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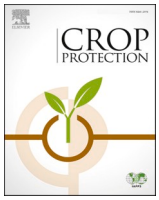

Hydraulic-based fixed spray delivery system: Homogeneity distribution among emitters and internal cleaning performances evaluation

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ABSTRACT

Fixed spray systems, an alternative to conventional pesticide application equipment, are under investigation in perennial fruit crops for improving spray applications. A prototype of a hydraulic fixed delivery spray system (31 m length) was evaluated for its suitability to be adopted as crop protection technology. In this research, two emitter densities selected from previous studies were used. Field trials were conducted to evaluate the performances of the system for spray mixture delivery, and to this extent, homogeneity distribution and cleaning performances were tested. Results showed that the emitter nearest to the injection point will deliver, the spray mixture first and water second, sooner than those further down the line. This delivery delay balanced the amount of spray mixture delivered by the fixed spray system along the line. Thus, the system delivered a similar amount (CV = 6.91%) of mixture from every sampled location in both emitter densities tested. Cleaning the line with water reduced the residue concentration by a factor greater than 300 in both emitter densities. In addition, the optimal time for cleaning that also reduced the water volume was identified as 2:30 and 4:30 min for high and low emitter densities, respectively. Linear regression models were built to estimate water volume consumption and cleaning step timing according to the fixed spray system's flow rate. In conclusion, emitter flow rate, emitter number, and spray mixture volume injected resulted the three key factors affecting dose applied, homogeneity of distribution among emitters, and cleaning performance.

1. Introduction

Pests and disease management in vineyards and orchards requires a large number of plant protection product (PPP) spray applications (Marucco et al., 2019; Pertot et al., 2017). Using PPPs protects crops to increase crop yield and quality (Popp et al., 2013). However, the intensive use of conventional chemical-based PPPs can cause adverse side effects on the environment and exposes operators and bystanders to PPPs (Butler Ellis et al., 2010; Damalas and Eleftherohorinos, 2011; Grella et al., 2020, 2023; Lopes Soares and Firpo de Souza Porto, 2009). Those concerns, associated with consumer demand for residue-free products, are stimulating/pushing farmers, manufacturers, and researchers to reduce chemical inputs for crop protection in agriculture by improving spray application operations (Grella et al., 2023). These improvements come mainly from three paths. One path is represented by using non-pathogenic microorganisms like biological control agents as alternatives PPP to chemical-based conventional ones (Grella et al., 2023a; Witkowicz et al., 2021), and/or field management recommendations like the use of cover crops to protect soil and groundwater pollution (Ortega et al., 2022). The second one is represented by the technological improvements in airblast sprayers. Mainly, researchers focused on developing airblast sprayers equipped with sensors and actuators able to adapt the spray application and airflow rates to canopy characteristics, like canopy shape/size and foliage density, thus applying variable rates of PPP (Bhalekar et al., 2023; Grella et al., 2022a, 2022b; Román et al., 2020; Wei et al., 2023; Xun et al., 2023). Variable rate sprayers are capable of reducing both the total PPP applied and off-target losses (Garcerá et al., 2017a, 2017b; Xun et al., 2023). The third path is represented by innovative spray application techniques alternative to airblast sprayers conventionally used in bush/tree crops. Examples include uncrewed aerial spray systems (UASS) (Biglia et al., 2022; Chen et al., 2020; Martinez-Guanter et al., 2020; Wang et al., 2022) and fixed spray delivery systems (Imperatore et al., 2021; Sahni et al., 2022; Sinha et al., 2019).

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Fixed spray delivery systems are composed of two main elements: i) the emitters, and ii) the pumping station. There are many designs to a fixed spray system (Sinha, 2018), but all have one to two main lines along the crop row with permanently positioned emitters either within or above the canopy The emitters deliver the PPP spray mixture to the target. The pumping station, which can be either mobile (like a conventional airblast sprayer) or stationary, usually is located outside the field and supplies the entire system with the spray mixture (Owen--Smith, 2017). Briefly, the pumping station ensures the spray mixture reaches all emitters regardless of their location. The benefits of this type of technology include i) application timeliness (e.g., possibility to operate exactly when needed independent of soil conditions like muddy soils), ii) time savings (e.g., the total time required for the spray application of the unit area, *i.e.* ha^{-1}, is lower than those required using airblast sprayers coupled to a tractor passing every row or either every two rows), iii) fuel efficiency (e.g., the use of a tractor is drastically reduced or avoided), iv) operator safety (e.g., in steep slope vineyards where the spray application are routinely carried out using tracked tractor this represent an effective more safe alternative) and, v) reduced environmental, operators and bystanders contamination (Ranjan et al., 2019; Sinha et al., 2020).

The two main categories of fixed spray systems are pneumatic spray delivery (PSD) and hydraulic spray delivery (HSD). In PSD, the spray mixture from the pumping station runs through the mainline to fill reservoirs and then the mainline is emptied with low pressure air. High pressure air is then used to inject the spray mixture through an emitter into the canopy (Sahni et al., 2022; Sinha et al., 2019). In HSD, spray mixture from the pumping station is moved, by hydraulic pressure, through the mainline to the emitters and delivered to the canopy (Agnello and Landers, 2006). PSD requires specific design and components, including a large air compressor and reservoirs systems (Sahni et al., 2022), while HSD may be able to utilize the existing irrigation systems in perennial crops as it can be adapted for pesticide spray application (Mozzanini et al., 2023). Peculiarly, in HSD systems the PPP spray mixture delivery and the cleaning of the system take place simultaneously: as pure water under pressure is used to push the mixture through the lines and towards the emitters for delivery, at the same time, the pure water flows through the hoses and emitters, performing the cleaning process (Dale Threadgill, 1985).

In a standard ground-based air assisted sprayer, the homogeneous distribution of spray in the canopy is influenced by proper adjustment of the sprayer to align with canopy shape (Grella et al., 2022c). Fixed spray system researcher has focused on determining the optimal position of various types of emitters across different canopy positions to maximize deposition and achieve homogeneous coverage (Mozzanini et al., 2023; Ranjan et al., 2021; Sharda et al., 2015). In fixed spray systems, droplets are delivered in absence of a large fan, thus their positioning in the canopy is fully relevant for a homogeneous canopy spray coverage. For HSD systems no research has investigated whether the same amount of PPP spray mixture is delivered by the emitters placed along the line(s) at increasing distances from the injection point. This is a crucial step in ensuring homogeneous spray application across the entire treated area, particularly in those systems where the PPP spray mixture travels long distances to reach emitters located far from the pumping station. So far, many challenges remain in managing operational phases, determining the appropriate spray mixture injection rate, and cleaning time for HSD systems to ensure effective and efficient spray application and to prevent over- or under-dosing. Finding the right balance between the spray mixture rate and the amount of pure water used to move the mixture through the spray lines is crucial, and further research is needed to establish the reliability of a modified irrigation systems to be used as HSD systems for PPP spray applications. A proper balance between the amount of PPP spray mixture and pure water to be flown into the spraying lines is essential to i) ensure an homogeneous distribution among emitters located at different distances from the pumping station, ii) avoid dilution of the spray mixture to an ineffective concentration due to excessive water use, and iii) clean the entire fixed spray system at the end of spraying. The latter point is important to prevent potential phytotoxicity in successive spray applications on different crops using the same pesticide application equipment, and to ensure environmental and operator safety (Grella et al., 2022).

