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Development of a fixed spray delivery system for Guyot-trained vineyards

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Gutta cavat lapidem non bis sed saepe cadendo:
sic homo fit sapiens bis non, sed saepe legendo

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General introduction

Pesticide application equipment used in steep slopes vineyards

Commercial vineyards often require several applications of plant protection products (PPP). The most common treatments are fungicide applications against powdery mildew, downy mildew, and botrytis, and insecticide applications against the *Lobesia botrana*, and *Scaphoideus titanus* (vector of the flavescence dorée). Even if the scientific world agrees on the necessity of PPPs to protect crops to increase crop yield and quality (Popp et al., 2013; Azimonti et al., 2024), the intensive use of PPPs can cause adverse side effects on the environment, operators, and bystanders (Butler Ellis et al., 2010). These concerns associated with today's demand for residue-free products and lower usage of PPPs, pushed many research areas to look for more efficient and alternative solutions to the conventional approaches for crop protection. Researchers focus today on technological improvements of conventional sprayers to optimize PPPs delivery. An example of this is the development of sensors and actuators able to adapt the spray application and airflow rates to canopy morphology and to the tractor forward speed, dealing to more efficient spray applications with chances to pesticide saving (Grella et al., 2022a; Bhalekar et al., 2023; Xun et al., 2023). However, it is worth noting that in the heroic and steep slope viticulture contexts, the field fragmentation (vineyard not always contiguous) and the orographic conditions, create impediments to mechanization and limit the use of conventional ground-based sprayers and tractors and, therefore, of the abovementioned technological improvements. The exploration of alternative spray technologies for steep slope areas, where tractors are difficult or even impossible to use and the only option is represented by knapsack mist blower, high-volume sprayer equipped with a spray gun (Michael et al., 2021) and long- range cannon sprayer applying from the border to inside the field, would represent a key point to improve the crop protection for these areas. The use of spray guns in terraced vineyards is laborious and time-consuming and, since inter-rows are very narrow (usually no more than 1.50 m) and the operating pressure often exceeds 0.20 MPa (Debuis et al., 2019), this application technique unavoidably puts the operator into direct contact with the spray mixture, resulting in a high risk of PPP exposure. Despite the high spray pressures and volumes involved, the biological efficiency of the treatments shows remarkable variability related to operator precision: some parts of the canopy could be improperly sprayed (under-dosage), while in others, there may be an over-dosage and spray mixture dripping to the soil (Michael et al., 2020). Furthermore, inadequate spray applications can lead to various issues, including pest resistance, environmental contamination, and increased operational costs (Damalas and Elefthrohorinos, 2011; Pop et al., 2013; Gill and Garg, 2014; Tudi et al., 2021). Unfortunately, these numerous issues and, in particular, the operator exposure and the strong efforts needed to grow crops in such landscapes, are driving to agriculture and land abandonment of steep slope areas.

Nowadays, through a common action of research institutions, companies, and policymakers, new alternative solutions to the conventional pesticide application equipment (PAE), and their related technologies, are under evaluation to facilitate the crop protection operation of steep slopes 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 (FSDS) (Imperatore et al., 2021; Sahni et al., 2022; Sinha et al., 2019). Although the increasing interest in using UASS for PPP application is not debatable, to date the interest in FSDSs is also increasing especially in the EU where the Directive of the European Union (EU) for sustainable use of pesticides (European Community, Directive 2009/128/EC; https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0128) prohibits aerial spray applications including those from UASSs.

A FSDS is a modified irrigation system that can deliver PPP and perform spray applications at a relatively low pressure (0.30 MPa). This novel pesticide application technology generally comprises a spray delivery system and an applicator unit. The spray delivery system consists of spray lines, which are the combination of a solid set of polyethylene pipelines and nozzles permanently positioned at predetermined locations, often in tiers (*i.e.*, the number of spray lines installed in a row), placed within the canopy according to crop, its training system, and the canopy characteristics, to deliver the spray mixture in the field (Sharda et al., 2015; Bondesan et al., 2016; Ranjan et al., 2021a, 2021b; Chen et al., 2023; Mozzanini et al., 2023a, 2023b). The applicator unit mainly consists of a tank to hold the spray mixture, a pump to inject the spray mixture from the tank into the spray delivery system, sensors/gauges for system fault detection, and a supply system that is used first, to deliver the spray mixture in the field (crop canopy) once it is injected into the spray delivery system and second, to clean the spray delivery system before the end of the spraying activity to mainly avoid components clogging.

The FSDS has already been tested for apple orchards grown on steep slopes and demonstrated to be a promising pesticide application technology (Bondesan et al., 2016; 2023; Niemann et al., 2016; Owen-Smith et al., 2019). The preliminary biological efficacy investigations demonstrated the FSDS's suitability in apple scab management, bloom thinning, and in being adopted in apple organic farming (Bondesan et al., 2016; 2023; Niemann et al., 2016).

The FSDS pesticide application technique, which bypasses the need of tractors and sprayers into the orchard/vineyard, would allow farmers to (i) avoid soil compaction (since no heavy equipment is used in the field), (ii) operate in complex scenarios like the “heroic agriculture” characterized by steep slopes environment (since there is no need to enter in the field physically), (iii) enhance operator safety (since the operator activates and deactivates the system from the outside of the field, or even the system is automatized), (iv) perform spray applications when the weather conditions are less favorable to drift phenomena (e.g., calm of wind, during the night) thanks to the possibility to spray large areas in a very short time in comparison to the ground based sprayer trailed by tractor, and/or (v) increase the spray application timeliness, or rather, to perform spray applications at the right time and in a short time-window when it is strategical to protect the crop against a disease (e.g., such as right after a severe rainfall when tractors and sprayers cannot enter into the field and it is necessary to perform the spray application). Therefore, FSDS results in an interesting solution for steep-sloped areas and flat ones where muddy fields would likely not be an issue to deliver PPPs anymore.

Since the promising results obtained by researchers in the apple case (above mentioned), authors recently focused their work in studying and optimize the FSDS for other crops e.g., citrus (Chen et al., 2023). However, to date, researchers primarily put their efforts on FSDS for vineyards to increase the opportunity for farmers to better protect their crops in an easier and faster way than the conventional methods, in both complex scenarios like steep slope (Imperatore et al., 2021) and flat areas where bigger vineyards are usually growth (Sinha et al., 2018; Sinha et al., 2019).

Early and modern research on FSDS

Chemigation

The concept of injecting PPP into irrigation systems is not new in agriculture, especially in open fields by mean of Pivot stations, and potted crops with pipelines and spaghetti tubes. The technical name is chemigation, consisting in the application of fertilizers and PPPs via irrigation systems (Sawyer and Oswalt, 1983; van der Gulik et al., 2007; Haman and Zazueta, 2017). Chemigation can be commonly categorized into five types based on the chemical product applied (Rolston et al., 1986; Bar-Yosef, 1999; Hedley et al., 2014): i) herbigation – which involves applying herbicides through irrigation systems to control weeds; ii) fungigation – that utilizes irrigation systems to distribute fungicides; iii) insectigation – applies insecticides via irrigation to control pest infestations; iv) fertigation – that integrates the application of fertilizers with irrigation; and v) nematigation – that is specifically for applying nematicides to control nematodes in the soil.

The concept of chemigation dates back to the late 1960s, marking the beginning of integrating PPP applications with irrigation techniques. One of the first discussions on chemigations in literature was by Bryan and Thomas (1958). The authors presented different PPP application techniques and chemigation was listed among the conventional ones back in those days. The earliest documented use of this method was in 1969 by Lange, Agamalian, and Sciaroni, who applied herbicides through irrigation systems to control weeds in ornamentals. This innovation laid the groundwork for the subsequent evolution of chemigation. The 1970s-80s witnessed significant strides in this field, promoting the understanding and adoption of chemigation, emphasizing its potential in weed control and its impact on crop yields and environmental sustainability. Further advancements in chemigation technology were seen in the following decades, including the diversification of chemicals applied through irrigation systems. This period also saw a growing emphasis on the environmental aspects of chemigation, leading to the development of safety measures to prevent contamination of water sources (Sawyer and Oswalt, 1983; Wilson, 1983; Carpenter et al., 1985, Threadgill, 1985). Since then, the adopted irrigation systems have been equipped with properly designed safety accessories to avoid contamination of water bodies. In addition, it was underlined the importance that the irrigation system would have been equipped with a pump designed to inject PPPs or fertilizers at a given rate so that the application would have been conducted on a proper rate per unit area basis (Threadgill, 1981). To give a rough quantification of how much chemigation was widespread, Threadgill (1985) and the Census of Agriculture (NASS, 1988) surveyed chemigation use in the US and found out that nearly 4 million ha, on more than 35,000 farms, were utilizing chemigation at least once during the season. Nowadays chemigation is still widely adopted in the US (Bekelja et al., 2024; Wang et al., 2024) and has also spread to other countries such as Israel (Darfy Yelin et al., 2024). However, from the original chemigation concept a pesticide application technology, dedicated to perennial 3D crops, was designed and studied in recent years: the solid set canopy delivery system (SSCDS) known also as fixed spray delivery system (FSDS).

From chemigation to FSDS variants

The first-ever experiment – using what can be defined as the first FSDS prototype – was conducted by Lombard et al. (1966) at the Southern Oregon Experimental Station in a pear orchard. At that time, overhead sprinklers for irrigation were under evaluation for their potential to provide frost and freeze protection in spring. Lombard et al. (1966) posited that a modification of the existing system, using micro sprinklers, would lead to a multi-purpose device able to potentially provide both cold hardiness and pest control management. Due to the technical limitations of their system, pest control, compared to a conventional ground-based sprayer, was inadequate. Results underlined that further studies were needed to optimize the sprinklers' spray pattern and reduce the time and water volumes used to perform the PPP application. After this first experience, most of the researchers focused on emitters design, characterization, and economic evaluation rather than testing a prototype in the field.

Emitters are nozzles and/or sprinklers installed on a FSDS and their selection is one of the key points to achieve a homogeneous spray distribution via a FSDS. Indeed, being the system a fixed spray technology it does not move as conventional ground-based sprayers do. Moreover, since it is not equipped with any fan or blowing device, the FSDS is not air-assisted, thus making spray canopy penetration a challenge. Therefore, only by selecting the most suitable emitter type/s and their related position within canopies (constituting the FSDS layout), it is possible to directly act on, and thus improve, the spray canopy penetration and reach a homogenous spray coverage and deposition both vertically (from the top canopy area to the grape band one) and horizontally (along the row). In recent years different types of emitters were evaluated, considering both sprinklers used for irrigation purposes and agricultural nozzles conventionally used with ground-based sprayers (Sharda et al., 2015; Guler et al., 2020; Ranjan et al., 2021b). All the basic research conducted for emitters (Sharda et al., 2015; Guler et al., 2020; Ranjan et al., 2021b) focused on two major aspects that are deeply studied for conventional sprayer nozzles, as they directly affect the spray quality: the droplet size spectrum and the horizontal spray pattern (Grella et al., 2022b). The droplet size spectrum is important to evaluate the potential canopy coverages and drift potential (Grella et al., 2020), and further categorize emitters better define their suitability to apply PPP characterized by different modes of action (e.g., contact or systemic) considering that droplet size can play a strategic role for the final biological efficacy of treatment.

In the FSDS case, two are the paths that were followed, and still are, for the emitter selection to target a homogenous vertical spray coverage and deposition. From one side, since the FSDS is not air-assisted, emitters that produce fine spray droplets would be capable of better penetrating the crop canopy. Despite this, a fine droplet size would potentially enhance the drift phenomenon and/or off target depositions (Sinha et al., 2019; Imperatore et al., 2021; Ballion and Verpont, 2023). On the other side, emitters that produce bigger spray droplets would theoretically face difficulties in canopy penetration, thus resulting in an overall low homogenous vertical spray coverage and deposition. On the contrary, the spray generated by these emitters would be less subjected to drift phenomenon and the spray kinetic would potentially enhance leaf movement, and thus promote canopy spray penetration (Mozzanini et al., 2023).

Major concerns were referred also to the importance of distributing a homogeneous amount of PPP along the lines of the fixed spray system (Sawyer & Oswalt, 1983; Wilson, 1983; Threadgill, 1985). To this extent, studies focused on layout identification and thus, on emitters' horizontal spray pattern investigations. Briefly, once the spray pattern is characterized for one emitter, it can be defined the emitter spacing to be used in the field to homogeneously spray along the crop row avoiding PPP under- and over-applications. In this context, the emitter spacing and installation height above the ground for the FSDS are important such as the nozzle spacing and boom height in boom sprayers.

Apart from the emitter studies, back in those days, safety procedures were also improved. Key FSDS features were enhanced, including the adoption of an anti-siphon check-valve to prevent the backflow of the PPP into the water body, a shut-off valve and check-valve on the PPP feed line to prevent over-injection of the mixture into the main line and backflow into the feed line, and the use of corrosion-resistant components to prevent operator contamination and environmental issues (Figure 1; Sawyer & Oswalt, 1983; Wilson, 1983; Carpenter et al., 1985; Threadgill, 1985).

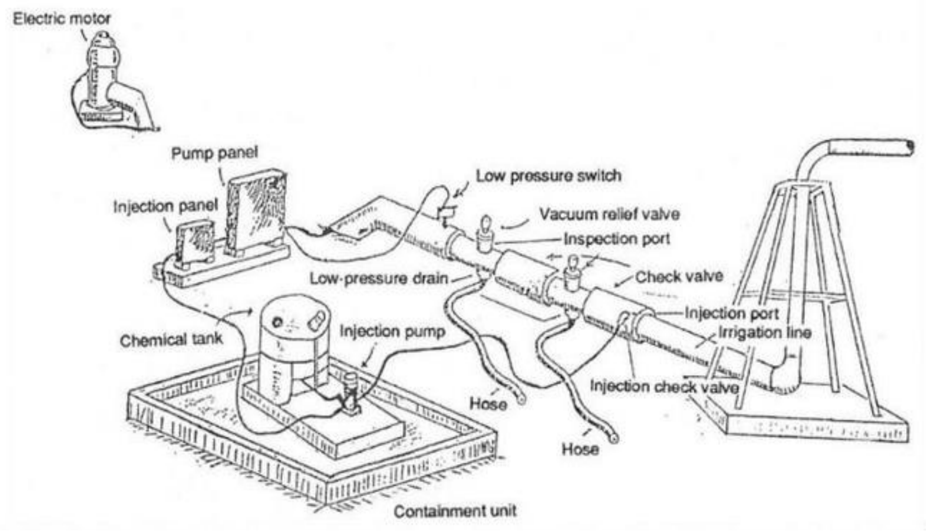

Figure 1. *Schematic representation (not drawn to scale) of a chemigation system and its main components to ensure the maintenance of the system, environmental safety, and prevent operator contamination (Source: https://extension.umn.edu/irrigation/chemigation-safety-measures).*

Along the years fixed spray systems to be used for perennial 3D crop spray application gained increasing interest. Since the 80s, fixed spray systems variants (*i.e.*, the FSDS) have been built and tested to explore PPP applications in apples (Carpenter et al., 1985; Agnello and Landers, 2006; Verpont et al., 2015; Niemann et al., 2016; Sinha et al., 2020; Ranjan et al., 2021a; Mozzanini et al., 2023b), cherries (Niemann et al., 2016), citrus (Chen et al., 2023), and grapes (Sinha et al., 2018; Sinha et al., 2019; Sinha et al., 2020; Mozzanini et al., 2023a, 2023b).

A milestone for FSDS was represented by the activity of Agnello and Landers (2006). The authors tested the biological efficacy of a hydraulic spray delivery-based FSDS (HSD-FSDS) (described at chapter "Modern FSDS types: HSD- and PSD-FSDS") in an apple orchard in 1998-99 seasons and, comparing the results with a conventional ground-based sprayer, they found no statistical difference in the performances of the two spray technologies. In that case, for the HSD-FSDS, the PPP was injected into the main line via a direct injection system and water was used as a propeller for the PPP delivery. Despite many modifications, the prototype was still not optimized enough to overcome the pressure drop issue along the line, the time activation delay of the emitters, and the big volumes of water consumption. To overcome the pressure-drop and the water consumption, Sinha et al (2019) at Washington State University, in collaboration with the Michigan State University, created a new type of FSDS: namely, the pneumatic spray delivery-based (PSD-FSDS). Reservoir units were introduced and installed along the line to hold a fixed amount of liquid (Figure 2a-b). To each reservoir unit, a fixed number of emitters were connected and installed into the canopy. Compressed air, used as a propeller instead of water, delivered the liquid from the reservoir into the crop canopy passing through the emitters. Therefore, the effect of pressure drop on the spray uniformity was minimized. Additional design optimization occurred on this FSDS type by optimizing the reservoir unit features in 2022 by Sahni and co-authors (Figure 2c-d). Such improvements were addressed to minimize the PPP leakage and reduce the reservoir dimension.

Concurrently further studies were carried out for the HSD-FSDS as well. To overcome the pressure drop along the line, Mozzanini and authors (2023a), thanks to previous activities conducted by Bondesan et al (2016) in apple orchards, identified and characterized a pressure-compensating irrigator (Figure 3) specifically designed to deliver water over long distances and according to a fixed flow rate irrespective of the operating pressure (as long as the pressure is kept between the range 0.25-0.40 MPa).

