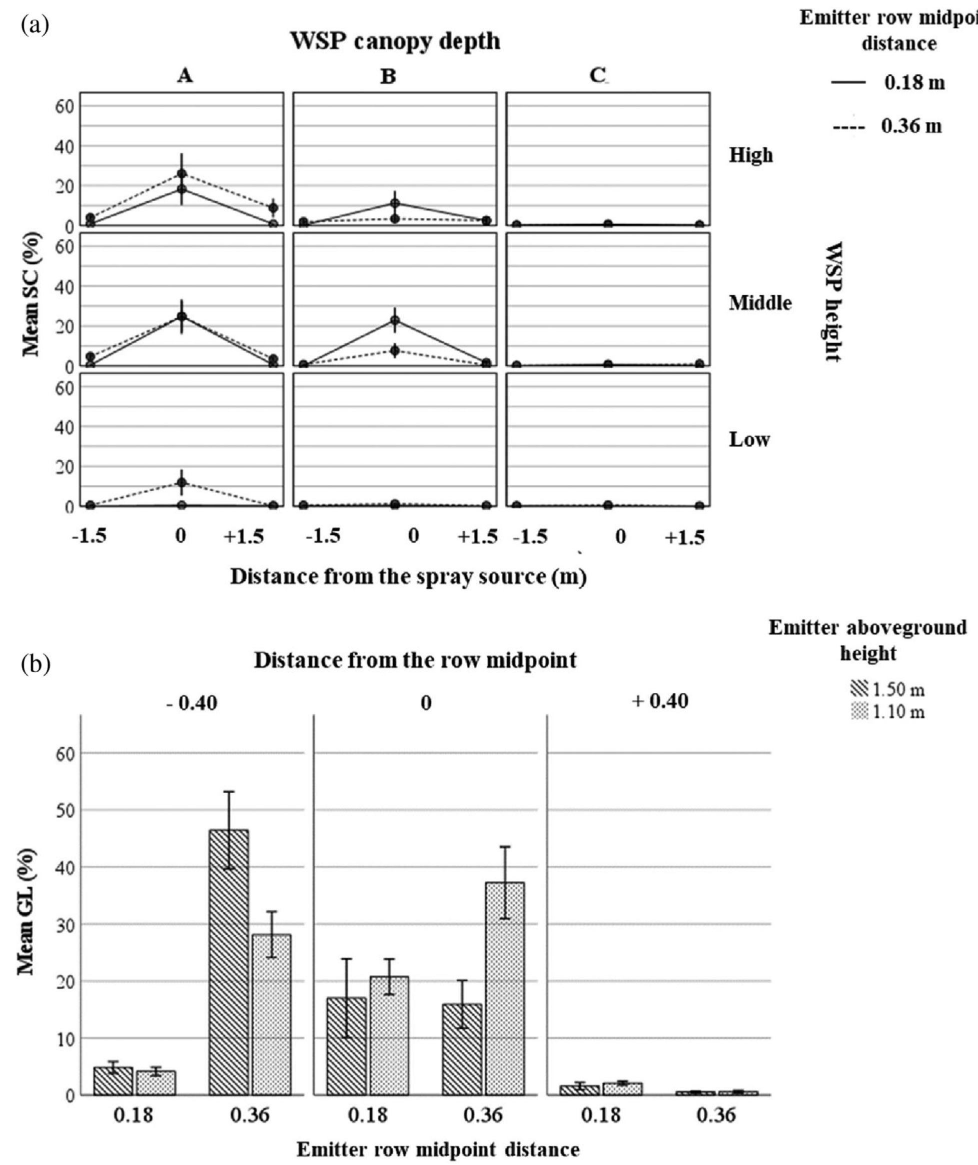

Figure 12. Circular emitter field test results. The following measures were taken for each sampling distance from the spray. (a) mean spray coverage (*SC*, %) evaluated at three canopy heights (low, middle, high) aboveground and three canopy depths (A, canopy test side; B, internal canopy; C, external canopy) and (b) mean ground losses (*GL*, %) evaluated at three sampling distances from the row midpoint (− 0.40 m, 0 m, + 0.40 m) for both emitter aboveground heights (1.10, 1.50 m) and emitter row midpoint distances tested (0.18, 0.36 m).

significant differences resulted from sampling distance [$F_{3,408} = 1.072$; $p = 2.09$ E-06] and canopy height [$F_{2,408} = 39.430$; $p = 2.21$ E-16], irrespective of leaf side. In addition, a significant interaction was observed between these two variables [$F_{6,408} = 6.473$; $p = 1.55$ E-06]. As discussed previously, single- and double-sided flat fan emitters are designed to be installed above the canopy top in order to reach large distances from the spray source. This resulted in higher average *SC* values along the canopy top, but not in the middle and low sampling areas, which agrees with others who have evaluated emitters used only for canopy top zone coverage in apple orchards[52] and vineyards.[20,53]

No significant *SC* differences were found for the emitter types [$F_{1,408} = 1.072$; $p = 0.301$]. However, a graphed difference was noticed along the sampling distance [Fig. 11(a)] that can be attributed to emitter type-specific spray pattern and droplet spectrum characteristics. Droplets produced by single- and double-sided flat fan systems exhibited off-target spray loss susceptibility. Despite adequate *VMD* and V_{100} values, finer airborne droplets were prone to trajectory changes, which in a Guyot-trained canopy (reduced width) could lead to off-target phenomena and reduced *SC*. This concept was confirmed by the *GL* (%) investigation. As Table 2 shows, significant differences in *GL* were detected with the interaction of emitter type and sampling distance [$F_{3,136} = 4.049$; $p = 0.57$ E-03]. High *GL* values were obtained at 3.75 m from the spray source, both for single- and double-sided flat fan systems [Fig. 11 (b)]. However, the single-sided flat fan emitter system resulted in higher *GL*, nearly 50% more than for the double-sided. Furthermore, *GL* trended proportionally and inversely with *SC* (Fig. 11).