Our research, conducted on an experimental HSD system, has three objectives: i) to gather information about the spray mixture concentration during spraying and along the lines; ii) verify if the system delivers a homogeneous spray mixture along the lines, and iii) evaluate the cleaning performances of the system.

2. Materials and methods

2.1. Fixed HSD system features

The fixed HSD system used for experimental purposes was composed of a pumping station, a water supply system (*i.e.*, tap water), and a spray delivery system (Fig. 1).

In particular, the pumping station was a trailed ECO3 PPP mixer (Polmac S.r.l., Mirandola, MO, Italy) powered by a 3.6 kW gasoline engine (Model: GX 160, Honda Motor Co., Ltd., Minato, Tokyo, Japan). It was equipped with a centrifugal pump (Model: SE2BRL, Pacer Pumps, Lancaster, PA 17601, USA) and a 280 l tank. A flowmeter (Model: Proflow magnetic, Polmac S.r.l., Italy) was installed at the pumping station outlet to measure the precise rate of spray mixture going into the mainline. The spray delivery system was directly connected to the public conduit tap water with a double check valve in between (Model: 5042019, cracking pressure: 0.002 MPa, Arag S.r.l., Rubiera, RE, Italy) to prevent backflow. The tap water, supplied at 0.30 MPa pressure, was used to i) pressurize the spray delivery system before spray mixture injection, ii) to push the spray mixture along the spray delivery system, and iii) to clean hoses and emitters after spraying. The spray delivery system consisted of a 31 m top and bottom main lines fitted with a different number of emitters and operated separately one from the other. Both lines (φ: 16 mm, Model: IDRO PEBD PN6, Idrotherm, 2000; Castelnuovo Garfagnana, LU, Italy) were mounted on the existing vineyard wires with plastic line holders at 1.90 m (top) and 0.70 m (bottom) above the ground. In the top line three emitters with 4.2 l min^{-1} total flow rate at 0.30 MPa (21 total emitter with 0.20 l min^{-1} flow rate each) were installed every 4.50 m of row length, resulting in an installation density equal to 2,710 emitter ha^{-1} (hereafter referred to as low emitter density). In the bottom line, two emitters with 15.6 l min^{-1} total flow rate at 0.30 MPa (78 total emitter with 0.20 l min^{-1} flow rate each) were installed every 0.80 m of row length, resulting in an installation density equal to 10,064 emitters ha^{-1} (hereafter referred to as high emitter density). The number of emitters selected for the experiments, namely 21 and 78, was based on the results achieved by Mozzanini et al. (2023) and represent the extremes for the installation of an effective layout. The emitters were connected to the main lines using a PeBd Soft micro-tube (φ: 0.80 mm, Netafim Ltd., Israel). The pressure compensating emitter models installed on the two lines were different (*i.e.*, VibroNet and StripNet; Netafim Ltd., Tel Aviv, Israel) but each one provided the same nominal flow rate (0.20 l min^{-1} guaranteed at 0.25–0.40 MPa working range). Both emitters deliver spray with an on-off pulse mode between 36 and 39 pulses per minute. Detailed information about emitters and different nozzle characteristics installed on the two lines are reported in Mozzanini et al. (2023). The two spray lines were connected to the pumping station and to the public conduit tap water through a three-way single union ball valve (Model: 45521116N, Arag S.r.l., Italy). This valve allowed for a quick and easy manual switch between the liquid circuits of three devices composing the HSD system. Therefore, tap water was excluded during the injection of the spray mixture and re-activated once the injection of the spray mixture was complete. Furthermore, the fixed HSD system was equipped with filters per each main component (*i.e.*, pumping station, tap water, and spray delivery system), to prevent clogging due to possible debris.

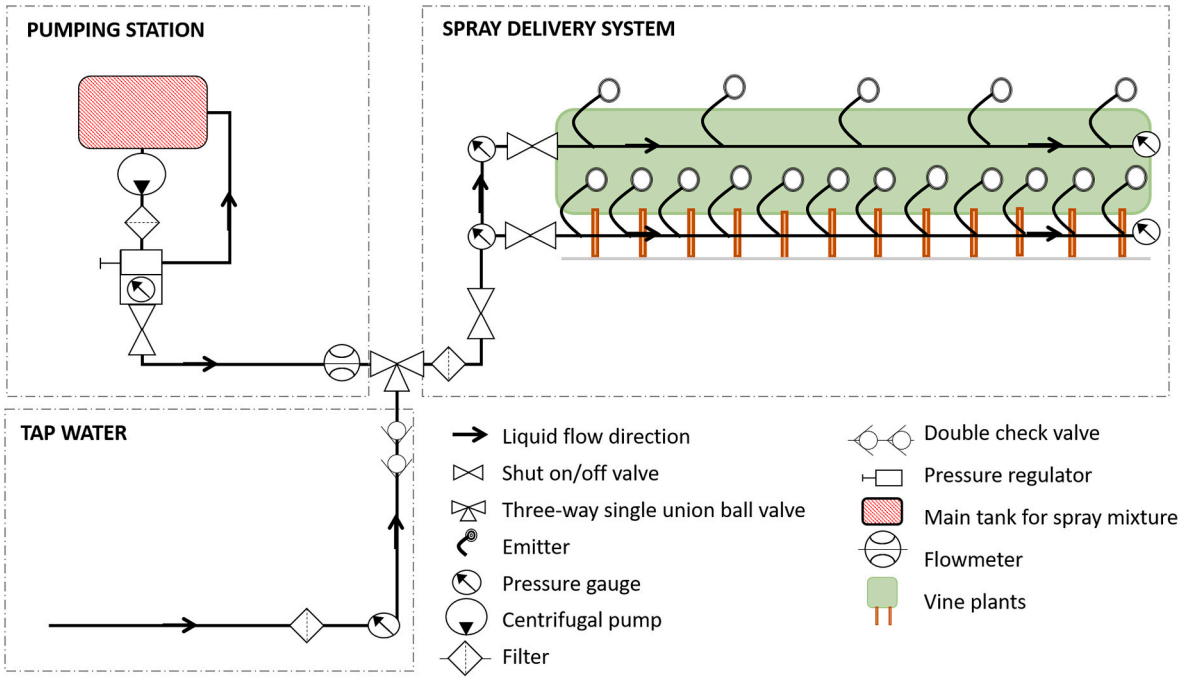

Fig. 1. Schematic of the fixed HSD system circuits as composed of three main devices *i.e.*, pumping station, tap water, and spray delivery system.