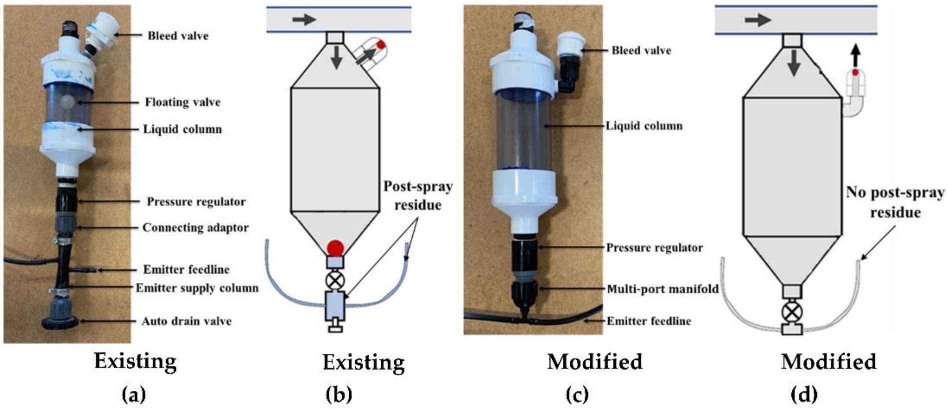

Figure 2. *Schematic and picture of the a-b) first reservoir type, and c-d) optimized one (Source: Sahni et al., 2022).*

Figure 3. *Schematic of the irrigator (i.e., HSD-FSDS emitter) identified and studied to overcome the pressure drop along the spray line for the HSD-FSDS (Source: Mozzanini et al., 2023a).*

Modern FSDS types: HSD- and PSD-FSDS

As mentioned in the previous section, the type of "propeller" used to deliver agrochemicals further categorizes the FSDS. In HSD-FSDS (Figure 4a) clean water, usually tap water (*i.e.*, through a water supply system), is used at low pressures with dual functions, to deliver the spray mixture and concurrently remove the spray mixture residues from the spray lines (Mozzanini et al., 2024a). In the HSD-FSDS reservoir units are not provided and the pressure drop issue is overcome by using a special kind of emitter equipped with a pressure-compensating component. The pressure-compensating component leads to uniformly deliver the spray mixture along the line (Mozzanini et al., 2023a).

Conversely, in the PSD-FSDS (Figure 4b) the air compressor component is included in the applicator unit, and compressed air is used in two separate steps. The first step is meant to deliver the spray mixture. The second removes spray mixture residues from the spray lines (Sahni et al., 2022). In this FSDS type, the spray delivery system is equipped, along the spray line, with small "tanks", called reservoir units, and emitters (installed to the reservoirs).

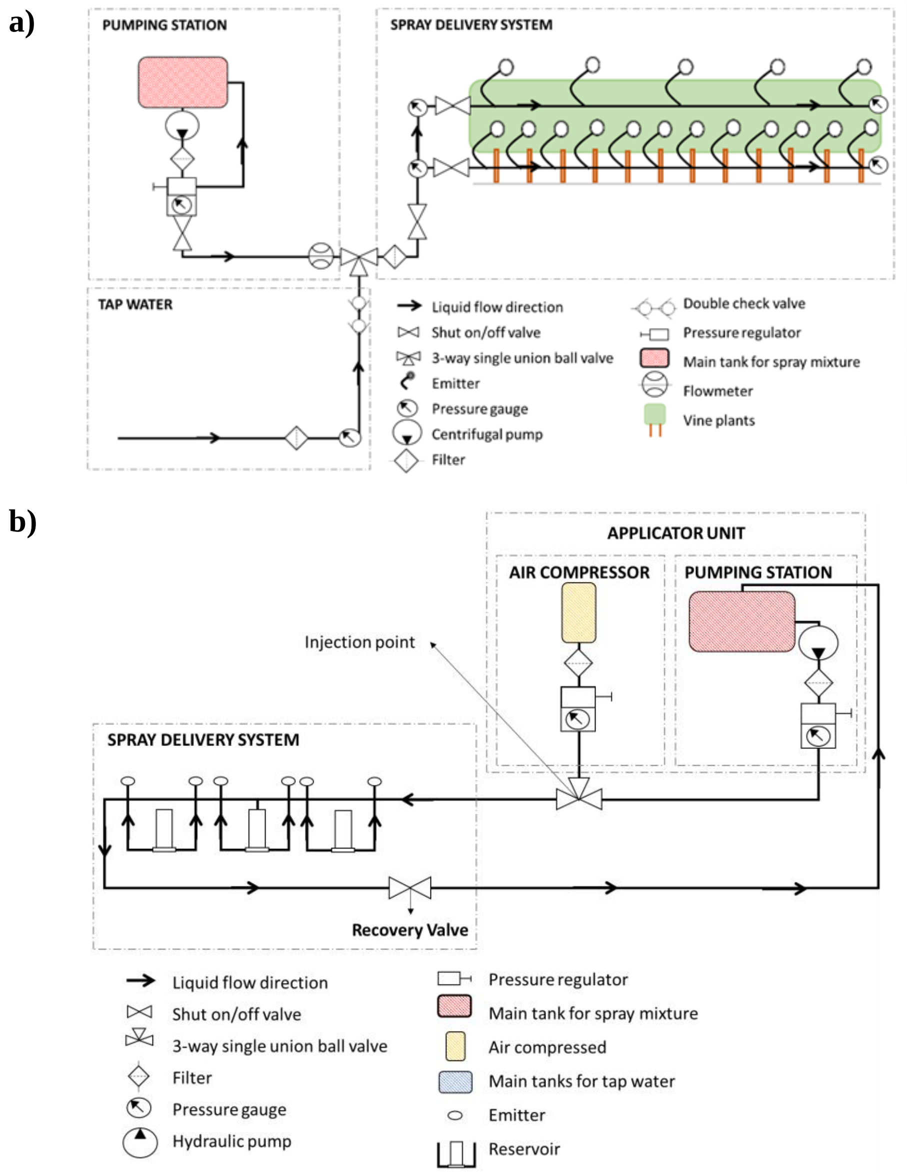

Figure 4. *Graphical representation of the main FSDS components of the a) hydraulic spray delivery (HSD; Source: Mozzanini et al., 2024a) and b) pneumatic spray delivery (PSD).*

FSDS spray mixture delivery stages

The spraying operation of the HSD-FSDS occurs in three steps: i) priming, ii) spray mixture injection, and iii) spraying/cleaning (Figure 4a; Figure 5) (Mozzanini et al., 2024a). During the priming step, the spray delivery system is pressurized at 0.30 MPa by feeding it with tap water from the supply system delivering pure water for 20 s (priming; Figure 5b). At this point, the water supply system is stopped, the second step begins and the crop canopy is sprayed at 0.30 MPa (spray mixture injection). A flowmeter automatically switches off the mixture injection as soon as the defined mixture volume (l), to match the target application rate (l ha^{-1}), is injected (Figure 5c). As the pumped spray mixture starts flowing in the main line, the emitters installed closer to the pumping station begin to deliver the mixture sooner than the emitters at a further distance. Next (spraying and cleaning step), the pumping system is stopped by turning the three-way valve, and clean water (from the water supply system) is allowed to flow again through the spray delivery system at 0.30 MPa (Figure 5d). Water pushes the spray mixture along the line and through the emitters until all spray mixture is delivered (Figure 5e and Figure 5f). At the end of this phase, water remains in the line (Figure 5a).

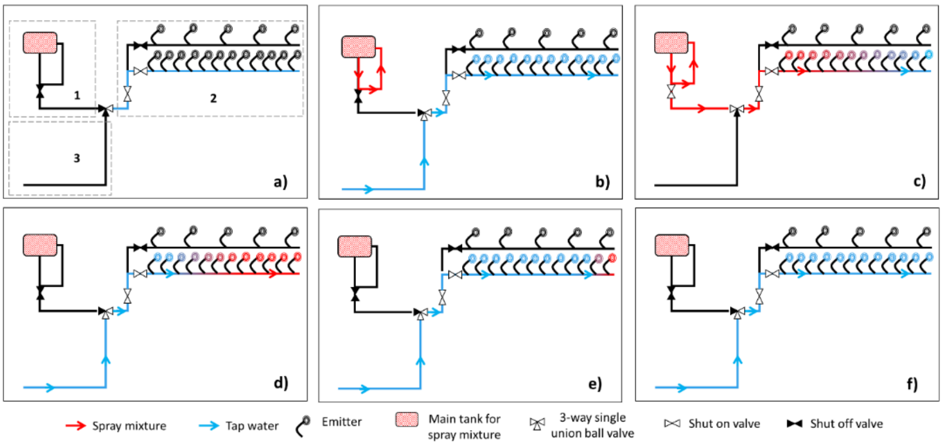

Figure 5. *Spraying operational steps of an HSD-FSDS (not drawn to scale). Schematic for the components a) are the pumping station (1), the spray delivery system (2), and the water supply system (3). At the beginning of the process, the spray delivery system is already filled with water from the cleaning step of the previous application. b) At the priming step, the system is pressurized at 0.30 MPa by filling with water. c) At the spray mixture injection step, from the pumping station a defined spray mixture rate into the mainline is injected. d) At the spraying/cleaning step, the pumping system is turned off and water is allowed to flow again through the spray delivery system. e) The tap water flow pushes the spray mixture along the line and through the emitters, f) until all spray mixture is delivered and only clean water remains in the system. Only spray delivery for the bottom spray line was colored in this diagram however the procedure is the same for both lines. (Source: Mozzanini et al., 2024a).*

The spraying operations of the PSD-FSDS follow four steps (Ranjan et al., 2019; Sinha et al., 2020, 2021), namely: i) filling, ii) recovery, iii) spraying, and iv) cleaning (Figure 4b; Figure 6). With the return line valve opened (Figure 6a), the spray delivery system is filled with spray mixture at an operating pressure of 0.10 MPa (filling). As soon as all the reservoir units are filled, the filling step is stopped. While a fixed volume of the spray mixture is stored in the in-line reservoir, the surplus in the spray delivery system is purged out and conveyed into the applicator unit tank, by running the compressed air at a low operating pressure of 0.10 MPa (recovery; Figure 6b). After the recovery step, the recovery valve is shut off, and compressed air at a higher pressure, equal to 0.31 MPa, is used to deliver the mixture from the reservoir units through the emitters (spraying; Figure 6c). The last step (cleaning; Figure 6d), is performed by running compressed air at 0.31 MPa per 30 s to purge out any mixture left in the reservoir units and emitters.

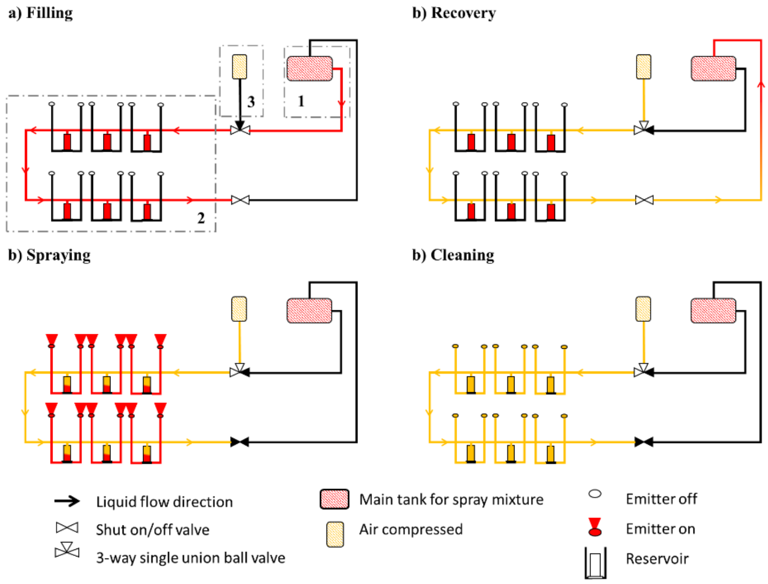

Figure 6. *Spraying operational steps of a PSD-FSDS (not drawn to scale). Schematic for the components a) are the pumping station (1), the spray delivery system (2), and the air compressor (3). The spray mixture is injected into the system at low-pressure air until the reservoir units are filled; b) the surplus mixture is pushed from the spray line into the main tank; c) the mixture is delivered through emitters increasing air pressure; d) high-pressure air purges droplets and residual mixture from the emitters.*

Cons and research gaps of the FSDS

Nowadays, among the FSDS types, the most developed and studied is the PSD-FSDS. Despite the engineering improvement of the PSD-FSDS, the use of the compressed air due to the high cost of the air compressor unit, and the reservoirs' dimensions and location in the field (installed close to the ground level and for that reason damageable by under-row operations), result to be the major limits to the commercial diffusion of the solution.

Even if, as proposed by other authors, (Ballion and Verpont, 2023) the reservoirs were installed overhead, the equipment cost would still be the main limitation for this spraying technology since, to reach specific volume rates, it would be necessary to install specifically designed reservoirs (*i.e.*, reservoir size is directly related to the amount of PPP contained and thus distributed).

For this reason, being an easier solution with respect to the PSD-FSDS, it was decided to focus on the HSD-FSDS. However, the issues that previous researchers faced in HSD-FSDS needed to be investigated and solved. The pressure drop is the major issue connected to the HSD-FSDS, thus a similar solution to the reservoir must be evaluated and adapted for this case as well. This tool/modification/component must also help in overcoming the emitter activation delay along the row. A solution to this could be to survey sprinklers (since are already designed to deliver water over long distances), characterize them and evaluate their performances both at the laboratory and field level. Once the promising emitters are defined, the overall HSD-FSDS layout can be proposed and installed. Only after this step, by evaluating the horizontal spray distribution of the HSD-FSDS, it would be ascertained that with this technology it is possible to evenly distribute PPPs along the row. At the same time, the internal cleaning performance must be evaluated to check the technology performances with respect to the conventional ground-based sprayers.

Once the previous aspects are defined, solutions to reduce the volume of water used while performing a spray application, the season-long biological efficacy of the identified layout, additional environmental aspects such as drift, the bystander and operator contamination still need to be evaluated.

Nowadays, the environment preservation and operator safety are becoming more and more important. A common methodology to check and certify that a FSDS is working properly and/or if it is finely adjusted, needs to be elaborated. Therefore, as done for conventional sprayers that are inspected periodically to ascertain their performances, the ISO standards referred to fixed and semi-mobile sprayers, such as ISO 16119-4 (ISO, 2014) and ISO 16122-4 (2015b), can be used as a baseline to develop an *ad hoc* EU inspection methodology for FSDSs due to their similarities to this novel technology. Such standards must be modified according to the FSDS equipment and working parameters.

Aim and thesis structure

This thesis aims to increase the knowledge on HSD-FSDS and provide aspects to consider when studying and installing this type of FSDS with regard to espalier-trained vineyards.

The thesis is divided into six chapters, one per each research gap that needed to be closed and further investigated. Each chapter corresponds to a paper published either in peer-reviewed journals or presented at international conferences. Chapter I focuses on HSD-FSDS emitter identification and characterization in laboratory conditions (Mozzanini et al., 2023a). This activity was performed according to *ad hoc* methodologies based on what is reported in EN ISO 5682-1 (ISO, 2017). In Chapter II, the best-performing emitter, in terms of horizontal spray pattern and droplet size spectrum (StripNet mod. STR31 2AN by Netafim Ltd. Company) among those characterized in the laboratory, was tested to measure the potential spray coverage of a single emitter in apple orchard and vineyard. Comparisons with modern spray drift reducing technologies (SDRT) were performed (Mozzanini et al 2023b). Chapter III focuses on a prototype of a HSD-FSDS, installed according to the outcomes presented in Chapter I (Mozzanini et al., 2023a), that was evaluated for its suitability to be adopted as pesticide application technology. Specific trials were performed to assess the homogeneity distribution among emitters installed along a row and the internal cleaning performances in accordance with EN ISO 22368-1 (ISO, 2004). Also, compliance with EN ISO 16119-4 (ISO, 2014) cleaning performance threshold was evaluated (Mozzanini et al., 2024a). In Chapter IV, since possible solutions for an effective internal cleaning performance for PSD-FSDS were never investigated, a modern

PSD-FSDS optimized for vertical shoot position-trained vineyards (Bhalekar et al., 2024) was tested at the Irrigated Agriculture Research and Extension Center (IAREC) of the Washington State University located in Prosses (WA, USA). The trial, similarly to what it was done while studying the HSD-FSDS (Mozzanini et al., 2024a), was performed in accordance with EN ISO 22368-1 (ISO, 2004) to evaluate compliance with EN ISO 16119-4 (ISO, 2014) cleaning performance threshold.

As FSDS is gaining interest and started spreading in the Trentino region apple orchards (North-East Italy), and no specific regulation is nowadays available to perform the functional inspection of FSDS, in chapter V a first methodology was proposed to cover this gap. When possible, the harmonized standard EN ISO 16122:2015 for general (part 1; ISO, 2015a) and specific (part 4; ISO, 2015b) components were followed (Mozzanini et al., 2023c).