Spray coverage and ground losses: circular emitter

Spray coverage analysis determined that a SSCDS layout should consider installing one circular emitter per canopy side to guarantee homogeneous spray coverage of both canopy sides. Significant differences, irrespective of leaf side, exist for sampling height and canopy depth level (Table 3). Emitter row midpoint distance did not influence *SC* significantly, but differences occurred in *GL* (Table 4). *SC* in the canopy top zone was 42% less than *SC* in the middle and low canopy zones [Fig. 12(a)]. The significant difference in *SC* that results from canopy depth level suggests that a single emitter installed (and spraying) on a single canopy side would not sufficiently cover and homogeneously spray throughout the canopy depth. Therefore, more than one circular emitter spraying at different canopy sides is recommended. To reach a homogeneous spray coverage all over the canopy, including the canopy top, then a flat fan emitter system [Fig. 11(a)] needs to be added as previous studies have found in vineyard.[53]

As Fig. 12(b) shows, *GL* originates from off-target droplets that were not intercepted by the canopy. The further the emitter is from the row midpoint, the greater are the ground losses. An emitter system installed at 0.36 m from the row midpoint provided nearly twice the average *GL* (+96%) as compared to an emitter positioned at 0.18 m, which deemed it preferable for reducing overall *GL* during spray application.

Optimal layout identification

Results derived from field trials (per each emitter type) led to better potential canopy spray coverage evaluations even if it is known the practical limitation in using WSP only. Indeed, authors reported difficulties obtaining reliable canopy deposition data just from WSPs. Generally, WSP characterized by coverage greater than ≈20% showed a stain overlap and/or touching leading to possible misinterpretation of deposition quantification.[4,54,55] In accordance with the experimental work objectives, WSP can be considered adequate to provide accurate estimation of spray coverage even if they cannot be used to quantify spray deposits.

Results found double-sided flat fan emitters were preferable for canopy top spray coverage. Although the single- and double-sided flat fan reached the same *SC*, the double-sided emitter system achieved lower *GL* values. Moreover, a combination of double-sided flat fan and circular emitter (see section3.1.2) potentially is the most able to spray the entire vine canopy homogenously. As for the top zone, double-sided flat fan and circular emitters should be placed every 7.5 m along the row and at 0.5 m above the canopy. The resulting emitter density equals 13 double-sided flat fan emitters and 26 circular emitter (one per each canopy side and installed parallel to the ground) per 100 m row length or 520 (double-sided) and 1040 (circular) emitters per hectare in a typical 2.5 m inter-row vineyard layout.

Circular emitters installed parallel to the ground (1.5 m above-ground height) and at 0.18 m to row midpoint per each side of the canopy resulted in a better homogeneous *SC* and reduced *GL*. Despite laboratory data suggesting that circular emitters be placed every 3 m along the row, the field trials indicated that the vine canopy negatively influenced their spray coverage capabilities. Owing to the irregular canopy density along the row (number of leaf layers), a more homogeneous spray coverage and maximum canopy penetration on both canopy sides results from circular emitters spaced ≤1 m apart. Thus, the final circular emitter installation density would result in 200 emitters per 100 m row length (100 per each canopy side) or 8000 emitters per hectare in a typical vineyard layout.

CONCLUSION

A combination of laboratory and field trials allowed emitters to be characterized in this study. Laboratory trials confirmed that emitters and their components maintain flow rates close to 0.20 L min^{-1} and adjust the liquid pressure over a wide range as declared by the manufacturer. Horizontal spray pattern analysis showed that the theoretical optimal installation spacing along the row offers the best coverage when a double-sided flat fan is combined with a circular emitter. Laboratory trials also revealed that droplet size spectra differed among the emitters. In fact, the coarser spray produced by the circular and double-sided flat fan emitters increased their suitability to above that of their single-sided flat fan counterparts. Indeed, the similarity in droplet size of these emitters with air inclusion nozzles suggests that they have adoption potential as spray drift reducing technologies.

Field trials indicated that an ideal vineyard SSCDS should have emitters installed at multiple locations to spray both the canopy top and middle/low zones. The double-sided flat fan turned out to be the better emitter to deliver PPP to the canopy top zone by producing a higher potential spray coverage and lower ground losses *versus* the single-sided flat fan. Based on data obtained from the single horizontal spray pattern through laboratory trials, a combination of double-sided flat fan and circular emitters could result best for delivering a homogenous spray to the canopy top zones. In this sense, circular emitters can be used also at the top canopy level to cover the lacking zone in the horizontal spray pattern beneath the double-sided emitter bodies. Circular emitters may result suitable for spray application of the middle and low zones of the canopy. In addition, from evidence obtained from field trials circular emitters could provide an adequate spray coverage just on the row side where the spray jet is faced. Thus, based on preliminary information, having a circular emitter on each side of the canopy could be the strategy to produce a more homogeneous canopy spray coverage throughout the canopy. Studies on spray coverage and deposits in the canopy, to test the emitter networking at the field scale, are needed to confirm or not the potential of solution proposed (e.g. number on emitters, positions in the canopy, type of emitters). Furthermore, it must be underlined that dedicated studies on the progressive calibration of SSCDS according to the vines' phenological stage will be needed to reduce the fraction of off-target losses concurrently enhancing canopy deposition. Our future research will focus on exploring circular and double-sided flat fan emitter deposition capabilities in the field applying tracers for precise and reliable quantification. These data will support further development and eventual commercial adaptation of this system.

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CONFLICT OF INTEREST DECLARATION

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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