The operation of the fixed HSD system occurs in three steps: i) priming, ii) spray mixture injection, and iii) spraying/cleaning (Fig. 2). During the priming step the spray delivery system was pressurized at 0.30 MPa by feeding it with tap water from the supply source. At this step, the system delivered pure water for 20 s (Fig. 2b). At this point, the tap water supply stopped, and the second step began with the spray mixture injected, and canopy sprayed at 0.30 MPa. The flowmeter automatically switched off the mixture injection as soon as the defined rate (l ha^{-1}) was sprayed (Fig. 2c). As the pumped spray mixture started flowing in the main lines, the emitters installed closer to the pumping station begun to deliver the mixture sooner than emitters at a further distance. During the last spraying and cleaning step, the pumping system was stopped by turning the three-way valve, and tap water was allowed to flow again through the spray delivery system at 0.30 MPa (Fig. 2d). Water pushed the PPP mixture along the line and through the emitters, until all spray mixture was delivered (Fig. 2e and f). At the end of this phase water remained in the line (Fig. 2a).

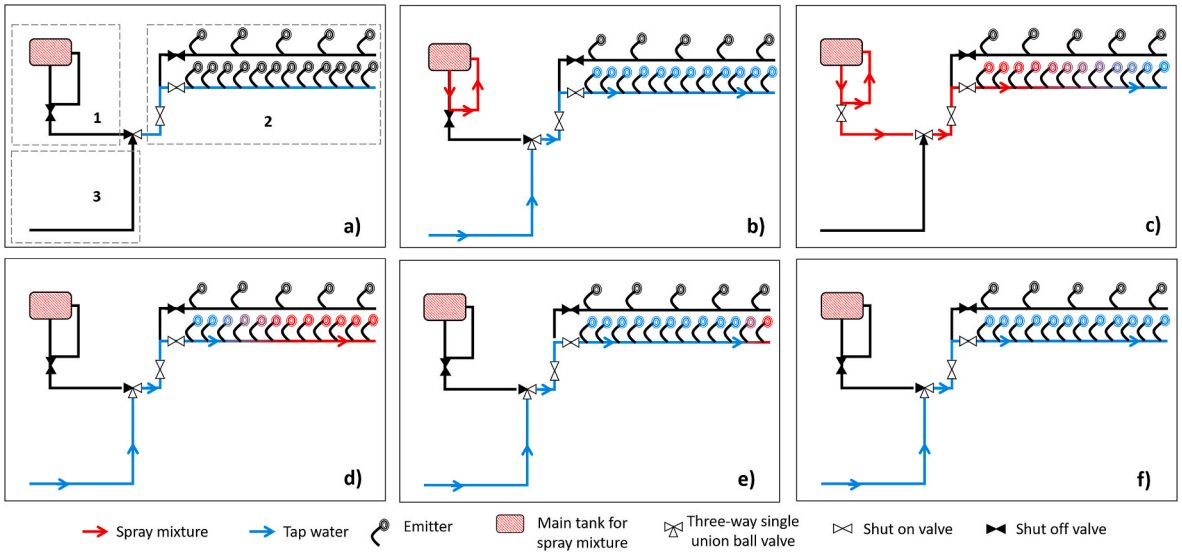

Fig. 2. Operational steps of experimental hydraulic spray delivery-based fixed spray system. Schematic for the fixed spray system components a) are the pumping station (1), the spray delivery system (2), and the tap water supply system (3). At the beginning of the process the spray delivery system is already filled with water from the cleaning step of the previous application. Step 1, priming b), system was pressurized at 0.30 MPa by filling with tap water supply and emitters sprayed for 20s. Step 2, spray mixture injection c), water delivery was stopped, and the pumping station moved a defined rate of PPP into mainline. Step 3, spraying/cleaning d), the pumping system was turned off and tap water was allowed to flow again through the spray delivery system. The tap water flow pushes the PPP mixture along the line and through the emitters, e) until all spray mixture was delivered and only tap water remained in the system f). Only spray delivery for the bottom spray line was colored in this diagram however the procedure is the same for both lines.

2.2. Experimental design

Trials were performed during summer 2022 at DiSAFA facilities in Grugliasco, Turin, Italy, (45° 3′ 54.6″ N 7° 35′ 28.9″ E) at a twelve-year-old Guyot-trained trellised vineyard (*Vitis vinifera* cv. 'Barbera') where a pilot HSD system was installed. Vineyard rows were spaced 2.5 m apart with an intra-vine distance of 0.8 m (5,000 vines ha^{-1}).

2.2.1. Measurement of spray mixture concentration and spray mixture homogeneity among emitters

To evaluate the increase, peak, and decrease of spray mixture concentration delivered by the emitters, different concentrations of tracer were collected at six distances along the spray line. A solution of water and E102 Tartrazine yellow dye tracer (85% w/w – Andrea Gallo di Luigi S.r.l., Genova, Italy) was used as spray mixture. Tartrazine was chosen as test product for its low degradation, high extractability, and high solubility (Pergher, 2001). Four parameters were tested, as a result of two spray mixture volumes (5 and 10 l) and two Tartrazine concentrations (10 and 20 g l^{-1}) per volume. It derived that different Tartrazine amounts, equal to 50 g (5 l at 10 g l^{-1}), 100 g (5 l at 20 g l^{-1} and 10 l at 10 g l^{-1}), and 200 g (10 l at 20 g l^{-1}), were injected into the system. Parameters were selected to evaluate the homogeneity of distribution of fixed spray system when applying spray mixture featured by different concentrations and by using different volumes. Different amounts of Tartrazine delivered were expected accordingly with exception of 5 l spray mixture at 20 g l^{-1} and 10 l spray mixture at 10 g l^{-1}, in which the same amount of Tartrazine delivered was expected. To perform the experiment, the operational steps (Fig. 2) were defined as detailed in Table 1 for both high and low emitter density spray lines.

Six sampling locations were selected and distributed along each spray line, corresponding to 4.0, 11.5, 20.0, 24.0, 28.5, and 31.0 m from the injection point. At the selected sampling locations, for trial purposes, two emitters were installed close to each other (50 mm distance as maximum), on the main line (at each location two out of three emitters at the top and two out of two emitters at the bottom are used). From one emitter at each distance spray (approximately 10 ml) was collected every 30 s in different plastic tubes for the whole duration of the trial (Table 1). These samples were analyzed to evaluate the spray mixture concentration at the selected distance (g l^{-1}). A plastic tube was placed over the second emitter and into a larger collection container (30.0 l capacity) to collect spray throughout the duration of each replicate. These samples were used to evaluate the total amount of Tartrazine delivered (g). To test for the presence of existing tracer concentrations, reference samples (50 ml) were collected before and after each replicate from the main tank of the pumping station and from the tap water system. Additionally, prior to each replicate, a single sample from each emitter was collected (blank procedure). The experiment was repeated three times resulting in a total of 12 total measurements per spray line (top and bottom); 3,936 samples (2 spray lines * 6 locations * 27 intervals * 2 vol * 2 concentrations * 3 replicates); and 144 samples measuring total volume (2 spray lines * 6 locations * 2 vol * 2 concentrations * 3 replicates).