In the last Chapter (VI), following the ISO 22522:2007 (ISO, 2007) standardized methodology, four HSD-FSDS layouts, results of the studies conducted on emitter characterization (Chapter I; Mozzanini et al., 2023a), were evaluated for their ground losses and canopy deposition (Mozzanini et al., 2024b).

Chapter I "Characterization of irrigator emitter to be used as Solid Set Canopy Delivery System: which is best for which role in the vineyard?"

Paper published in a peer-reviewed international journal:

Mozzanini E., Grella M., Marucco P., Balsari P., Gioelli F. (2023a) Characterization of Irrigator Emitter to Be Used as Solid Set Canopy Delivery System: Which Is Best for Which Role in the Vineyard? Pest Management Science, 79:584–97. https://onlinelibrary.wiley.com/doi/abs/10.1002/ps.7228

The paper presents the characterization of three irrigators, commonly used in vineyards/apple orchards for anti-frost and irrigation purposes, and already used as FSDS emitters in apple orchards, for their suitability to be used as FSDS emitters to deliver agrochemicals in a Guyot-trained vineyard. First, flow rate variability, horizontal spray pattern, and droplet size spectra were measured in the laboratory to identify the best configuration of each emitter to be further tested in the field. Second, potential canopy spray coverage and potential ground losses were measured for each emitter type in the field. The field-test dataset of emitter positions inside vine canopies and their relative distance and density along vine rows were then used to determine a possible FSDS emitter network configuration (*i.e.*, FSDS layout) that would provide maximum homogenous spray coverage in the field.

Chapter II "Preliminary evaluation of irrigator emitters for pesticides application trough solid set canopy delivering system in apple orchard and vineyard"

Paper published in an Scopus indexed international journal:

Mozzanini E, Grella M, Bondesan D, Marucco P, Rizzi C, Ioriatti C, Balsari P, Gioelli F. (2023b) Preliminary Evaluation of Irrigator Emitters for Pesticides Application through Solid Set Canopy Delivering System in Apple Orchard and Vineyard. Angers (FR): ISHS Acta Horticulturae. 13778:227-236. https://doi.org/10.17660/ActaHortic.2023.1378.30

The paper presents the results of the evaluation of StripNet emitter (mod. STR31 2AN) conducted in trellised apple orchards (semi-pedestrian-trained) and vineyards (Guyot-trained). Emitter performance was compared with those of conventional sprayers equipped with SDRT. Higher homogeneity in spray coverage was observed for the apple orchard case. In vineyards, the top canopy area had high spray coverage, but lower values were registered in the medium and lower canopy parts (grape band area), affecting overall uniformity. While StripNet mod. STR31 2AN proved feasible for PPP application in apple orchards, further research is needed for vineyards to determine the emitter type and position ensuring uniform deposition along the canopy structure.

Chapter III "Hydraulic-Based Fixed Spray Delivery System: Homogeneity Distribution among Emitters and Internal Cleaning Performances Evaluation"

Paper published in a peer-reviewed international journal:

Mozzanini E, Grella M, Marucco P, Hoheisel G-A, Biglia A, Balsari P, Gioelli F. (2024a) Hydraulic-Based Fixed Spray Delivery System: Homogeneity Distribution among Emitters and Internal Cleaning Performances Evaluation. Crop Protection, 175:106440. https://doi.org/10.1016/j.cropro.2023.106440

The paper presents the trials carried out on a HSD-FSDS prototype, built according to the Mozzanini et al. (2023a) outcomes, to consider its use for plant protection product application. To evaluate the system's behavior, field trials were conducted comparing two FSDS emitter installation densities (high and low). A water solution of Tartrazine (E102 – yellow dye tracer) was used as a spray mixture. The delivered spray mixture concentration over time and the homogeneity distribution among emitters were measured. Also, the internal cleaning performance compliance to EN ISO 16119-4 (ISO, 2014) threshold was assessed by using a water solution of copper oxychloride as a spray mixture. To this extent, the EN ISO 22368-1 (ISO, 2004) was followed (when possible). Water was demonstrated to be able to effectively clean the system regardless of emitter density. Optimal cleaning times were also identified. Finally, two linear regression models were developed to estimate water consumption and cleaning timing based on the fixed spray system's flow rate.

Chapter IV "Cleaning performance evaluation of pneumatic spray delivery based solid set canopy delivery system"

Paper published in a peer-reviewed international journal:

Mozzanini E., Bhalekar D.G., Grella M., Hoheisel G.-A., Samy S., Balsari P., Gioelli F., Khot L.R. Cleaning performance evaluation of pneumatic spray delivery based solid set canopy delivery system. Journal of the ASABE. (*Accepted for publication* on 26th April 2024) - https://doi.org/10.13031/ja.15944

The paper presents the internal cleaning performance of a pneumatic spray delivery-based Solid Set Canopy Delivery System (PSD-SSCDS). Given the critical importance of proper equipment cleaning for environmental and operator safety, laboratory, and field tests, based on EN ISO22368-1 standard (ISO, 2004), were performed. The Pyranine (Pyranine 10G biodegradable fluorescent tracer) residue measurements in SSCDS components after application were used for evaluation. The manuscript outlines a series of laboratory trials with five cleaning techniques, including air injection and water rinse, tested on various PSD-SSCDS components. The most effective technique (water rinse) was then field-tested in a large-scale grapevine layout. Results indicated that a triple water rinse achieved a cleaning performance exceeding 99.67%, meeting the ISO16119-4 standard (ISO, 2014). Considerations for incorporating new components, managing remnants, and determining the timing of water rinses are also presented.

Chapter V "Proposal of a methodology for the functional inspection of a fixed spray delivery system"

A paper is under publication in the Proceedings of an international Conference:

Mozzanini E., Balsari P., Grella M., Marucco P., Gioelli F. (2023c) Proposal of a methodology for the functional inspection of a fixed spray delivery system. Standardised Procedure for the Inspection of Sprayers in Europe (SPISE). 2-4 May 2023, Naaldwijk, NL. https://spise.julius-kuehn.de/index.php?menuid=xxmenuidxx&downloadid=289&reporeid=xxreporeidxx – https://wissen.julius-kuehn.de/spise/en/spise-workshops

The paper presents a first set of technical indications about the steps to be followed for carrying out a functional inspection of FSDS. Indeed, as the FSDS is a pesticide application technology, it shall comply with the EU Directive on the Sustainable Use of Pesticides (2009/128/EC), article 8, and shall be subjected to a periodical mandatory functionality inspection. To date, no specific regulations are available for this technology. Since Italian Trentino region apple orchard farmers already started to install FSDS in their orchards, as already done with the conventional pesticide application technologies, it is of primary importance to provide specific regulations and requirements also for this technology. Trying to cover this gap, when possible, the harmonized standard EN ISO 16122 for general (part 1; ISO, 2015a) and specific (part 4; ISO 2015b) components were followed. The paper also reports the FSDS components that deserve to be subjected to functional inspection such as the required functional limits for the different components and the methods to carry out their inspection.

Chapter VI "Quantifying canopy deposition and ground losses of fixed spray delivery system layouts for trellised vineyards"

A paper has been published in the Proceedings of an international Conference:

Mozzanini E., Grella M., Marucco P., Balsari P., Gioelli F. (2024b) Quantifying canopy deposition and ground losses of fixed spray delivery system layouts for trellised vineyards. International Advances in Pesticide Application (AAB-IAPA). 23-25 January 2024, Brighton, UK. https://web.cvent.com/event/4f6543ca-334e-43d6-8a62-dcfa7a55d055/summary

The paper presents the first field study conducted in a Guyot-trained vineyard with a HSD-FSDS. The spray performances of four HSD-FSDS layouts, obtained by combining three emitter types and a different number of emitters along the row and following the outcomes presented in Chapter I (Mozzanini et al., 2023a), were evaluated and compared using Tartrazine (E102 – yellow dye tracer) dissolved in water as a spray mixture. Spray deposition and ground losses were assessed by sampling vine leaves and by placing Petri dishes on the ground, respectively. Samples were then analyzed using spectrophotometry. The dataset analysis showed a statistically significant effect of layout on mean deposition and ground losses. In general, layouts with a higher emitter density should promote depositions, but in the HSD-FSDS, resulted in lower canopy deposits. The emitter density and layout resulted in being the key factors affecting the spray performance of the HSD-FSDS.

Chapter I

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

1. 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 3-D crops (vineyards and orchards).

Generally, spray application improvements have come from two research paths. One path tailor 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 labor costs[14,15] and operator risk[16].

Delivering PPPs in commercial orchards and vineyards via a Solid Set Canopy Delivery System (SSCDS) represents a sustainability-promoting modern version of fixed spray methods. 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] and off-field drift control[22,23]. However, until now, only a 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. While 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 due to the varieties) and plant training systems (trellised-, pergola-, or tendone-trained vineyards). To this end, this study has five objectives: i) evaluate the flow rate variability of three emitters/irrigators, ii) investigate their spray patterns, iii) measure and characterize the droplet size spectra generated by the emitters in the laboratory, and iv) evaluate the potential canopy spray coverage in field tests in a Guyot-trained trellised vineyard.

2. 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 were then used to determine the emitter network configuration that would provide maximum homogenous spray coverage in a trellised vineyard.

2.1 Emitter components and functioning

The emitters used in this study had two components—a Pulsar™ system (Netafim Ltd. Company, Derech Hashalom 10, Tel Aviv, Israel 67892) and a nozzle mounted atop the system. Several sub-components comprise the Pulsar™ system: i) a fuchsia-coloured pressure compensating dripper (colour not referred to ISO 10625:2018[29]) (Figure 1a) installed on the main hose feeding the emitter, ii) a micro-tube (Figure 1b) connecting the pressure compensating dripper to iii) the Pulsar™ tube (Figure 1c) 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 (Figure 1**Errore. L'origine riferimento non è stata**

trovata.d). Nozzles are installed downstream of the Pulsar™ system (Figure 1e).

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 as 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. Company) 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.

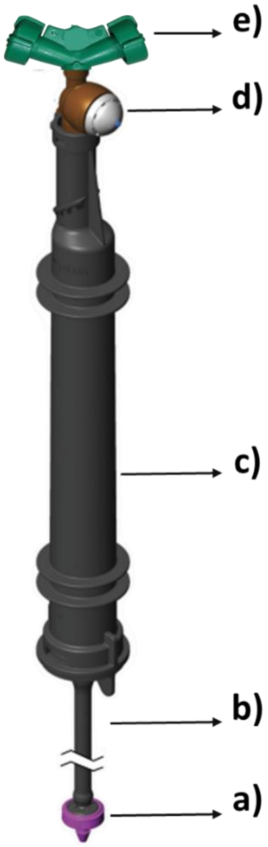


Figure 1. Schematic of the emitter used in the experiment by assembling PulsarTM system and nozzle. The PulsarTM system has several pieces: a) pressure compensating dripper, b) micro-tube connecting the compensating dripper to the c) Pulsar™ tube with an internal airbag that acts like a pressure compensator,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

2.2 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™ mod.STR31 1AN), double-sided flat fan (StripNet™ mod. STR31 2AN), and circular (VibroNet SD™ mod.50) nozzle (Netafim Ltd. Company).

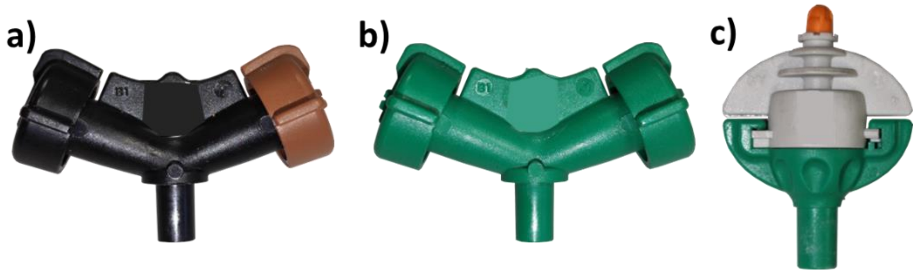


Figure 2. Nozzles combined with the PulsarTM system determines the different emitter systems tested: a) single-sided flat fan (StripNet™ mod.STR31), b) double-sided flat fan (StripNet™ mod. STR31 AN), c) circular (VibroNet SD™ mod.50) nozzles.

2.2.1 Flow rate measurements

The flow rates of the three "emitter systems" (Pulsar™ system + nozzle) were determined using ISO:5682 (2017) standardized 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.) for moving the liquid through the main hose, a manual pressure regulator (GR 30 - Cod. 879 - Annovi Reverberi S.p.a., Modena, Italy) installed upstream of the main hose for adjusting the pressure of the liquid, and a pressure gauge (WIKA Alexander Wiegand SE & Co. KG, 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, Germany) was collected using a plastic cylinder. The total amount of liquid was measured using an electronic analytical balance (precision level of 0.01g - BCE4200 - Orma S.r.l., 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 IBM SPSS Statistic (Version 28) predictive software for Windows™. Data were tested for normality using the Shapiro-Wilk test. Residual analyses were also 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 ($p < 0.05$).

2.2.2 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) (Figure 3). Petri dishes were individually weighted with an analytical balance (mod. 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 above the ground at 0.30 m from the first Petri dish row (1L) (Figure 3). The five circular emitters were positioned parallel and 1.10 m above the ground over the Petri dishes (11P) (Figure 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.

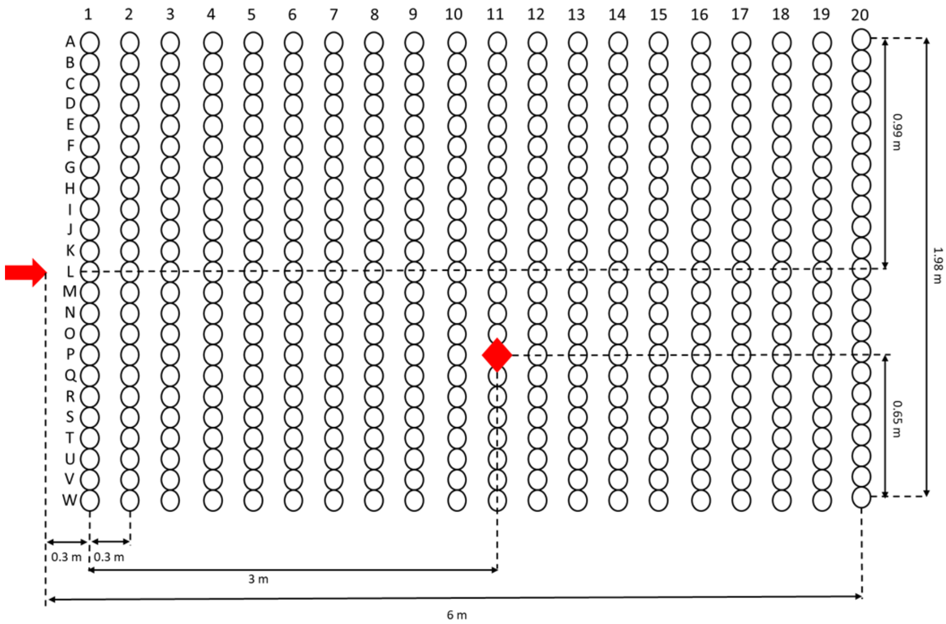


Figure 3. Spray patternator design used for emitter horizontal spray pattern investigation using plastic Petri dishes covering a total ground area of 11.88 m2. Red arrow indicates the location and the spray jet direction considered for the sampling of both single- and double-sided emitter systems. Red squares indicate circular emitter system location.

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 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 was then used to define the position of different systems inside the vine canopies and their relative distances along the row.

2.2.3 Droplet size spectrum

The droplet size spectra were characterized using a Malvern Spraytec™ laser diffraction system (mod. STP5342, Malvern Instruments Ltd., Worcestershire, UK) as others 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 the spray streamed perpendicular to the laser beam, with the nozzle orifice placed at 0.50 m from the beam. Prior to 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 11003) at 0.30 MPa. Emitters were always connected to the portable pumping station set at 0.30 MPa pressure (see § 2.2.1). Three replicates per each emitter system type resulting in a total of 45 measurements. The measurements were carried out at 1 kHz and at least 10,000 droplets were recorded per each trial. Room temperature and relative humidity (RH, %) conditions were monitored with a thermo-hygrometer (mod. Testo 625, Testo Spa, 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 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 Eq. 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 smaller than 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].

2.3 Field trials: experimental design

2.3.1 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 (Figure 4a). 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 (Figure 4b).

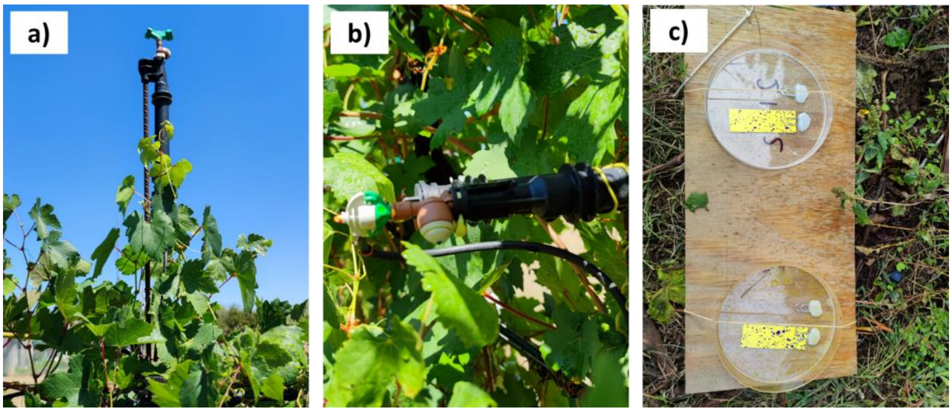


Figure 4. Examples of in-field collocations: a) double-sided flat fan, b) circular emitter systems, and c) water sensitive paper (WSP) used for ground loss (GL, %) investigation.