Table 1
Operational steps and specific timing use for high and low emitter density spray lines. Based on the different spray mixture volumes to be injected (5 and 10 l), spray mixture injection timing is provided.

Spray line	Spray line total flow rate (l min^{-1})	Operational step timing			
		Priming (s)	Spray mixture injection (s)		Spraying/ cleaning (s)
			5 l	10 l	
High emitter density	15.6	30	19	38	600
Low emitter density	4.2	30	72	144	600

2.2.2. System cleaning performances

To evaluate the cleaning performances of the system, a 1% suspension of copper oxychloride (PATROL 35 WP, Certis Europe B.V., Saronno, VA, Italy) was used as spray mixture (Grella et al., 2022) to comply with the requirements set by the ISO 22368-1:(2004). The copper oxychloride was used as test material for the evaluation of internal sprayer cleaning performances because it is sticky and difficult to remove. Based on the results obtained from the first set of field trials (§2.2.1), the spray mixture injected, system operational steps, and the number of sampling locations were selected because it showed the highest concentrations of tracer which would lead to the worse-case scenario for cleaning. In detail, 5 l of spray mixture was used to avoid unnecessary environmental pollution as well it showed to be the minimum volume to ensure readability of the samples (5 *vs.* 10 l). To perform the experiment, operational steps (Fig. 2) were defined as follow: priming lasted 30 s; spray mixture injection used was 19 and 72 s for high and low emitter density, respectively; spraying/cleaning lasted 20 min. Three sampling locations were selected and distributed along each spray line corresponding to 11.5, 20.0, and 28.5 m from the injection point, to keep an 8.5 m fixed distance between them. At the selected sampling locations, one emitter was selected from which only the sample concentration was measured (at each location one out of three emitters at the top and one out of two emitters at the bottom are used); according to the experimental aims, in this last experiment using copper oxychloride the total mass concentration was not investigated. Procedures for collecting reference and emitter samples were collected in similar methods defined in section §2.2.1 except that they were collected every 60 s between the minutes 1:30 to 7:30, and then after 21:00 and 22:00 min for high and low emitter density, respectively, from the beginning of the trials. Increased timing in sample collection ensured collection of even trace amounts of copper oxychloride. In total 198 samples were collected (2 lines * 3 locations * 9 timings * 3 replicates).

2.3. Data processing

2.3.1. Tartrazine quantification

Tartrazine concentration was determined by measuring at 427 nm wavelength the absorbance of samples with a spectrophotometer (Model: UV-1600PC VWR, VWR International, USA), and comparing the results to a calibration curve. In all cases, dilution of samples was carried out when the Tartrazine concentration resulted out of the optimal instrument reading range. Spray mixture concentration (C, g l^{-1}) was calculated according to Eq. (1)

$$C = \left[\frac{\left(P_{smpl} - P_{blk}\right) \times \varepsilon}{1,000}\right] \quad (1)$$

where P_{smpl} is the measured absorbance of the sample (dimensionless), P_{blk} is the measured absorbance of the pure water provided by the supply system (dimensionless), ε is the volume of dilution liquid (ml) equal to 1 if no dilution occurred.

Total Tartrazine delivered (g) was calculated by multiplying Eq. (1) per the total spray liquid volume (l) collected from the single emitter used at each sampling location.

2.3.2. Copper oxychloride quantification

Copper oxychloride concentration (mg l^{-1}) was detected by atomic-absorption-spectrometry from United States Environmental Protection Agency (EPA) methods: EPA 3005a, EPA 6010d, and EPA 3015a (US EPA, 2019a, 2019b, 2015).

Each sample was homogenized with a stirrer (Model: SP88857108, Thermo Fisher Scientific S.r.l., Waltham, MA, USA) for 30:00 min at 500 rpm. An aliquot (2.5 ml) was transferred to a microwave digestion vessel (Milestone S.r.l., Milano, Italy). Samples were dried in an oven (Model: M120-VN/VF, Tecno-lab S.r.l., BS, Italy) at 105 °C for 48 h before adding 4.0 ml of HNO_3 (Merck 84378 - puriss. p.a., 65.0–67.0%) and 1.0 ml of

H_2O_2 (35% Merck 1086001000). Next, a microwave-assisted acid digestion, was performed through a START D microwave digestion system (Milestone S.r.l., Milano, Italy) using the following program: 25:00 min at 1,200 W from room temperature to 220 °C, 2:00 min 1,200 W from 220 °C to 250 °C, and 15:00 min at 1,200 W at 250 °C. After cooling, samples were hydrated with 20 ml deionized water and processed in a NexION 350D ICP-MS Mass Spectrometer (PerkinElmer, Waltham, MA, USA). Accuracy was checked using reference copper oxychloride concentration solutions. Percentage of copper oxychloride concentration reduction (*CCR*, %) was calculated according to Eq. (2)

$$CCR = 100 - \left(\frac{C_{smpl}}{C_{mix}} \times 100\right) \quad (2)$$

where C_{smpl} is the copper oxychloride concentration of the sample (g l^{-1}), and C_{mix} is the copper oxychloride concentration of the mixture (g l^{-1}).

2.3.3. Data processing and statistical analysis

All statistical analyses were performed using IBM SPSS Statistic (Version 28; Chicago, USA) predictive analytical software for Windows©.

All values were tested for normality using Shapiro-Wilk test and by visual assessment of the Q-Q plots of Z-scores. An Arcsin transformation was used to achieve residual normality and homoscedasticity of data, expressed as a percentage. Residual analyses were also performed. Data for total Tartrazine delivered (g) and copper oxychloride concentration reduction (%) were analysed in two separate datasets: high and low emitter density.

To evaluate if the spray mixture was homogenous, a three-way ANOVA was used to test the effects of distance from the injection point (4.0, 11.5, 20.0, 24.0, 28.5, and 31.0 m), spray mixture volume (5 and 10 l) and Tartrazine concentration (10 and 20 g l^{-1}) on the total Tartrazine delivered (g).

To evaluate the efficacy of the cleaning step, the reduction of copper oxychloride concentration (%) was analysed to determine optimal cleaning efficacy to water volume used and optimal time needed to achieve adequate cleaning. As no specific regulation exists for cleaning evaluation of fixed spray systems, the conventional reference threshold value for fixed and semi-mobile sprayers (ISO 16119–4:2014) was used. This ISO standard expects a copper oxychloride concentration reduction >99.67%. A two-way ANOVA was used to test the effects of distance from the injection point (11.5, 20.0, and 28.5 m) and spraying/cleaning step timing (high density 2:30, 3:30, 4:30, 5:30, 6:30, and 20:00 min; low density 4:30, 5:30, and 20:00 min), on the dependent variable copper oxychloride concentration reduction (%). In all cases, the means were compared using a Duncan *post-hoc* test for multiple comparison ($p < 0.05$).

A visual comparison analysis between the copper oxychloride and Tartrazine spray mixtures concentration was carried out. For this purpose, concerning the Tartrazine, only the spray mixture dataset featured by the same volume (5 l) and concentration (10 g l^{-1}), as those used in evaluating the system's cleaning performance (§2.2.2), was considered. Similarly, only the common sampling distances from the injection point (11.5, 20.0, and 28.5 m) and the timings (0:00, 1:30, 2:30, 3:30, 4:30, 5:30, 6:30, and 7:30 min) were taken into account. For a broad comparison, the obtained dataset was standardized as percentage, where 100% correspond to 10 g l^{-1} (reference concentration for both spray mixtures). The analysis objective was to provide additional insights into the HSD-based spray system while delivering different spray mixture (copper oxychloride suspension and Tartrazine solution).

As last, two linear regression models were fit to describe the relationship between the flow rate and the time to clean, and the relationship between the flow rate and water use. The goal was to provide reference equations to be used in the HSD-based spray systems design.

3. Results and discussion

3.1. Spray mixture concentration

Results indicate that the HSD system delivered the spray mixture at each sampling location (Fig. 3).

As expected, during the spray mixture injection step, there is a direct relationship between distance from the injection point and time of first concentration to appear in an emitter (Figs. 3 and 4). The average time delay to reach the concentration peak per emitter, between the sampled distances, resulted 7 and 32 s while testing high and low emitter densities, respectively. In addition, the emitter density affected the speed at which the spray mixture is delivered. On one hand, considering the timing between the start of spray mixture injection and the end of spraying/cleaning steps, high emitter density delivered both spray mixture volume (5 and 10 l) in 2:30 min when all mean concentrations reached zero (Fig. 3a). On the other, low emitter density delivered all the concentration 5 and 10 l spray mixture in 7:00 and 9:00 min (Fig. 3b), respectively.

There were differences in performance of each emitter reaching the maximum concentration. In addition, the low emitter density (Figs. 3b and 4b) could reach spray mixture concentrations close to the main tank at each sampling location. No deviation higher than ±14.72% was observed for the recorded peaks along the line, suggesting the system's ability to deliver an even concentration of mixture throughout the lower emitter density both at 10 and 20 g l^{-1}. In addition, for the low emitter density case, considering each sampling location from the injection point, 95 s in average were necessary to shift from the maximum to the minimum mixture concentration delivered in each sampling point (Figs. 3b and 4b). A decrease equal to 75% from the maximum spray concentration (10 g l^{-1}) was recorded in the high emitter density because the spray mixture, due to the high spray line flow rate (15.6 l min^{-1}) was mixing with the water from and during the spraying/cleaning step. Further analysis in the spray mixture homogeneity among emitters will examine the total grams per emitter (§3.2 Spray mixture homogeneity among emitters).

Increasing the Tartrazine concentration (10 and 20 g l^{-1}) showed no difference between the recorded trends. In contrast, increasing the volume of the spray mixture injected (from 5 to 10 l), for each Tartrazine concentration, had two effects. First, for the high emitter density, the recorded mixture concentration delivered per each sampling time increased (Fig. 4a). Second, for the low emitter density, it increased the plateau timing of mixture concentration delivered for each sampling distance (Fig. 4b).

3.2. Spray mixture homogeneity among emitters

Despite differences in concentrations, emitters delivered an equal amount of spray mixture throughout all sampled distances, for both high and low emitter densities (Fig. 5) thus demonstrating the capability of HSD system to provide homogeneous spray application without under- and/or over application along the lines. Three-way ANOVA showed a significant interaction between the two variables spray mixture volume (5 and 10 l) and Tartrazine concentration (10 and 20 g l^{-1}), for both the emitter densities (Table 2). The average spray mixture homogeneity among the sampled emitters showed a coefficient of variation (CV) equal to 6.91%. This result demonstrated that the experimental HSD system, even if being fixed, was able to achieve spray mixture homogeneity values close, for example, to the one achieved by conventional pesticide application equipment (PAE) equipped with direct injection systems (Dai et al., 2019; Vondricka and Schulze Lammers, 2009).

Comparing the total Tartrazine delivered by the two spray lines (high *vs.* low), the amount was in all cases lower for the high emitter density. These results are expected and proportional to the injected Tartrazine levels of 50 g being the lowest, 100 g being doubled, and 200 g quadrupled (Fig. 6). Considering the same volume injected the ratio

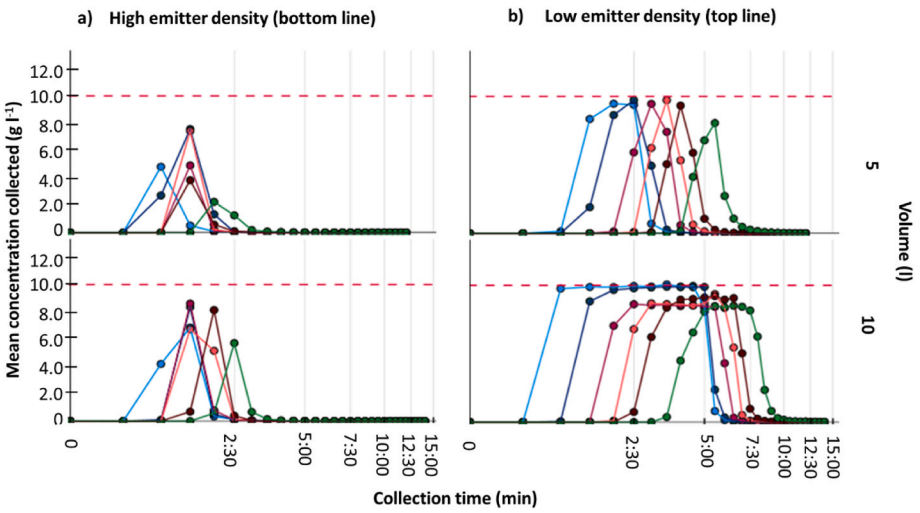

Fig. 3. Average spray mixture concentration (g l^{-1}), measured over the time (min) per the 5 and 10 l spray mixture volume at 10 g l^{-1} concentration. Different colors denoted different sampling locations from the injection point: light blue (—) = 4.0, purple (—) = 11.5, magenta (—) = 20.0, pink (—) = 24.0, brown (—) = 28.5, and green (—) = 31.0 m per a) the high emitter density and b) the low emitter density spray lines. Red dashed line (- -) indicates the concentration of the mixture in the tank (10 g l^{-1}).