2.3.2 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* 'Barbera'). As has been done for other 3-D 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 above the ground. 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"[43] growth 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 relative humidity ranged between 35.0 and 78.1 %. All trials were conducted in "light air" conditions[44]; *i.e.*, the wind speed averaged < 1.5 m s^{-1}, which is an optimal condition for spray application as defined by TOPPS BMPs[45]. Detailed weather data recorded during field trials are shown in Table 1.

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).

configuration	Emitter	Temperature [°C]		RH [%]		Wind speed [m s^{-1}]			Wind direction [azimuth]	
		Mean	∆ h1-h2	Mean	∆ h1-h2	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

Emitter configuration	Emitter	Temperature [°C]		RH [%]		Wind speed [m s^{-1}]			Wind direction [azimuth]	
		Mean	**∆ h1-h2**	**Mean**	**∆ h1-h2**	**Min**	**Max**	**Mean**	**Dominant**	**Mean [°]**
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

Emitter configuration	Emitter	Temperature [°C]		RH [%]		Wind speed [m s^{-1}]			Wind direction [azimuth]	
		Mean	∆ h1-h2	Mean	∆ h1-h2	Min	Max	Mean	Dominant	Mean [°]
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

2.3.3 Experimental layout and spraying parameters

A six-meter 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 (Figure 5a) 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) (Figure 5b). 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 one minute to provide the test quantity of pure water using the single-sided emitter system; two minutes 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 of pure water. Side spray to a row from a circular emitter system can affect spray coverage and ground losses according to its positioning above the ground and depth in the canopy. Therefore, the circular 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 (Figure 5b). Both the laboratory and field trials utilized the same portable pumping station to feed the emitter systems (0.30 MPa pressure, § 2.2.1). Three test replicates per each emitter system were performed for 18 total measurements.

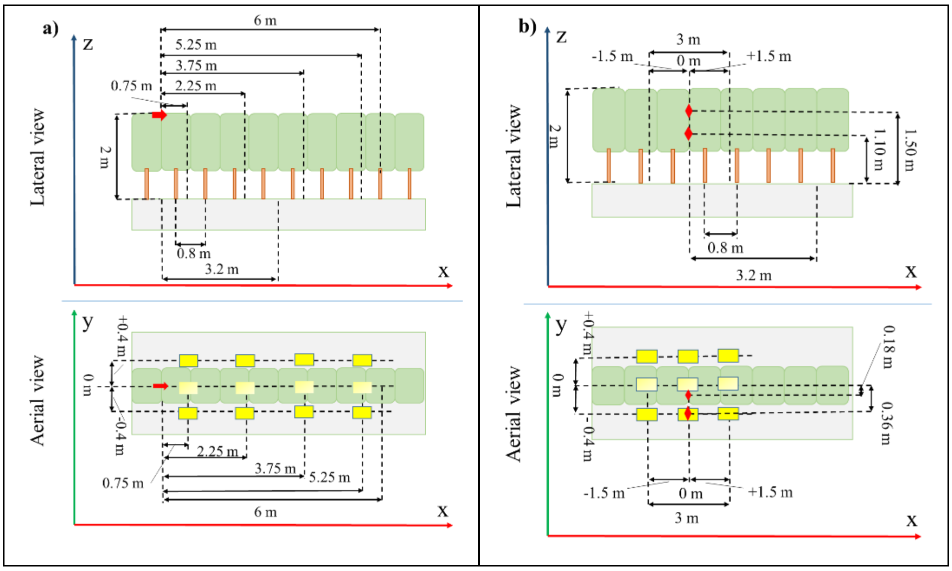


Figure 5. Schematic of emitters positions and sampling distances used for spray coverage evaluation (SC, %) for the a) single- and double-sided flat fan (0.75, 2.25, 3.75, 5.25 m) and for the b) circular emitter systems (-1.50, 0, 1.50 m). The circular system was tested at two different aboveground heights (1.10, 1.50 m) and at two different row midpoint distances (0.18, 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 square indicates 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, 0, +0.40 m). Yellow rectangles indicate the locations of the GL samplers.

2.3.4 Experimental layout and spraying parameters

To measure the canopy spray coverage (SC, %) of a single emitter system relative to its row and canopy position (§ 2.3.3), water-sensitive papers (WSPs) (76 mm x 26 mm - Syngenta Crop Protection AG, Basel, Switzerland) were placed at different canopy heights and depths at each sampling distance (§ 2.3.3). 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 were also evaluated using WSPs (76 mm × 26 mm - Syngenta Crop Protection AG). Petri dishes of 140 mm in diameter (APTACA S.p.a., Canelli, Italy), modified with glued clips to hold one WSP each, were placed on the ground (**Errore. L'origine riferimento non è stata trovata.**Figure 4c). 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.

2.3.5 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, California, USA) scanned the WSPs and obtained 600-dpi resolution images. Image processing software (ImageJ, version 1.52n, Wayne Rasband, National Institutes of Health, Bethesda, MD, USA) converted the image to grayscale 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 82-97 %).

2.3.6 Statistical analysis

Statistical analyses were performed using IBM SPSS Statistic (Version 28) 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 were also 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 m, 2.25 m, 3.75 m, 5.25 m), emitter type (single-, double-sided flat fan), and sampling height above the ground (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 m, 2.25 m, 3.75 m, 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 ($p < 0.05$).

3. RESULTS AND DISCUSSION

3.1 Laboratory trials

3.1.1 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 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 (Figure 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 over-application can occur when the emitter system feeder hose exceeds a pressure 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.

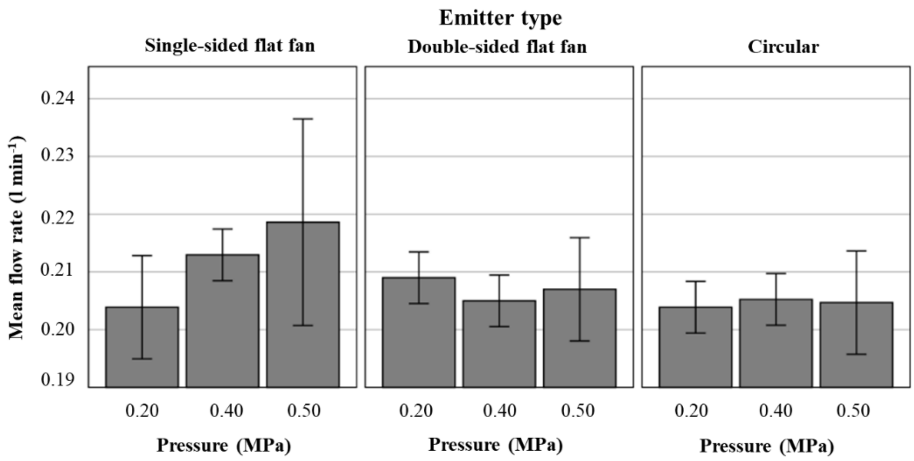


Figure 6. Mean flow rate (l min^{-1}) measured three liquid pipeline pressures (0.20, 0.40, and 0.50 MPa) for the five set-ups selected for each single- and double-sided flat fan and circular emitters. Bars show emitter mean flow rate ± standard error of the mean.

3.1.2 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 (§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 produced long-range jets (4.50 m for single-sided and 3.60 m for double-sided) (Figure 7a, 7b) of low amplitude (1.08 for single-sided and 1.26 m for double-sided) as viewed from above (Figure 8a, 8b). 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 (Figure 7c, 8c).

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 (Figure 7a), while two peaks are noticed at 1.50 and 3.00 m from the spray source for the double-sided system (Figure 7b). The CV value between the two peaks of the double-sided flat fan system (CV = 7.41%) showed 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.

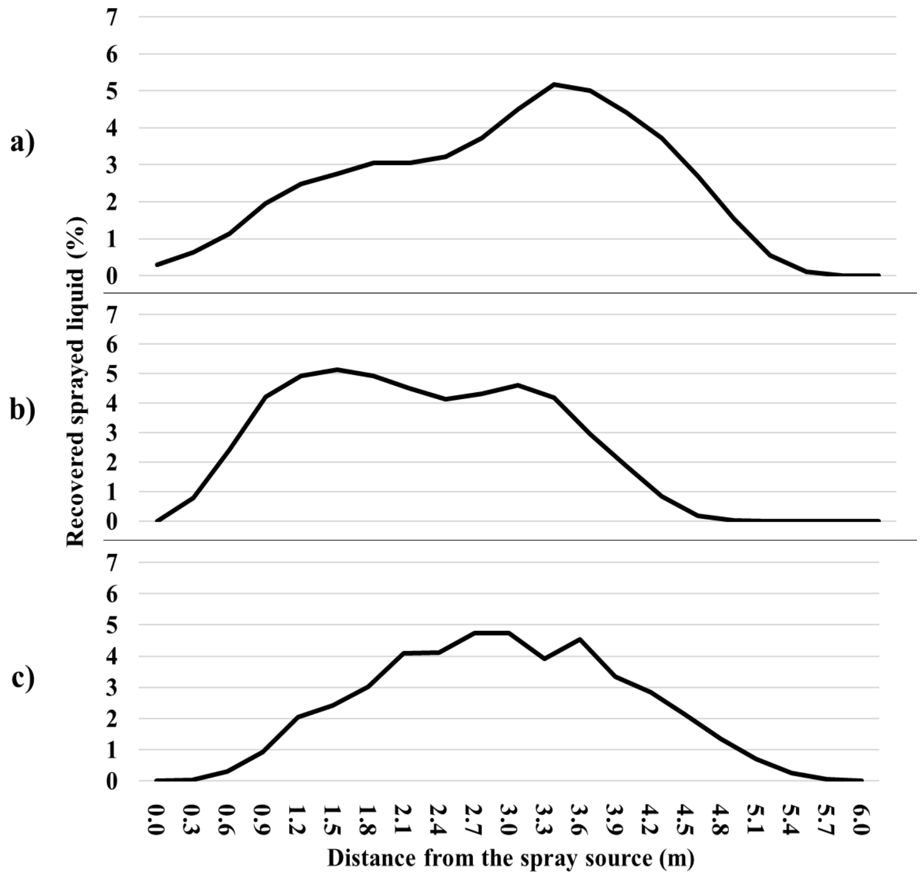


Figure 7. Lateral view of horizontal spray pattern profiles described by the amount of spray liquid (%) recovered at different distances (m) from the spray source for a) single-sided flat fan (spray source at 0 m), b) double-sided flat fan (spray source at 0 m), and c) circular emitter systems (spray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

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. While 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 (Figure 7b), when they were combined with a circular emitter, they raised the level of coverage in under-sprayed 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 is also 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 (Figure 9a). 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 (Figure 9c) resulted in a CV = 6.3 % and total average spray volume = 4.6 %.

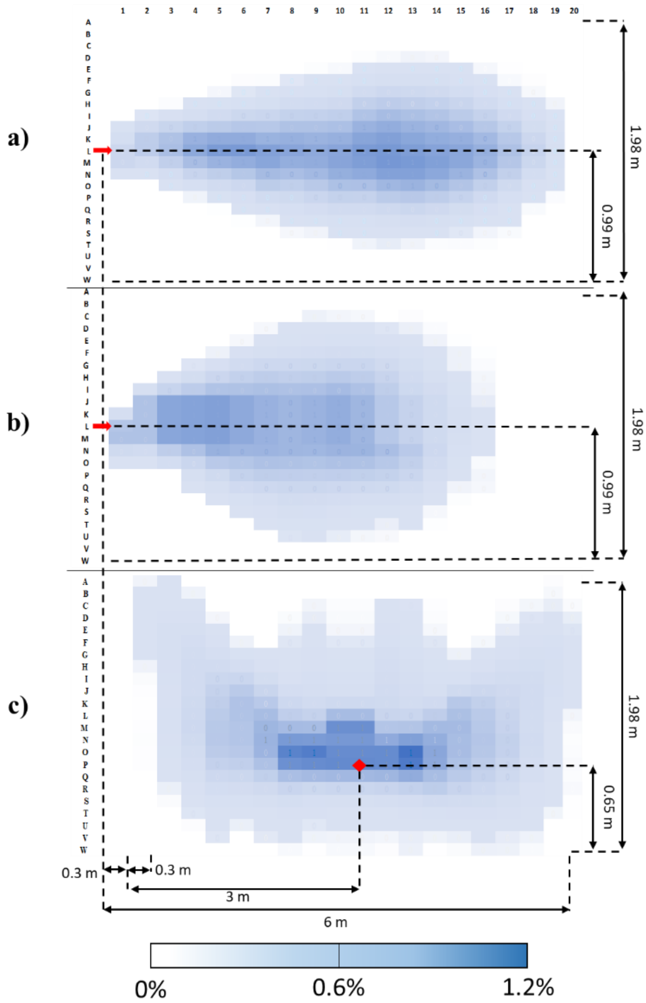


Figure 8. Aerial view of horizontal spray pattern profiles described by the amount of spray liquid (%) recovered at different sampling points (m) from the spray source for a) single-sided flat fan emitter, b) double-sided flat fan emitter, and c) circular emitter. Red arrows indicate the location and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

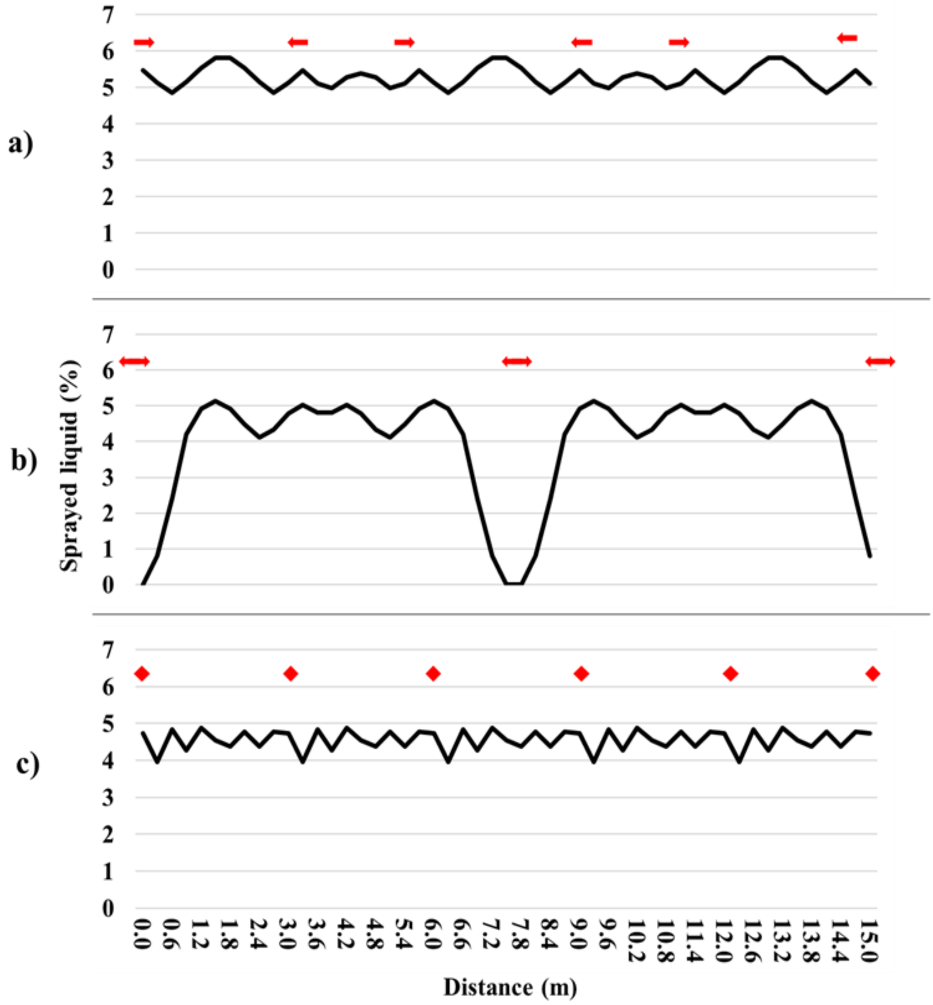


Figure 9. Spray distribution achieved with the horizontal spray pattern of single emitter systems (per each type). The graphs were built from variation in the spacing of emitters to the target area: a) single-sided flat fan, b) double-sided flat fan, and c) circular emitters. Red single arrows indicate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

3.1.3 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 (Figure 10) moved between the 'coarse' and 'extra coarse' spray quality thresholds according to the ASABE classification[39]. On the contrary, 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 ± 40.6 µm, $D_{V0.1}$ = 138.1 ± 7.3 µm and $D_{V0.9}$ = 416.8 ± 52.5 µm, while the double-sided flat fan emitter system had a VMD = 453.1 ± 37.9 µm, $D_{V0.1}$ = 193.8 ± 20.8 µm and $D_{V0.9}$ = 879.8 ± 42.5 µm. The circular emitter system produced a VMD = 338.1 ± 6.8 µm, $D_{V0.1}$ = 121.7 ± 2.2 µm and $D_{V0.9}$ = 1005.6 ± 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]. On the contrary, 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.