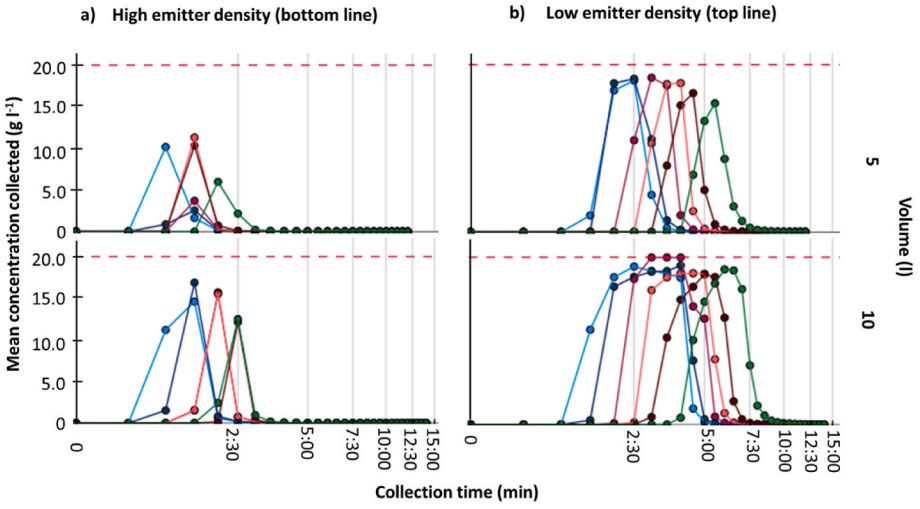

Fig. 4. Average spray mixture concentration (g l^{-1}), measured over the time (min) per the 5 and 10 l spray mixture volume at 20 g l^{-1} concentration. Different colors denoted different sampling locations from the injection point: light blue (—) = 4.0, purple (—) = 11.5, magenta (—) = 20.0, pink (—) = 24.0, brown (—) = 28.5, and green (—) = 31.0 m per a) the high emitter density and b) the low emitter density spray lines. Red dashed line (- -) indicates the concentration of the mixture in the tank (20 g l^{-1}).

between different concentrations (10 *vs*. 20 g l^{-1}), in general, was close to the expected value. In fact, being the 10 g l^{-1} the double of 20 g l^{-1}, a ratio target value equal to 2 would have been expected. More precisely, were obtained 2.25 (5 l volume) and 2.15 (10 l volume) for the high and 2.02 (5 l volume) and 1.98 (10 l volume) for the low emitter densities. In addition, the high (78 total emitters) and low (21 total emitters) densities resulted able, with respect to the reference concentration, to deliver 85.8 *vs.* 99.8% when injecting 5 l of spray mixture at 10 g l^{-1} (50 g Tartrazine injected in total), 85.8 *vs.* 96.6% when injecting 10 l of spray mixture at 10 g l^{-1} (100 g Tartrazine injected in total), 93.6 *vs.*94.5% when injecting 5 l of spray mixture at 20 g l^{-1} (100 g Tartrazine injected in total), and 93.6 *vs.* 96.6% when injecting 10 l of spray mixture at 20 g l^{-1} (200 g Tartrazine injected in total). It derives that on average a 0.14% deviation from expected value per emitter occurred while sampling. This small deviation, when multiplied by huge emitter number lead to big gap between values measured and expected target values of total tartrazine delivered. Therefore, the higher the emitter number per line the higher the gap.

3.3. *System cleaning performances*

Trials, conducted on cleaning evaluation, indicated that pure water was able to properly clean the spray delivery system. This task is not easy to accomplish even with conventional PAE where frequently cleaning agents (Marucco et al., 2010) or multiple rinsing (Doerpmund et al., 2011) are suggested in order to reach the values achieved while testing the pilot HSD system. Results showed that copper oxychloride concentration reduction, observed at the farther sampling location from the injection point (28.5 m), higher than 99.67% were achieved by the high (99.98%) and low (99.93%) emitter densities after 2:30 and 4:30 min of spraying/cleaning step timing, respectively (Fig. 7a and b). Two-way ANOVA (Table 3) for the high emitter density spray line, indicated that sampling location from injection point and sampling time significantly affect the copper oxychloride concentration reduction. No

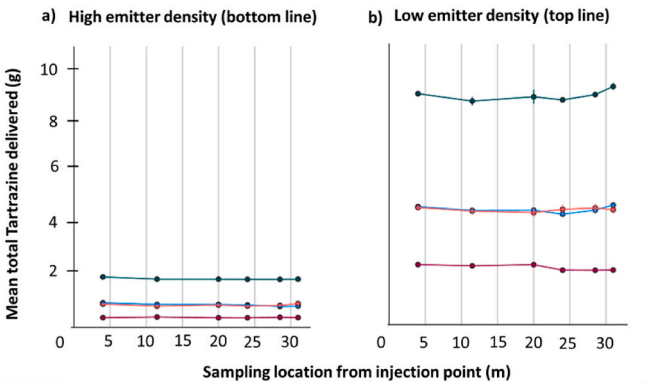

Fig. 5. Average total Tartrazine delivered (g) per a) the high emitter density and b) the low emitter density spray lines. Different colors denoted differences about the four spray mixtures injected (combination of 5 and 10 l spray mixture volumes and 10 and 20 g l^{-1} Tartrazine concentrations): red (—) = 50 g (5 l at 10 g l^{-1}), light blue (—) = 100 g (5 l at 20 g l^{-1}), orange (—) = 100 g (10 l at 10 g l^{-1}), and green (—) = 200 g (10 l at 20 g l^{-1}). The measurements were taken at six sampling locations (at 4.0, 11.5, 20.0, 24.0, 28.5, and 31.0 m from the injection point) along each spray line.

significant interaction was observed between these two variables. Significant copper oxychloride concentration reduction differences were found, for the low emitter density (Table 3), both for sampling location from injection point and sampling time. In addition, there was a significant interaction between these two variables such that as the cleaning time increased, so did the copper oxychloride concentration reduction. However, there is a desire to decrease water consumption while achieving maximum cleaning results. Looking at the relationship between copper oxychloride concentration reduction (%) and water consumption (l) per each sampling time (Table 4) there is very little improvement in cleaning (percent reduction) with increased timing or water use. Considering high emitter density, tested cleaning timing showed a maximum copper oxychloride concentration reduction improvement equal to 0.01%. In detail, to achieve this value, with respect to the water volume consumed at 2:30 min of spraying/cleaning step, using 3:30, 4:30, 5:30, 6:30, and 20:00 min would be requested 45, 80, 120, 160, and 700% more water, respectively. On the other hand, looking at the low emitter density, tested cleaning timing showed a maximum copper oxychloride concentration reduction improvement equal to 0.05%. In this case, with respect to the water volume consumed at 4:30 min of spraying/cleaning step, using 5:30, and 20:00 min would be requested 22:00, and 344% more water, respectively. Considering these results and to save both water and time needed to perform spray application, it is preferable to choose the minimum timing that gives copper oxychloride concentration reduction results higher than the threshold (99.67%). This result highlight that, even if the flow rate ratio between the high and low emitter densities is equal to 3.7, the water consumption and cleaning time ratio doesn't respect the same value being equal to 2.1 and 1.8, respectively.

The comparison of standardized concentration of Tartrazine and copper oxychloride showed very similar trend across time (Fig. 8). In particular, during the spray mixture injection step, for both high and low emitter density, there was an increase in the concentration of the spray mixtures as well as an abrupt decrement after the peak. In general, the proportion between Tartrazine and copper oxychloride concentration was maintained throughout time and sampled distances. These results suggest that the HSD tested behave consistently irrespective of spray

Table 2
Results of three-way ANOVA ($p < 0.05$) for total Tartrazine delivered (g) of the high and low emitter densities spray line.

	High emitter density			Low emitter density		
	DF	$p >$ (F)	Signif.[a]	DF	$p >$ (F)	Signif.[a]
Main effect						
Spray mixture volume (A)	1	1.86E-39	***	1	8.02E-47	***
Tartrazine concentration (B)	1	2.94E-39	***	1	9.05E-47	***
Sampling location from injection point (C)	5	0.305	NS	5	0.116	NS
Interactions						
A × B	1	2.70E-19	***	1	1.15E-25	***
A × C	5	0.484	NS	5	0.127	NS
B × C	5	0.736	NS	5	0.395	NS
A × B × C	5	0.923	NS	5	0.930	NS

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

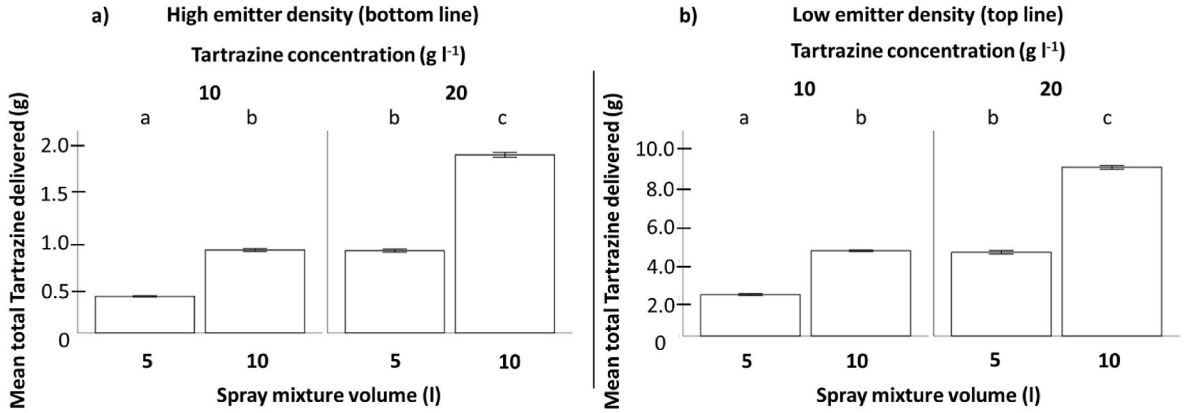

Fig. 6. Average total Tartrazine delivered (g), from the six emitters sampled per a) the high emitter density and b) the low emitter density spray lines. Different bars showed the combination of mixture volume (5 and 10 l) and Tartrazine concentration (10 and 20 g l^{-1}). Different letters indicate significant differences per emitter density tested.

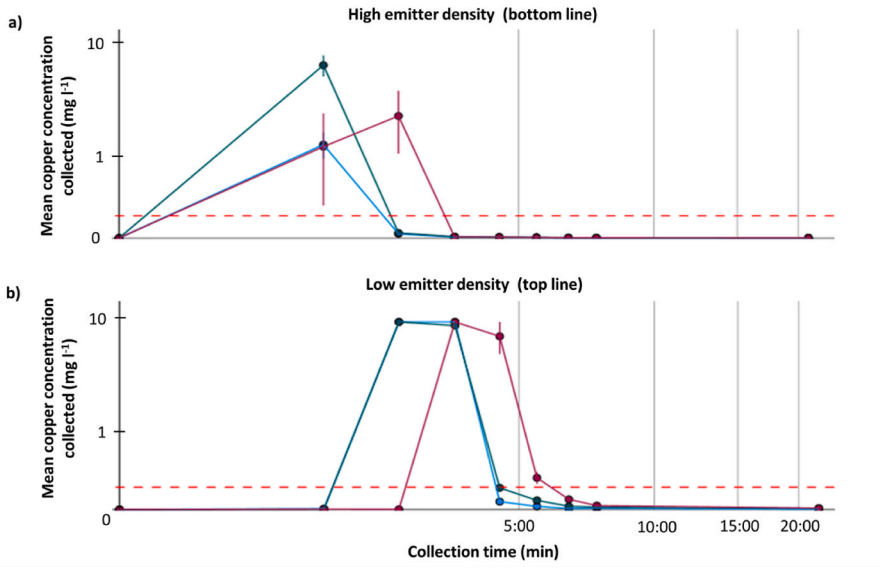

Fig. 7. Average copper oxychloride concentration (g l^{-1}, in logarithmic scale), per a) the high emitter density and b) the low emitter density spray lines. Different colors denoted different sampling location from the injection point: light blue (▬) = 11.5 m, green (▬) = 20.0 m, and red (▬) = 28.5 m. Red dashed line (▬ ▪) represents the threshold, below which the copper oxychloride concentration is reduced by 99.67% with respect to the concentration of the copper oxychloride in the tank.

Table 3
Results of two-way ANOVA ($p < 0.05$) for average copper oxychloride concentration reduction (%) of the high and low emitter densities spray line.

	High emitter density			Low emitter density		
	DF	$p > (F)$	Signif.[a]	DF	$p > (F)$	Signif.[a]
Main effect						
Sampling location from injection point (A)	2	3.96E-04	***	2	6.03E-06	***
Sampling time (B)	5	1.07E-15	***	2	2.62E-05	***
Interactions						
A × B	10	0.112	NS	4	2.34E-04	***

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

Table 4
Spraying/cleaning step timing (min), correspondent water consumption (l), and average copper oxychloride concentration reduction (%) at 28.5 m from the injection point for the high and low emitter densities.

Emitter density	Step timing (min)	Water consumption (l)	Average copper oxychloride concentration reduction (%)
High	2:30	39.0	99.9847
High	3:30	56.6	99.9889
High	4:30	70.2	99.9918
High	5:30	85.8	99.9945
High	6:30	101.4	99.9964
High	20:00	312.0	99.9974
Low	4:30	18.9	99.9348
Low	5:30	23.1	99.9673
Low	20:00	84.0	99.9874

mixture delivered making it suitable for the application of a wide range of PPP characterized by different chemical properties. Indeed, it has to be noticed that while Tartrazine is well-known for its high solubility (Pergher, 2001), up to 70 g l^{-1}, copper oxychloride exhibits the opposite behaviour being difficult to be properly mixed and also sticky (Grella et al., 2022). For this reason, it is used as test material for cleaning performance evaluations according to ISO 22368-1:(2004). Noteworthy, also considering the cleaning performances, the HSD behave similar irrespective of spray mixture tested. In fact, considering the farthermost sampling distance from the injection point (gray and black solid lines in Fig. 8), the cleaning efficiency values were very close. On one hand, after