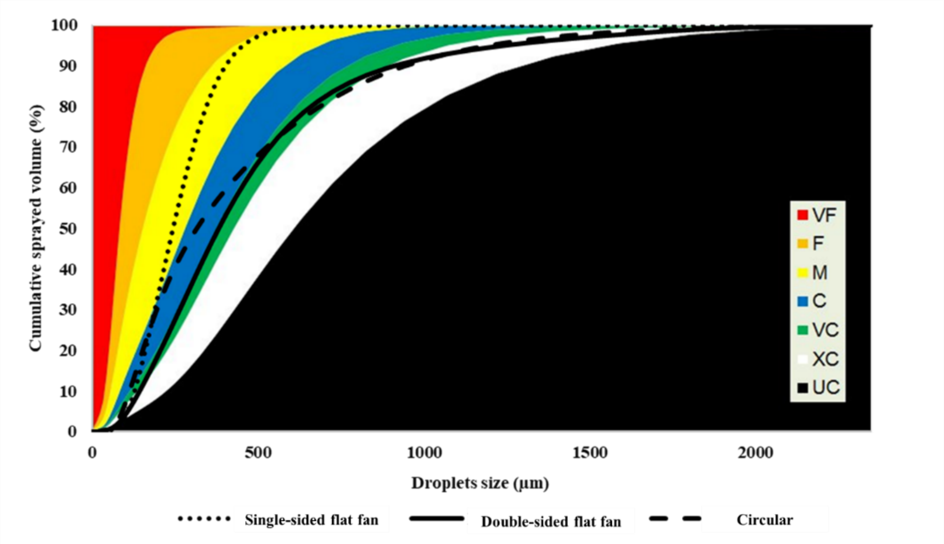


Figure 10. Cumulate sprayed volume (%) curves as a function of droplet size (µm) per each emitter system type. VF, very fine; F, fine; M, medium; C, coarse; VC, very coarse; XC, extremely coarse; UC, ultra-coarse/unclassified; (ASABE S572.1).

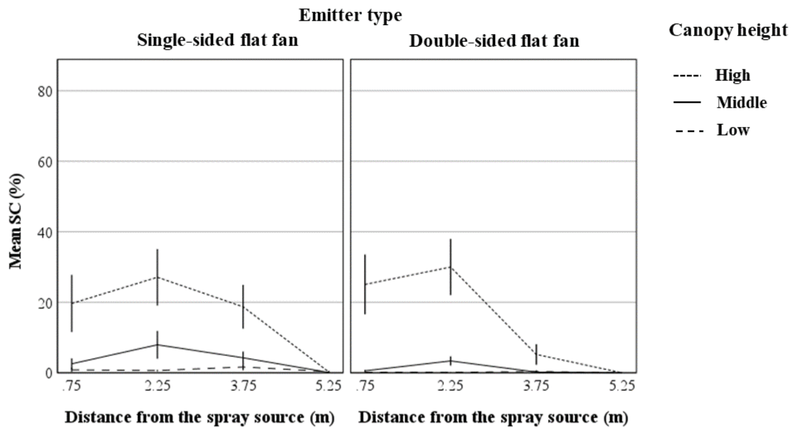
3.2 Field trials

3.2.1 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 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 (Figure 11a) 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 ground loss (GL, %) investigation. As Figure 11 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 (Figure 11b). 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 (Figure 11).

a)



b)

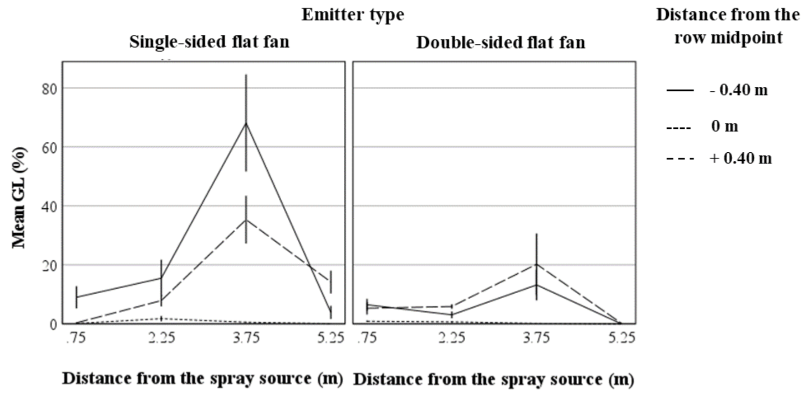


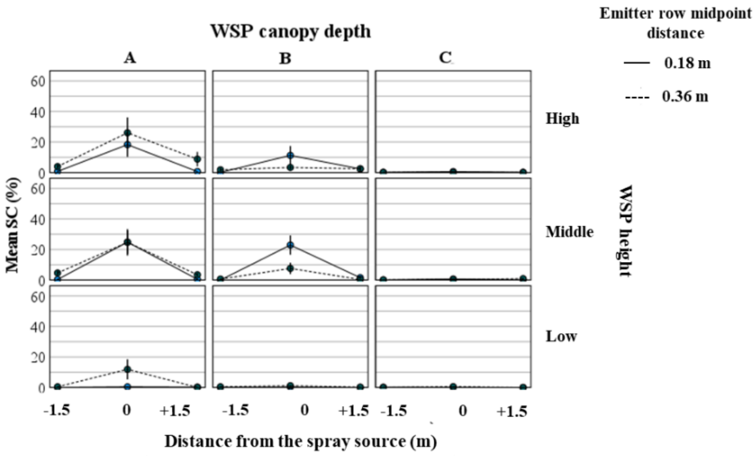
Figure 11. Single- and double-sided flat fan emitter field test results. The following measures were taken for each sampling distance from the spray source: a) mean spray coverage (SC, %) evaluated at three canopy heights (low, middle, and high) above the ground and b) mean ground losses (GL, %) evaluated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

3.2.2 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 (Figure 12). Emitter row midpoint distance did not influence SC significantly, but differences occurred in GL (Figure 12). SC in the canopy top zone was 42 % less than SC in the middle and low canopy zones (Figure 12a). 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 (Figure 12a) needs to be added as previous studies have found in vineyard[53].

As Figure 12b shows, GL originate 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.

a)



b)

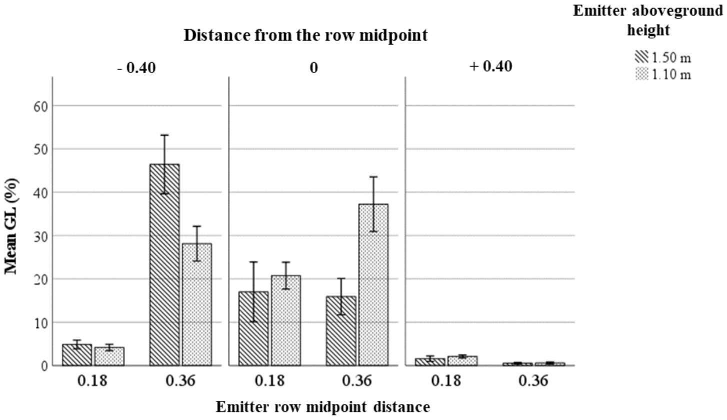


Figure 12. Circular emitter field test results. The following measures were taken for each sampling distance from the spray source: a) mean spray coverage (SC, %) evaluated at three canopy heights (low, middle, and high) above the ground, and three canopy depths (A, canopy test side; B, internal canopy; 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).

3.2.3 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 about 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. While single- and double-sided flat fan reached the same SC, double-sided emitter system achieved lower GL values. Moreover, a combination of double-sided flat fan and circular emitter (see § 3.1.2) are potentially 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 1,040 (circular) emitters per hectare in a typical 2.5 m inter-row vineyard layout.

Circular emitters installed parallel to the ground (1.5 m aboveground 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. Due 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 no more than 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 8,000 emitters per hectare in a typical vineyard layout.

4. 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 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, etc.). Furthermore, 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 the 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.

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.

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Chapter II

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Preliminary evaluation of irrigator emitters for pesticides application trough solid set canopy delivering system in apple orchard and vineyard

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Abstract

Recently, valuable alternatives to conventional pesticide application equipment are under investigation in 3D crops for improving pesticide spray application efficiency. Customized solid set canopy delivery systems (SSCDSs), tested in apple orchard and vineyard showed potential to reduce plant protection products (PPPs) spray drift while guaranteeing adequate spray deposition on the target and biological efficacy. Based on these premises, this study evaluated the feasibility to use a flat fan pulsed emitter (StripNet® – Netafim), usually installed in orchard and vineyard for irrigation and frost/heat-stress damage mitigation purposes, also to perform PPP spray applications. Laboratory tests were made to characterize the emitter flow rate at different pressures and the droplet size spectra generated. Semi-field trials were then carried out to measure StripNet® spray coverage in semi-pedestrian trained trellised apple orchard and Guyot espalier trained trellised vineyard. The performance of StripNet® flat fan emitter was evaluated comparing the spray coverage obtained with the one achieved using conventional sprayers equipped with spray drift reducing technology (SDRT), both in apple orchard and vineyard.

StripNet® emitter was characterized by a VMD value of 453.1 µm and 4.60% of V_{100} indicating potential in reducing spray drift. Semi-field trials indicated differences between crops in terms of spray coverage attributable to the canopy shape and density, with higher homogeneity at all canopy height and depth in apple orchard case. In vineyard, a high spray coverage was observed on the top of the canopy, while lower values were registered in the medium and lower parts of the rows, thus affecting the overall uniformity of spray distribution. The use of StripNet® for PPPs application from the top of the canopy resulted therefore a feasible option in apple orchard, while for vineyard further studies are necessary to define the type of emitter and its position into the canopy able to guarantee the necessary uniformity of the deposition along the canopy structure.

Keywords: emitter, pesticide application, orchard, SSCDS, canopy coverage, vineyard

1. INTRODUCTION

The need for changing agricultural practices were recently strengthened by EU policy and officially presented through the EU Green Deal and the Farm to Fork Strategy. Indeed, new technologies are needed to optimize spray application, minimize risks for end-users and guarantee food and environmental safety. Since many years, in orchards and vineyards PPPs are usually delivered using air-assisted sprayers (Grella et al., 2020a, 2022a). Due to inadequate Pesticide Application Equipment (PAE) adjustment and poor technology, however, most of the spray volume applied is generally lost out of the target and spray drift represents an important issue to face (Grella et al., 2017; Sinha et al., 2019). As the current trend concerning orchards and vineyards training systems is to minimize the size and density of the canopy, it is possible to consider spray application systems without air assistance. On the other hand, the increasing need to be as much flexible as possible for the timing of treatments, encourage the study of PAE able to operate independent of soil conditions (e.g. wet soils after rain events). One promising alternative to conventional PAE is currently represented by fixed spray systems. Solid

Set Canopy Delivery System (SSCDS), the modern variant of such fixed spray systems, that could play a key role in achieving the desired goals in terms of environmental, food and human safety, while guaranteeing the necessary efficacy of treatments (Agnello and Landers, 2006; Grieshop et al., 2015; Owen-Smith et al., 2019). A SSCDS typically consists of a network of irrigation polyethylene hoses, a permanently installed series of emitters positioned along the rows and a pumping station placed outside the sprayed area. The spray mixture prepared in a tank at the pumping station is delivered to the hoses and released by the emitters varying the duration of their activation, which is usually of a few minutes, controlling PPP application rate (Grieshop et al., 2015). Previous studies on SSCDS, conducted in apple orchard and vineyard, have demonstrated they provide equivalent pest control and reduced off-field drift with respect to air-assisted sprayers (Imperatore et al., 2021; Sinha et al., 2019).

To date, the cost for installing the system is relatively high. Nevertheless, the adoption of a SSCDS would allow to save money in terms of manpower and sprayer costs. Furthermore, it would offer the opportunity to have a multipurpose device which, besides for treatments, could be used for irrigation and/or conditioning of the vineyard/orchard. Recently, authors reported SSCDSs are reliable to reduce spray drift (Sinha et al., 2019). In this sense, in Italy SSCDSs are under evaluation to be used as alternative to airblast sprayers, especially in sensitive areas with the aim to reduce environmental impact of spraying operations. In particular, it is currently under assessment the possibility to use the already existing irrigation systems as SSCDS in apple orchard and vineyards. Considering that SSCDS would be used as Spray Drift Reducing Technology (SDRT), preliminary evaluations of its spray performances are of primary importance.

Therefore, the main goal of this research was to compare the spray coverage capabilities of a flat fan pulsed irrigator, tested in apple orchard and vineyard, with conventional SDRTs.

2. MATERIAL AND METHODS

Experimental trials were carried out in two steps: (i) laboratory tests to characterize the emitter flow rate variation and droplet size spectrum and (ii) semi-field trials to measure potential spray coverage of a single emitter in apple orchard and vineyard.

The first step was carried out at DiSAFA facilities (University of Turin, Italy). The second one was conducted in a semi-pedestrian trained trellised apple orchard (*Malus domestica* 'Golden Delicious') at Mezzolombardo (TN) and in a guyot trained trellised vineyard (*Vitis vinifera* 'Barbera') at DiSAFA facilities (TO). As SDRT an airblast sprayers were used after an appropriate calibration, in order to reduce off-target deposition and maximize canopy coverage in accordance to best management practices (http://www.topps-life.org/).

2.1 Tested emitter and components

Emitter consisted of a plastic Pulsar® system, which enabled the typical emitter pulsating spray mode (Netafim Ltd. Company, Derech Hashalom 10, Tel Aviv, Israel 67892), coupled with a double-side flat fan StripNet® plastic nozzle (mod. STR31 2AN - Netafim Ltd. Company).

The Pulsar® system components were i) a fuchsia model pressure compensated dripper, installed on the main pipeline to feed the emitter, ii) a micro-tube connecting the pressure compensated dripper to iii) the Pulsar® tube , featured by a chamber accommodating an air bag that acts like a pressure compensator, and iv) a blue-pin calibrated anti-drip valve installed at the outlet of the Pulsar® tube, which opens the system once 0.25 MPa of internal pressure is reached.

The main pipeline supplied the emitter with pure water at 0.30 MPa. At the inlet of the Pulsar® system, the pressure compensated dripper guaranteed 0.20 l min^{-1} flow rate in the pressure range 0.25-0.40 MPa. The Pulsar® system components create a self-compensating mechanism which generates a stable flow rate at its outlet, regardless of the water pressure at its inlet, allowing to overcome pressure variations along the pipeline. Moreover, it ensures a stable pressure at the inlet of the emitter regardless of its location in the field.

Throughout experimental trials, emitters were connected to a portable pumping station. Briefly, the pumping station consisted in (i) a main pipeline on which the emitter was connected, (ii) a pressure gauge (WIKA Alexander Wiegand SE & Co. KG, Germany) installed to check and guarantee a constant liquid pressure, (iii) a GR 30 - Cod. 879 manual pressure regulator (Annovi Reverberi S.p.a., Modena, Italy) installed upstream on the main pipeline and (iv) a membrane pump (AR252 BlueFlex™ - Annovi Reverberi S.p.a.) which fed the main pipeline.

2.2 Laboratory tests

2.2.1 Flow rate variation

Emitters were connected to the portable pumping station previously described. Different liquid pressures (0.20, 0.30, 0.40 and 0.50 MPa) were tested to investigate the possible emitter flow rate variation when the pressure compensated dripper works out of its optimal condition (namely 0.30 MPa). Three replicates per each pressure were carried out. Mean flow rate and coefficient of variation (CV, %) were afterwards calculated.

2.2.2 Droplet size spectrum

Droplet size spectrum of the emitter, spraying pure water, was measured using a Malvern Spraytec® laser diffraction system (mod. STP5342 - Malvern Instruments Ltd., Worcestershire, UK) applying similar methodology to that described by Grella et al. (2020b). The orifice of flat fan nozzle installed on the emitter was positioned at 0.50 m distance and perpendicular to the laser beam. The emitter was connected to the portable pumping station set at 0.30 MPa pressure. Tests were replicated three times. $D_{V0.1}$, Volume Median Diameter ($D_{V0.5}$) and $D_{V0.9}$ (µm) values were measured. In addition, V_{100} (%) parameter was calculated.

2.3 Semi-field tests

2.3.1 Canopy characteristics and environmental conditions

Trials were conducted at late growth stage (vegetation fully developed) both in apple orchard and vineyard. The average apple orchard height from the ground was 2.31 m with a vegetative strip of 1.80 m and canopy width of 0.40 m. The average vineyard height from the ground was 2.08 m with a vegetative strip of 1.54 m and a canopy width of 0.52 m. The two crops were characterized by different canopy density: very low density for apple and higher density for vineyard (Figure 1).

Environmental conditions were monitored during field trials to accomplish the optimal conditions, namely wind speed below 2 m s^{-1}.

Figure 1. Field plots, namely a) semi-pedestrian trained trellised apple orchard and b) Guyot trained trellised vineyard, during spray application using the tower shaped airblast sprayers.

2.3.2 SSCDS and airblast sprayers spray parameters

StripNet® emitter was installed on a support, to hold it in a vertical position at 0.50 m above the top of the canopies, in the middle of row width (row aerial view area projected on the ground). Nozzle orifices were aligned along the rows. The emitter was connected to the portable pumping station set at 0.30 MPa pressure. SSCDS configuration of the emitters was evaluated both in apple orchard and in vineyard with three replicates.

A tower shaped trailed airblast sprayer Mitterer VV series (Mitterer S.a.s., Terlano, Bolzano, Italy) was used as reference in apple orchard study case. It was featured by an 800 L polyethylene tank and 7+7 TVI8001 air inclusion activated nozzles (Albuz, Evreux cedex, France). The axial fan, 810 mm in diameter, was deactivated during spray application according to the local spray drift reducing techniques. The Power Take Off (PTO) was set at 450 rev min^{-1} to feed the pump. Even if axial fan is normally used to convey spray to the target and enhance its penetration, the semi-pedestrian apple training system is characterized by very low canopy density that can avoid air assistance.

For the vineyard case, a trailed tower shaped airblast sprayer Caffini Synthesis (Caffini S.p.a., Palù, Verona, Italy), was used as reference. The latter was featured by an 800 L polyethylene tank and 6+6 AI8002 air inclusion activated nozzles (TeeJet, Spraying Systems Co., Illinois, USA). The sprayer was equipped with a 700 mm axial fan generating 14,200 m^3 h^{-1} air flow rate using the PTO set at 450 rev min^{-1} combined with the low fan gear speed. According to Grella et al. (2022b) the reduced PTO speed to further reduce fan air flow rate and air speed on the target was considered the best option to increase the spray application efficiency. A liquid pressure of 1.40 and 0.40 MPa were combined with a forward speed of 7.8 and 5.5 km h^{-1} to achieve an application rate equal to 421 and 425 L ha^{-1} for apple orchard and vineyard, respectively. Three spray application replicates were carried out in both crops.

2.3.3 Spray coverage

A row-length portion, accounting for 6 m, was used to measure the spray coverage performances of a single emitter and the tested sprayers both in apple orchard and vineyard study cases. Within the 6 m row length two sampling locations were distributed resulting in different distances from the spray source, namely 2.25 and 3.75 m.

To measure the potential canopy spray coverage (%), water sensitive papers (WSPs) (76 mm x 26 mm - Syngenta Crop Protection AG, Basel, Switzerland) were placed at different canopy heights and depths at each defined sampling distance from the spray source. At each canopy sampling position (Figure 2), WSPs were directly stapled on the leaves and paired onto the adaxial (hereafter, called upper) and abaxial (hereafter, called lower) leaf surfaces. Due to reduced canopy density and width for apple trees, six canopy sampling positions (2 canopy depths namely, A and C, and 3 canopy heights, namely Low, Medium, High) were selected. Meanwhile, nine canopy sampling positions (3 canopy depths namely A, B,C and 3 canopy heights, namely, Low, Medium, High) were selected for vines similarly to the sampling strategy used in previous studies (Grella et al., 2022a; Sinha et al., 2020).

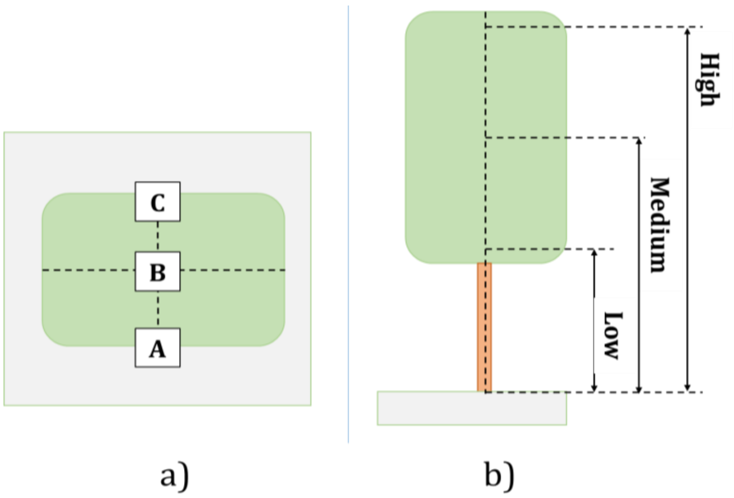

Figure 2. Schematic of the spray coverage canopy sampling locations valid for apple orchard and vineyard: a) aerial view for canopy depths (A, B, and C) and b) lateral view for canopy heights above the ground (Low, Medium, and High).

2.4 Data processing and statistical analysis

After drying, WSPs were collected and then scanned at a 600-dpi resolution. The obtained images were analyzed using ImageJ processing-based software (version 1.52n, Wayne Rasband, National Institutes of Health, Bethesda, MD, USA). Spray coverage (%) was calculated as the ratio between the spray deposits area (area covered by stains) and the total area effectively analyzed on the WSP. Deposit density, calculated as the total number of stains per WSP surface unit, was also reported.

Statistical analyses were performed using IBM SPSS Statistic (Version 28) predictive analytical software for Windows. ANOVA were used to establish the effects of leaf surface (upper or lower), sampling depth (A, B, C), sampling height above ground (Low, Medium, High), and PAE adopted (SSCDS and airblast sprayer) on the dependent variable spray coverage. ANOVA tests were performed separately for apple orchard and vineyard. Means were compared using a Duncan *post-hoc* test for multiple comparison ($p < 0.05$).

3. RESULTS AND DISCUSSION

3.1 Laboratory tests

Tests conducted at 0.30 MPa pressure showed the highest flow rate variation (0.20 ±0.03 l min^{-1}) followed by those conducted at 0.50 MPa (0.21 ±0.02 l min^{-1}), 0.20 and 0.40 MPa (0.21 ±0.01 l min^{-1}). However, the flow rate differences among configurations were not statistically significant [F (3,8) = 0.200; p=0.894]. Furthermore, CV (%) values were in all cases lower than 1% underlining a low flow rate variability within pressures. Thus, Pulsar® system resulted able to compensate the flow rate variation due to possible pressure losses/gains along the main pipeline in

the tested pressure range. It derives that this type of solution would be an easy way to control the flow rate of emitters installed in a SSCDS irrespective of their position along the main pipeline.
The emitter droplet size spectrum was characterized by a Volume Median Diameter (VMD) equal to 453.1 µm, $D_{V0.1}$ = 193.8 ± 20.8 µm and $D_{V0.9}$ (µm) = 879.8 ± 42.5 µm. Laboratory results confirmed the potential of emitters to be used as SDRT because of the coarse spray quality generated. Indeed, the cumulative curves obtained for tested emitters were comprised between the coarse and extra coarse thresholds spray quality according to the ASABE classification (ASABE S572, 2009). This was further confirmed by the V_{100} values, recognized by authors as the driftability droplets threshold (Van de Zande et al., 2008), that resulted equal to 4.6%. This result was fully in line with droplet size spectrum of air inclusion nozzles tested under field conditions (Grella et al., 2017) and laboratory conditions (Van de Zande et al., 2008) and proved capable to significantly reduce spray drift.

3.2 Semi-field tests

3.2.1 Spray coverage

3.2.1.1 SSCDS in apple orchard and vineyard

Spray coverage (%) differed significantly among the studied sampling distances from the spray source in apple orchard [$F_{(1,48)}$ = 10.633; p=0.002], but not in vineyard [$F_{(1,72)}$ =3.136; p=0.081]. Furthermore, the canopy depths did not affect the spray coverage in both apple orchard [$F_{(1,48)}$ = 0.004; p=0.951] and vineyard [$F_{(2,72)}$ = 0.047; p=0.954]. Contrarily, the leaf side significantly affected the spray coverage in apple orchard and vineyard showing significant interaction with the sampling height [F (2,48) = 3.836; *p*=0.028 and F (2,72) = 28.428; *p*=7.95 E-10, respectively]. As expected, lower values were in all cases measured on the lower leaf surfaces, with coverage diminishing from the top to the bottom canopy portions for both upper and lower leaf surfaces (Figure 3).

Figure 3 outlines spray coverage (%) amount reached by emitter in apple orchard and vineyard. Regardless leaf surfaces, the highest mean coverage was reached in the top of the canopy at 2.25 m from the spray source reaching 39.92 ± 38.64 % and 32.43 ± 35.69 % for apple orchard and vineyard, respectively. Lower mean coverage was reached in the low portion of the canopy at 3.75 m from the spray source reaching, respectively for apple orchard and vineyard, 11.83 ± 7.02 % and 0.43 ± 1.28 %. Measured values underlined a consistent average spray coverage result of 30% or more especially in top canopies, even if huge variations were noticed. This result was not surprising due to the emitter position at the top of the canopies. Indeed, spraying from the top of the canopy, the spray penetration results difficult especially in vineyard context where the canopies are denser than those of apple orchards. To this respect Figure 3 shows in the apple case a coverage on the WSPs placed at the medium height of the row higher than those reported for vineyards, underlining the capability of spray to penetrate apple tree canopies, thus resulting in a more uniform spray coverage along the canopy height. However, an abrupt reduction can be anyway noticed in the low height, as the higher the distance from the spray source the higher is the difficulty to penetrate into the canopy. Moreover, difficulties in canopy penetration could be further enhanced by the emitter coarse droplets produced, which negatively affect canopy penetration (He et al., 2022), especially in PAE without air assistance.

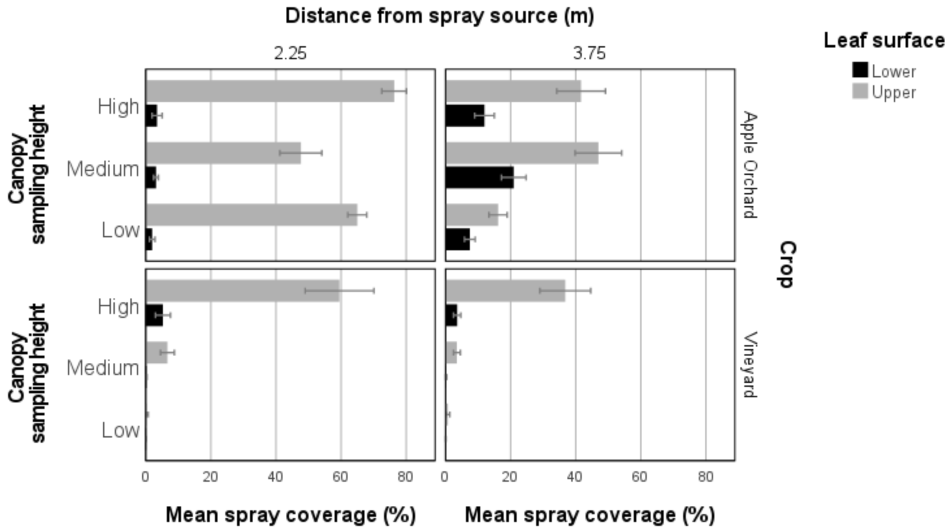

Figure 3. Mean spray coverage (%) for the two sampling distances from the spray source (2.25 and 3.75 m). Data are reported for apple orchard and vineyard crops, upper and lower leaves surface per each canopy sampling height above ground (Low, Medium, High).

3.2.1.2 Airblast sprayers versus SSCDS

The type of PAE used significantly affected the spray coverage for both cases, namely apple orchard [F (1,96) = 4.613; *p*=0.034] and vineyard [F (1,144) = 69.225; *p*=6.11 E-14]. In general, airblast sprayers achieved on average higher spray coverage when compared to SSCDS (Figure 4). Also, the canopy sampling height showed a significant effect on the spray coverage with significant interaction with PAE factor in apple orchard [F (2,96) = 13,554; *p*=6.53 E-06] and in vineyard [F (2,144) = 26.667; *p*=1.40 E-10].

As shown in Figure 4, airblast sprayers were able to better cover the lower canopy height (i.e., Low and Medium) as the distance between the target and the spray source was reduced. For the vineyard case, droplets were conveyed into the canopy thanks to the fan airflow. Contrarily, for the apple orchard case, switching off the sprayer fan negatively affected deposition in the top part of the canopy that is the farthest portion away from the spray source. Indeed, regarding the top part of the canopy, SSCDS reported at least the same coverage as for the one with the airblast sprayer in vineyard (26.3%) and an amount three times higher for the apple orchard case (33.4%). A more uniform vertical spray profile was achieved, in apple orchard case, thanks to the use of SSCDS.

Figure 5 shows pictures of representative WSPs collected from different canopy sampling areas for upper leaf surface according to tested PAE and canopy height. Visual analysis of WSPs images indicated that, irrespective of crops, the emitters were characterized by skewed stains at all the sampled heights. Meanwhile, the airblast sprayers equipped with air inclusion nozzles showed more rounded stains. Noteworthy, for the airblast used in apple orchard, smaller stains were noticed even if air inclusion nozzles were used. This was likely due to the high pressure used (1.40 MPa), generating finer spray quality.

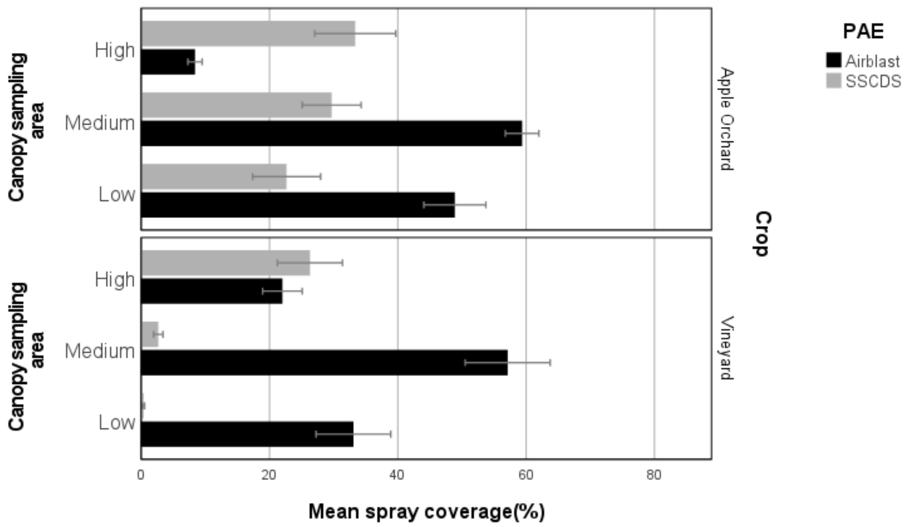

Figure 4. Spray coverage (%) at different canopy sampling height above ground (Low, Medium, High) for the tested Pesticide Application Equipment (PAE) per the evaluated crops (apple orchard and vineyard).

Figure 5 also shows coverage values and deposit density for the showed WSPs. As already reported by other authors (Fox et al., 2003; Grella et al., 2020a, 2022a), for the higher coverage values very low deposit density was noticed. Indeed, for the WSPs characterized by coverage higher than 18-20% the deposit density is not a reliable value due to stains joining or overlapping. For this reason, in order to evaluate the PAE spray application based on the WSP-based measurements, two thresholds suggested by Syngenta are usually considered, namely i) WSPs characterized by deposit density higher than 70 stains cm^2 and ii) WSPs with not more than 30% of coverage, as higher values represent over-spray situation. Difficulties in achieving adequate spray distribution on the target, both in terms of coverage and deposit density, resulted evident in the lower portion of the vineyard row. If for the apple orchard case the emitters installed just on the top of the canopy can provide a sufficient spray coverage and deposit density, in vineyard the spray application just from the top of the canopy is not adequate to guarantee a sufficient spray coverage and deposit density at all canopy heights. Similar findings were reported also by previous studies (Sinha et al., 2020) suggesting to use emitters of different types at multiple locations within the vineyard rows so to optimize SSCDS spray performances.

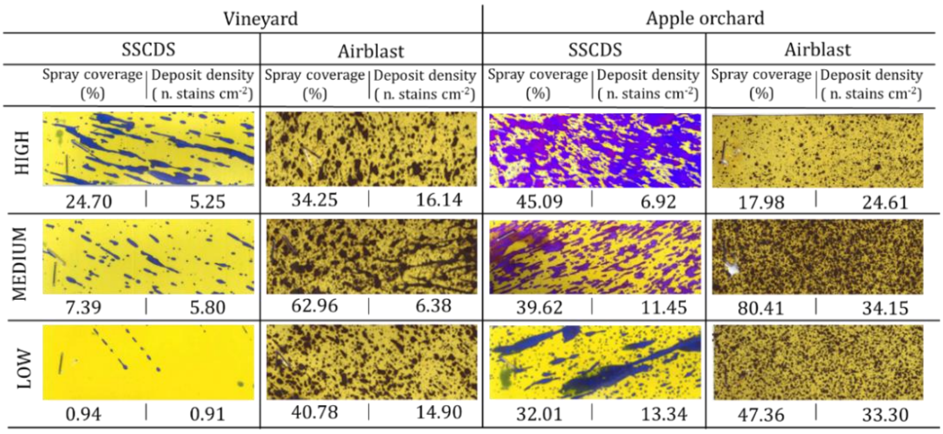

Figure 5. Pictures of representative water sensitive papers placed on the upper leaf surface during field trials. Spray coverage (%) and deposit density (number of stains per cm-2) of each representative picture are also provided. Pictures and data are reported by crop (vineyard and apple orchard), Pesticide Application Equipment (SSCDS and airblast sprayer) and canopy sampling height above ground (Low, Medium, High).