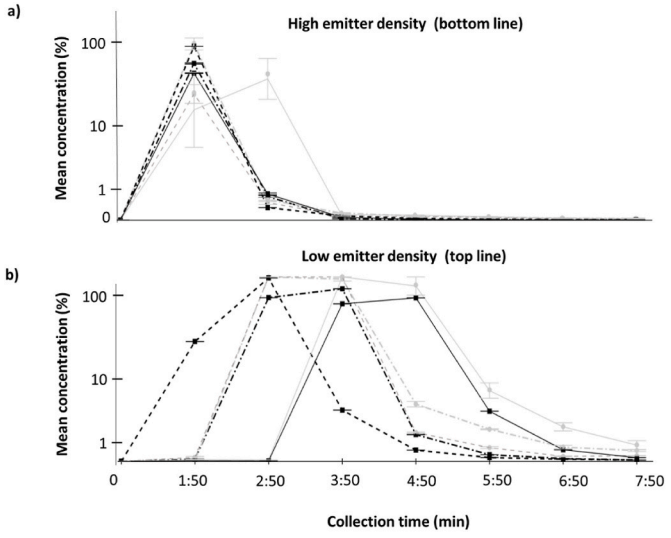

Fig. 8. Average percentage concentration (%, log scale), per a) the high emitter density and b) the low emitter density spray lines. Copper oxychloride (5 l at 10 g l^{-1}) and Tartrazine (5 l at 10 g l^{-1}) spray mixture sampling locations from the injection point are reported in gray (●) and black (■) color, respectively. Different dashed lines denoted different sampling locations from the injection point: dashed (▬ ▬ = 11.5 m), dash-dotted (▬ ▪ = 20.0 m), and solid (▬ = 28.5 m) lines.

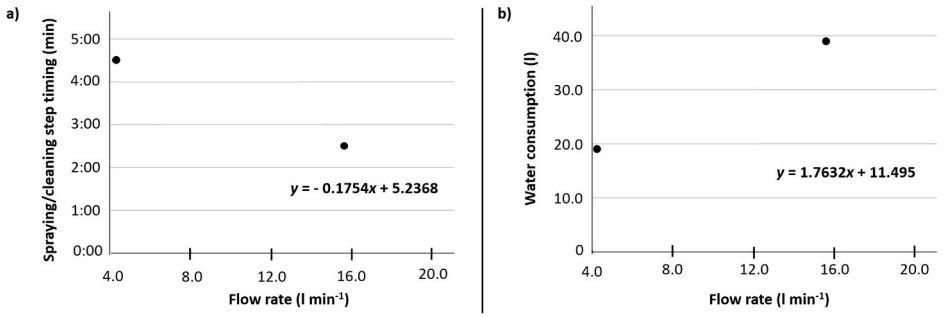

Fig. 9. Linear regression models of the spray delivery system evaluated. Flow rate was evaluated to be 4.2 and 15.6 l min^{-1} for the low and high emitter density, respectively. a) Spraying/cleaning step timing (min) and flow rate (l min^{-1}), and b) water consumption (l) and flow rate (l min^{-1}) relationships.

2:30 min of spraying/cleaning step timing, were obtained values equal to 99.92% (Tartrazine) and 99.98% (copper oxychloride) for high emitter density. On the other hand, after 4:30 min of spraying/cleaning step timing, were obtained values equal to 99.68% (Tartrazine) and 99.93% (copper) for low emitter density.

Based on the results achieved two linear regression models were developed to estimate spraying/cleaning step duration and pure water consumption according to the spray flow rate. Flow rate was evaluated to be 4.2 and 15.6 l min^{-1} for the low and high emitter density, respectively. Fig. 9a shows that as spraying/cleaning step timing decreases, so did the spray flow rate, in order to achieve a copper oxychloride concentration reduction >99.67%. Conversely, Fig. 9b shows that pure water consumption increases as the spray flow rate decrease. These regression lines can be used as a starting point when building or modifying an HSD system.

Using the models, it is possible to estimate the spraying/cleaning step duration and water consumption per each flow rate between 4.2 and 15.6 l min^{-1}. For instance, if a 100 m long HSD system spray line was built according to the low emitter density criteria, the general flow rate would be 13.54 l min^{-1}. Therefore, specific spraying/cleaning step duration and water consumption would approximately 3:00 min and 35.38 l, respectively.

4. Conclusion

The experimental trials conducted in this study provided insights into how the pilot HSD system delivers the spray mixture. It was observed that the time taken for the system to be cleaned, after the injection of the spray mixture, is greater than the time taken for the mixture to travel through the spray delivery system. The spray mixture is cleared from the topmost part of the line to the bottommost emitter, which balances the amount of mixture delivered from the emitters through the system. To deliver a precise rate and homogeneous spray mixture, the HSD system should consider three key factors: emitter flow rate, emitter number, and the volume of the spray mixture injected. These key factors are dependent between each other because they affect the dose of spray mixture delivered (*i.e.*, quantity of product sprayed into the canopy), installation cost, and spraying/cleaning step timing to properly clean the system without consuming unnecessary pure water volumes and avoid cross-contamination between treatments. The present study represents the first investigation and validation of how spray mixture injection and delivery work in a HSD system. While hydraulic calculations can provide accurate estimates, it is crucial then to scientifically demonstrate that the system sprays homogeneously through all its emitter. A key factor in any PPP application technique is the PAE ability to apply a homogeneous product amount at all distances, which helps avoid over- or under-dosing along the row. This last point is even more critical than considering emitters layout into the canopy. Additionally, the HSD system showed it was easy to clean and capable of complying with the ISO thresholds (cleaning efficiency >99.67%). The comparison between the spray mixtures tested (Tartrazine solution and copper oxychloride suspension), suggested that the HSD tested behave consistently irrespective of spray mixture delivered making it adequately for the application of a wide range of PPP characterized by different chemical properties. Results indicate that a low emitter density potentially has to be preferred in order to deliver higher total product by each emitter, increasing the chance to better distribute the spray mixture onto the canopy. Nevertheless, a low emitter density would allow to save more water involved in the spraying/cleaning step. It has to be considered that the emitter density has to be defined based on the spray application performances (e.g., canopy deposit achieved in the different canopy parts) and not just based on cleaning performances of the system itself. In general, it derives that HSD featured by minimum number of emitters and able to achieve with effective spray application must be preferred to HSD featured by higher density even if better spray application performance can be obtained. Anyway, additional studies on spray deposit and quality in the canopy, to test the HSD at the field scale, are needed to further explore and optimize the proposed HSD spray system (e.g., number on emitters, positions in the canopy, type of emitters).

These data will support the further development and eventual commercial adaptation of the system.

CRediT authorship contribution statement

Eric Mozzanini: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Marco Grella:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization, Supervision. **Paolo Marucco:** Conceptualization, Writing – review & editing. **Gwen-Alyn Hoheisel:** Investigation, Writing – review & editing. **Alessandro Biglia:** Investigation, Writing – review & editing. **Paolo Balsari:** Conceptualization, Writing – review & editing. **Fabrizio Gioelli:** Conceptualization, Methodology, Resources, Investigation, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

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

Data will be made available on request.

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