4. CONCLUSIONS

According to laboratory results, the tested emitter (*i.e.*, Pulsar® system coupled with StripNet® nozzle) is able to guarantee a precise flow rate in a wide range of operative pressures. Also, results confirmed the emitter can be potentially used as SDRT thanks to the coarse spray droplet spectrum generated. Therefore, StripNet® flat fan pulsed emitter could be potentially used also for PPPs spray applications in sensitive areas as alternative to conventional SDRTs. Under field conditions, as configured in the present study, the adoption of StripNet® flat fan pulsed emitter resulted a feasible option as SSCDS emitter to achieve an adequate spray coverage in apple orchard. Differently, in vineyard the flat fan emitters spraying just from the top of the vines canopy didn't allow to provide adequate deposits in the lower portion of the canopy (e.g., grape band). Thus, a combination of different emitter types placed in different positions in the vine canopies, in addition to StripNet® flat fan pulsed emitters, is recommended in order to reach a uniform and adequate spray distribution also at the medium and low canopy heights. Further studies are therefore ongoing to investigate new SSCDS configurations to increase spray coverage in this specific crop vine canopies.

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Chapter III

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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.

Keywords: Environmental impact; plant protection product spray

application; distribution uniformity; cleaning evaluation; fixed spray delivery system; solid set canopy delivery system

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).

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 1 to 2 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) efficient application timing (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. MATERIAL 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: Pro-flow 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.

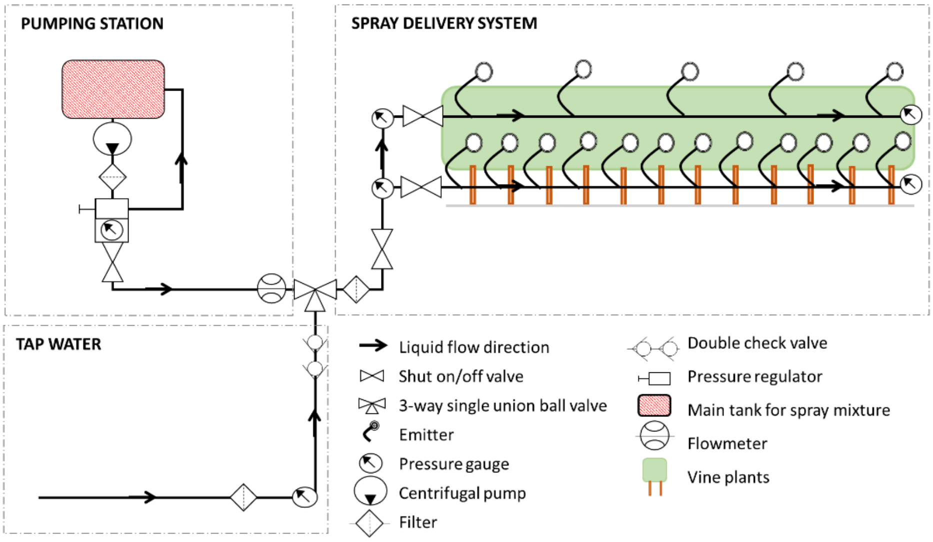

Fig. 1. Schematic of the fixed HSD system circuits as composed of three main devices i.e., pumping station, tap water, and spray delivery system.

The 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 31m 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 3-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.

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 Fig. 2f). At the end of this phase water remained in the line (Fig. 2a).

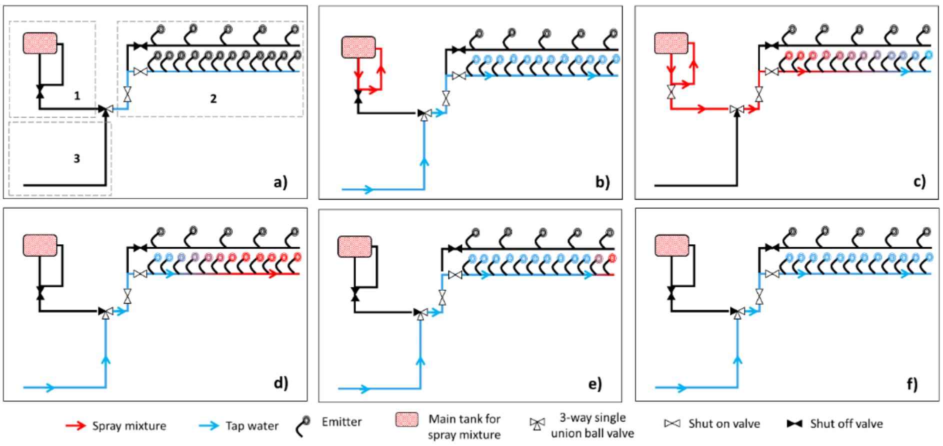

Fig. 2. Operational steps of experimental hydraulic spray delivery-based fixed spray system. Schematic for the fixed spray system components a) are the pumping station (1), the spray delivery system (2), and the tap water

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.

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

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 volumes * 2 concentrations * 3 replicates); and 144 samples measuring total volume (2 spray lines * 6 locations * 2 volumes * 2 concentrations * 3 replicates).

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 2.1 except that they were collected every 60 s between the minutes 1:30 to 7:30, and then after 21 and 22 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).

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

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 (*TPD*, 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 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 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 hours 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 min at 1,200 W from room temperature to 220 °C, 2 min 1,200 W from 220 °C to 250 °C, and 15 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 (Perkin Elmer, 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).

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

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 analyzed 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 analyzed 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. RESULT 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 (Fig. 3, Fig. 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 (Fig. 3b and Fig. 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 (Fig. 3b and Fig. 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).

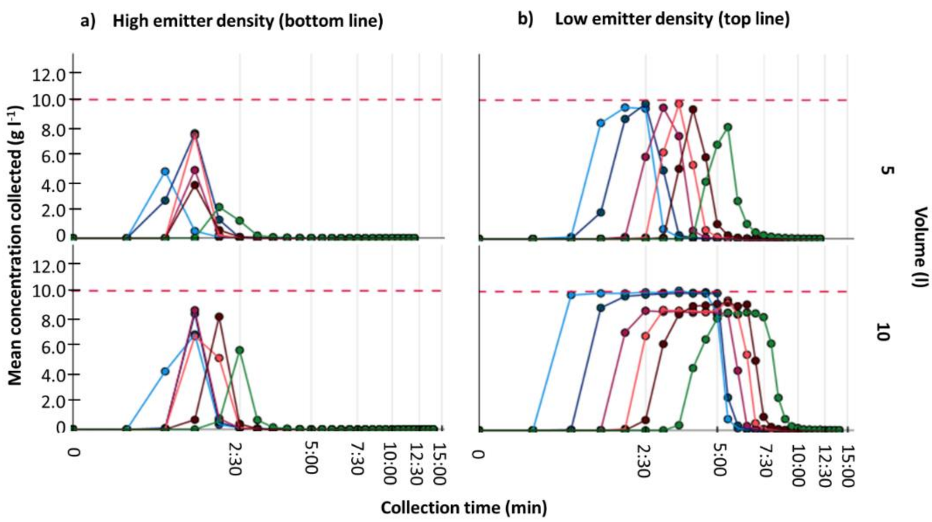

Fig. 3. Average spray mixture concentration (g l^{-1}), measured over the time (min) per the 5 and 10 l spray mixture volume at 10 g l^{-1} concentration. Different colors denoted different sampling locations from the injection point: light blue (▬) = 4.0, purple (▬) = 11.5, magenta (▬) = 20.0, pink (▬)= 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}).

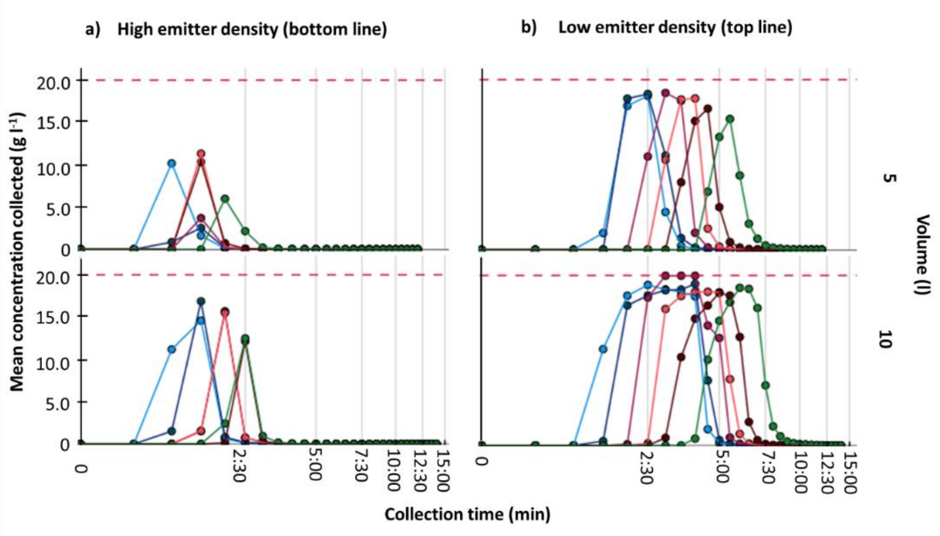

Fig. 4. Average spray mixture concentration (g l^{-1}), measured over the time (min) per the 5 and 10 l spray mixture volume at 20 g l^{-1} concentration. Different colors denoted different sampling locations from the injection point: light blue (▬) = 4.0, purple (▬) = 11.5, magenta (▬) = 20.0, pink (▬)= 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}).

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 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.

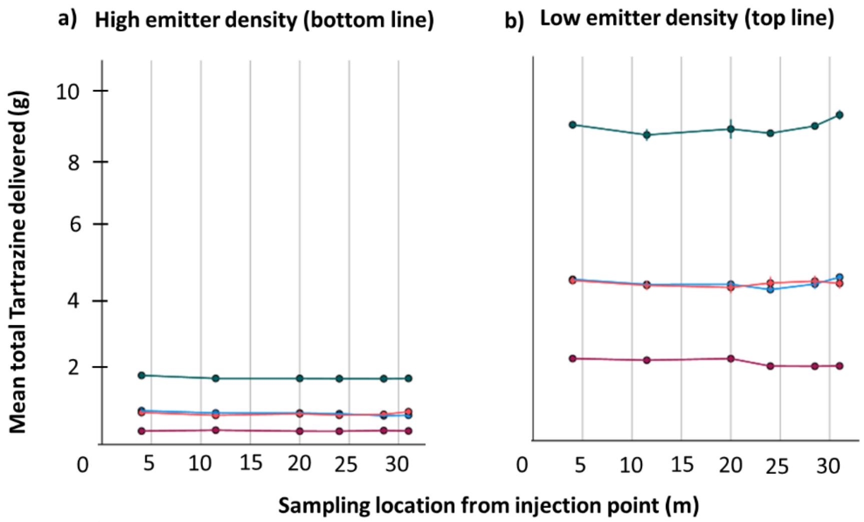

Fig. 5. Average total Tartrazine delivered (g) per a) the high emitter density and b) the low emitter density spray lines. Different colors denoted differences about the four spray mixtures injected (combination of 5 and 10 l spray mixture volumes and 10 and 20 g l^{-1} Tartrazine concentrations): red (▬) = 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.

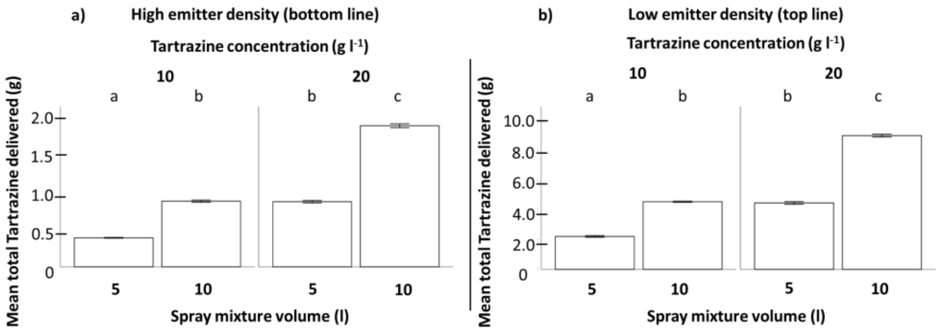

Fig. 6. Average total Tartrazine delivered (g), from the six emitters sampled per a) the high emitter density and b) the low emitter density spray lines. Different bars showed the combination of mixture volume (5 and 10 l) and Tartrazine concentration (10 and 20 g l^{-1}). Different letters indicate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

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 $p > 0.05$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

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, Fig. 7b). 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 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 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 min would be requested 22, 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.

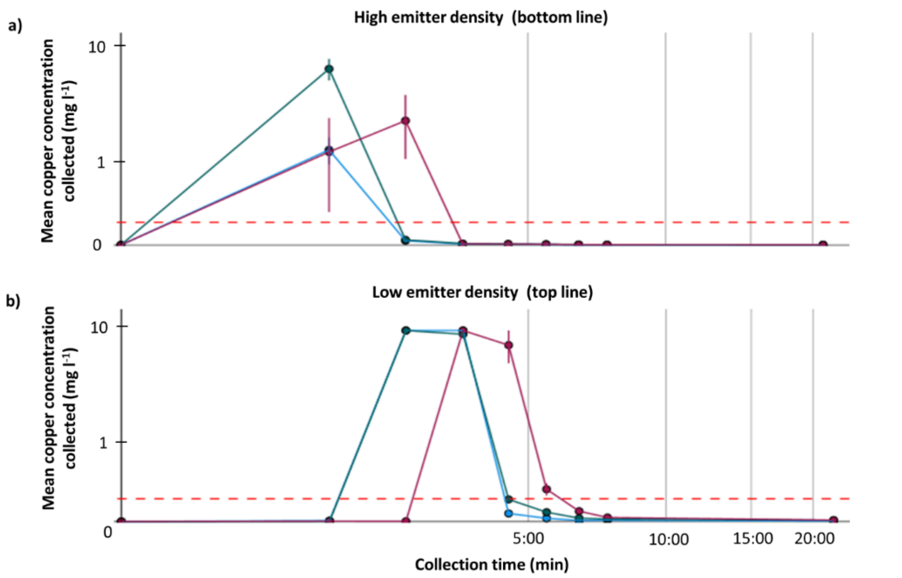

Fig. 7. Average copper oxychloride concentration (g l^{-1}, in logarithmic scale), per a) the high emitter density and b) the low emitter density spray lines. Different colors denoted different sampling location from the injection point: light blue (▬▬) = 11.5 m, green (▬▬) = 20.0 m, and red (▬▬) = 28.5 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

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 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 behavior 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 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.

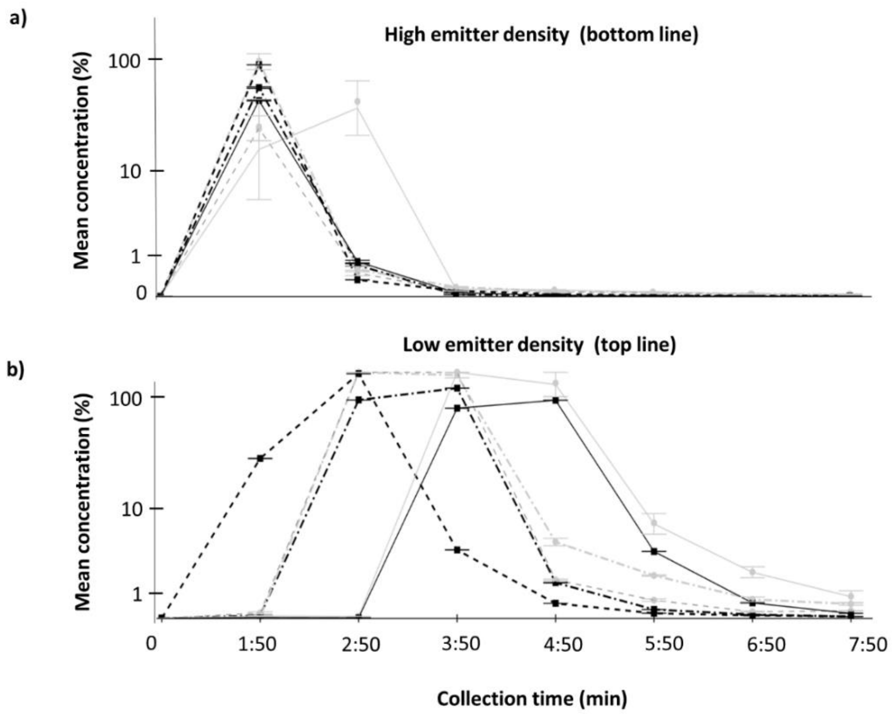

Fig. 8. Average percentage concentration (%, log scale), per a) the high emitter density and b) the low emitter density spray lines. Copper oxychloride (5 l at 10 g l^{-1}) and Tartrazine (5 l at 10 g l^{-1}) spray mixture sampling locations from the injection point are reported in gray (●) and black (■) 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.

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. Figure 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, Figure 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.

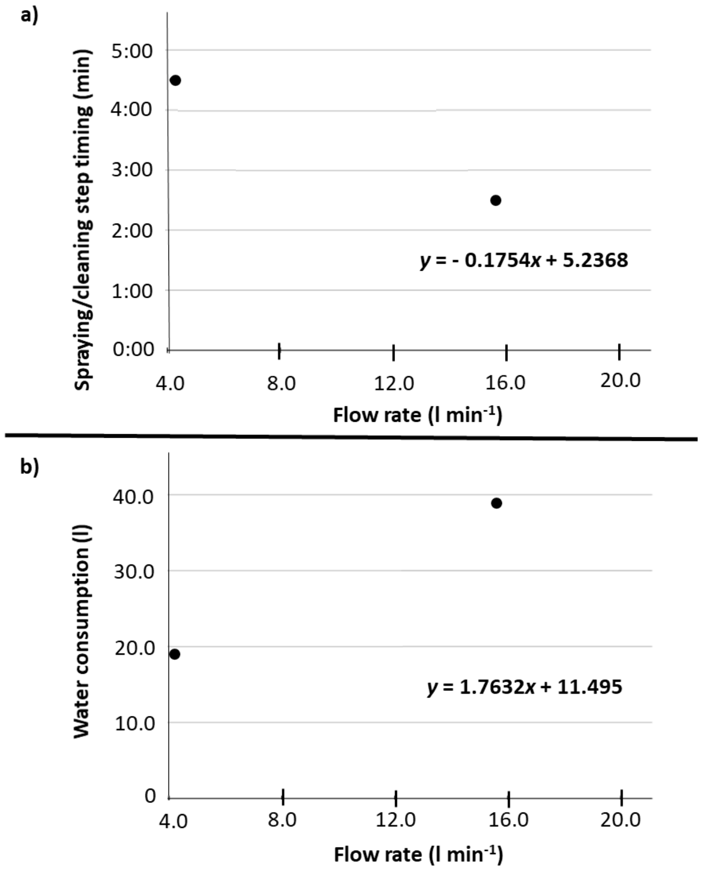

Fig. 9. Linear regression models of the spray delivery system evaluated. Flow rate was evaluated to be 4.2 and 15.6 l min^{-1} for the low and high emitter density, respectively. a) Spraying/cleaning step timing (min) and flow rate (l min^{-1}), and b) water consumption (l) and flow rate (l min^{-1})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

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.

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.

Acknowledgments

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Chapter IV

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Cleaning performance evaluation of pneumatic spray delivery based solid set canopy delivery system

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Highlights

- *Ad hoc* methodology was assessed to evaluate the Pneumatic Spray Delivery-Solid Set Canopy Delivery System (PSD-SSCDS) cleaning performance
- Evaluated were the five viable cleaning techniques including air injection and water rinse
- System performance meet the ISO16119-4 internal cleaning requirements
- Amongst tested methods, water rinse was the most effective cleaning technique

Abstract

Solid set canopy delivery system (SSCDS), a fixed spray system variant, has potential to realize automated and timely spray applications in modern grapevine production systems typical to Washington State in the United States. Optimized SSCDS configuration could be a viable replacement to conventional pesticide application equipment (PAE) and can also help with abiotic stress management. However, SSCDS as a PAE should effectively mitigate risks and environmental impacts associated with pesticide use. This study was thus aimed to evaluate a pneumatic spray delivery (PSD)-SSCDS, first in laboratory and then under field conditions, to understand systems cleaning performance according to a methodology based on the ISO22368-1:(2004) standard for such fixed and semi-mobile sprayers. The cleaning performance was quantified as the percent amount of residues in the SSCDS components after the spray application. A pilot laboratory setup was used to evaluate the PSD-SSCDS components *cleaning performance. The system was cleaned using five viable cleaning techniques: air injection for 30 (conventional cleaning technique), 60, 90, and 300 s, and one water rinse after 30 s air injection. The technique that performed best was field evaluated in a large-scale modern grapevine layout. Overall, the use of water to rinse the system component achieved cleaning performance >99.67%. Field trials also demonstrated that PSD-SSCDS layout was easy to clean through a triple water rinse and capable of meeting the ISO16119-4:(2014) set threshold.*

Keywords. *Spray application technology; pesticide application equipment; pesticide residues; internal cleaning; fixed spray delivery system.*

1. INTRODUCTION

Pests and diseases pose significant challenges in bush/tree crops, necessitating numerous applications of plant protection products (PPP) (Azimonti et al., 2024). While PPP protect crops and enhance yield and quality (Popp et al., 2013), their extensive use can cause adverse environmental effects and expose humans and animals to potential health risks (Butler Ellis et al., 2010; Damalas and Eleftherohorinos, 2011).

There are three main phases related to spray applications: (i) spray mixture preparation and filling of pesticide application equipment (PAE), (ii) spray application, and (iii) PAE cleaning and spray mixture tank remnants management (TOPPS-Prowadis Project, 2014).

Due to raising interest from consumers, markets, and policy makers in topics related to chemical inputs in agriculture (e.g., the EU Green Deal and Farm to Fork Strategy, and US sustainability requirements through Global G.A.P. and company initiatives) (Von der Leyen, 2019, Grella et al., 2022a, 2023a; Globalgap.org, 2024), much of the recent research focuses on reducing the amount of PPP used by improving spray application technologies related to the variable rate application (Salcedo et al., 2021; Grella et al., 2022b, 2022c; Xun et al., 2023), replacing synthetic PPP with organic or biocontrol agents (Grella et al., 2023b; Ortega et al., 2023), or changing field conditions to reduce off-target pollution (Pergher et al., 1997; Otto et al., 2015).

Despite this, point source pollution can contribute to 40-90% of the surface water bodies contamination (TOPPS-Water protection Project, 2017). The PPP point source pollution can be 25-55% higher to the PPP diffuse one, mainly related to the field spray application (e.g., spray drift) (Jaeken and

Debaer, 2005; Roettle et al., 2012; TOPPS-Prowadis Project, 2014; TOPPS-Water protection Project, 2017). Thus, a series of actions and projects (MAgPIE-Project (2013); TOPPS-Prowadis Project, 2014; TOPPS-Water protection Project, 2017), mainly related to the agricultural operators training (e.g., BTSF academy – https://better-training-for-safer-food.ec.europa.eu/training/course/info.php?id=168), have been undertaken since 2005 to disseminate best management practices (BMP) related to the different phases of PPP spray applications. In this context, TOPPS outlined the importance of reducing the internal and external contamination of PAE at the end of spray application by adopting adequate procedure (TOPPS-Water protection Project, 2017; Balsari, 2019) and devices (Pauwelyn and Vanwijnsberghe, 2019) to minimize environmental contamination risks related to pesticide use, such as preventing point source contamination, PPP cross-contamination, and phytotoxicity of non-target crops. Some of these studies were focused on the importance of residues/remnant management to avoid damaging the environment and humans, by suggesting a series of tools to help farmers in this operation (Debaer and Jaeken, 2006; De Wilde et al., 2007; Grella et al., 2019; Pauwelyn and Vanwijnsberghe, 2019). Previous studies have delved into the comparison of different cleaning methodologies, both external and internal. These studies meticulously assessed the cleaning performance, outlining the respective pros and cons associated with each approach. Depending on factors such as sprayer type, specific operations, and cost considerations for farmers, recommendations were made for the most effective cleaning methods (Marucco et al., 2010; Doerpmund et al., 2011; Balsari and Marucco, 2017; Doruchowski, 2019; Grella et al., 2023d).

Internal cleaning is a transversal issue in PAE. To date, different cleaning techniques (e.g., triple water rinses, continuous rinse, use of cleaning agents) have been investigated both for airblast and boom sprayers (Doerpmund et al., 2011; Marucco et al., 2017; Wachter et al., 2019; Wegener and Wehmann, 2019; Grella et al., 2022d). Novel PAE are becoming commercially available, and warrant investigations on their capability of internal cleaning. This research would provide information useful for regulatory agencies and in grower education. Among the novel PAE, solid set canopy delivery system (SSCDS) is rapidly gaining interest in trellised perennial fruit crops, such as grapes and apples. SSCDS has several advantages linked to the reduction of tractor-use and manpower-needs, the possibility to safely spray in steep-sloped areas, improved timeliness of application considering preferred environmental conditions (temperature, wind, rainfall), and the possibility of being used to manage abiotic stressors (such as heat and frost) (Bondesan et al., 2016; Caravia et al., 2017; Sinha et al., 2020; Ballion and Verpont, 2023; Mozzanini et al., 2024). Furthermore, such technology has the potential to minimize PPP operator exposure, as all the necessary inputs for a PPP spray application are executed entirely from outside of the sprayed area with potential full-automated operation (Ranjan et al., 2019). Additionally, by eliminating the need for tractors and conventional sprayers, the adoption of the SSCDS would significantly decrease the risk of over-turning when PPP spray applications are made in steep slope areas thus increasing operator safety. The SSCDS stands to mitigate worker health and safety risks (Ranjan et al., 2019; Sinha et al., 2020a).

In general, a SSCDS is composed of a spray delivery system (installed in the field) and an applicator unit (located outside the sprayed area). The spray delivery system consists of solid set of polyethylene pipelines and emitters permanently positioned at predetermined locations, often in tiers, within the canopy according to crop training system and canopy characteristics (Sharda et al., 2015; Bondesan et al., 2016; Ranjan et al., 2021a, 2021b; Chen et al., 2023; Mozzanini et al., 2023a, 2023b). The mobile or fixed applicator unit mainly consists of a spray tank, a pump, air compressor, and sensors/gauges for system fault detection. The type of "propeller" used to deliver agrochemicals further categorizes the SSCDS into i) pneumatic spray delivery (PSD) or ii) hydraulic spray delivery (HSD). In PSD-SSCDS compressed air is used in two separate steps. The first step aimed to deliver the spray mixture and the second aimed to remove spray mixture residues from solid set of pipelines and emitters (Sahni et al., 2022a). In HSD-SSCDS, clean water is used at low pressures with dual functions, i.e., to deliver the spray mixture and concurrently remove the spray mixture residues from the pipelines and emitters (Mozzanini et al., 2024). Through prior efforts, HSD-SSCDS has been tested to ensure a homogeneous distribution of spray mixture among emitters, located at different distances from the injection point, and the capability of removing the PPP internal residues (Mozzanini et al., 2024) at thresholds set by EN/ISO 16119-4:(2014) (ISO, 2014). However, the internal cleaning performance of a PSD-SSCDS, particularly the solid set of pipelines and emitters within the canopy, has not been evaluated per the EN/ISO 16119-4 standards (ISO, 2014). If the existing cleaning method (Sahni et al., 2022a) proves insufficient, it becomes important to implement effective modifications to reach the cleaning performances required by EN/ISO 16119-4 standard (ISO, 2014). Indeed, considering the multipurpose aims of PSD-SSCDS, this is crucial to guarantee its safe use when performing overhead irrigation, freeze/frost protection, and conditioning. Furthermore, effective internal cleaning is crucial to prevent clogging, therefore guaranteeing the proper liquid-delivering throughout the vineyard plot, and avoiding potential cross-contamination arising from incompatibility of successive injected PPP (Gandini et al., 2020). The above two aspects are the key focus of this study. Since SSCDS applicator units are scaled down version of airblast sprayer tank/pump assembly, it already complies with the requirements set by the EN/ISO 16119-3:(2013) (ISO, 2013).

The main study goal was achieved through specific activities that evaluated the internal cleaning performances of the PSD-SSCDS components by testing various cleaning techniques under controlled laboratory conditions using a fluorescent tracer. The specific aim was to identify the best cleaning technique suitable to clean the PSD-SSCDS. This cleaning technique with due modifications was field validated, with copper oxychloride (ISO, 2004) as a tracer, on a PSD-SSCDS configuration optimized for spray applications in vertical shoot positioning (VSP) trained grapevines.

MATERIALS AND METHODS

Laboratory trials with PSD-SSCDS

The cleaning performance of a PSD-SSCDS was investigated in a laboratory at the Center for Precision and Automated Agricultural Systems (CPAAS) facilities of the Washington State University (WSU), Prosser, Washington State, USA (46° 15' 8.39" N, 119° 44' 24.47" W). The PSD-SSCDS experimental setup was comprised of two pumping stations, an air compressor, and a small-scale spray delivery system (fig. 1).

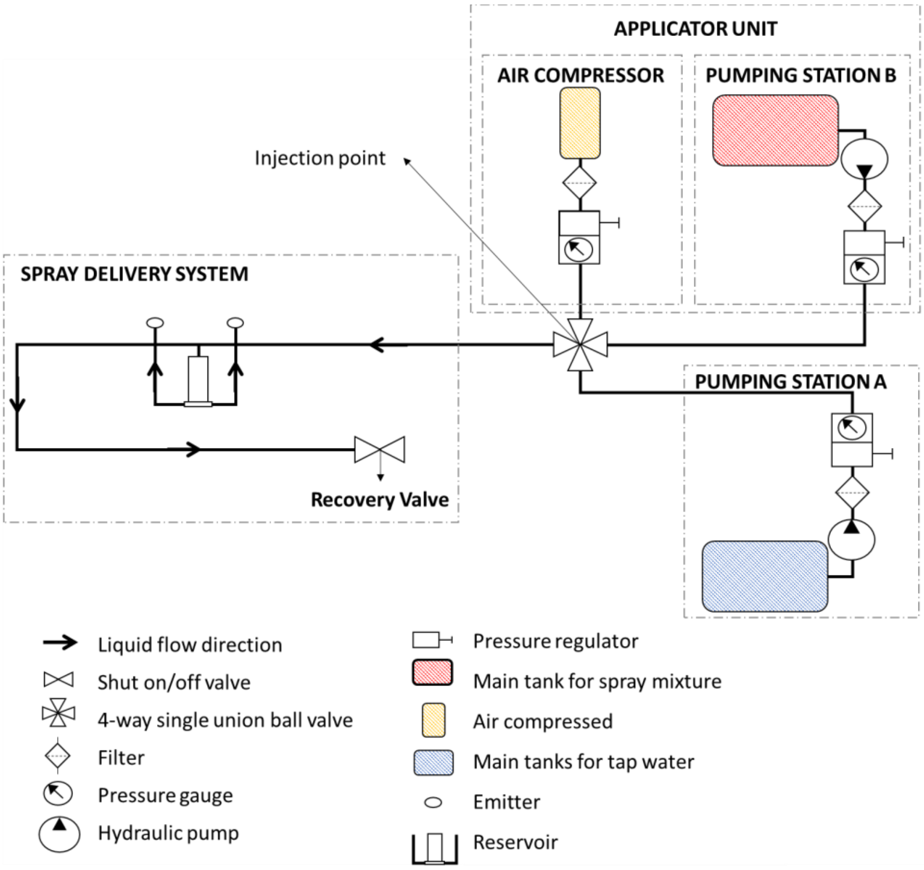

Figure 1. Schematic (not drawn to scale) of the small-scale PSD-SSCDS experimental setup as composed of four main devices *i.e.*, pumping station A (water supply), pumping station B (spray mixture supply), air compressor, and spray delivery system (reservoir, emitters, and spray line). Pumping station B and air compressor together represent the applicator unit that normally is adopted in the field to deliver agrochemicals.

Each pumping station was equipped with a 12V DC hydraulic pump (Model: 5850-101C, Delavan Fluid Power, Minneapolis, MN, USA). One pumping station (hereafter referred to as pumping station A, fig. 1), with a 378 L liquid tank, was used to fill the spray delivery system with tap water. The second (hereafter referred to as pumping station B, fig.1), with a 57 L liquid tank, was used to fill the system with a mixture of water and biodegradable fluorescent tracer (Pyranine 10G, Keystone Inc., Chicago, IL, USA) at 500 ppm concentration (hereafter referred to as mixture). The air compressor was used i) to push spray mixture through the lines (*i.e.*, spray mixture delivery), and ii) successively push air through the system to remove internal mixture residues from the components (*i.e.*, cleaning). The pumping station B and the air compressor represent the components of the applicator unit that are conventionally used in the field to deliver agrochemicals. The small-scale spray delivery system (fig. 1) consisted of a 5 m loop length with pipeline (hereafter referred to as spray line; φ: 25 mm), a reservoir – installed at 1.80 m from the injection point, and emitters (Model: modified 90° modular Flat Fan, Jain Irrigation Inc., Fresno, CA, USA). The existing reservoir unit designed and studied by Sahni et al. (2022a) were used for the laboratory trials. Briefly, a reservoir unit consisted of a liquid column, a 90° oriented bleed valve, a pressure regulator (Model: PGW-500, Elitech Technology Inc., San Jose, CA, USA; operating pressure: 0.20 MPa), and a multiport manifold (Rain Bird Inc., Azusa, CA, USA) which connects the emitter feedline (PE tube, φ: 6 mm) to the reservoir. Functionally, the bleed valve allows the air release while the liquid column is filled by a spray mixture, up to the reservoir's maximum volumetric capacity. Once the reservoir is filled, the bleed valve seals the reservoir and, by increasing the internal pressure, the spray mixture is delivered by the emitters by passing, in order, through the pressure regulator, multiport manifold, and emitter feedline. The four main components (fig. 1) were connected to each other through a 4-way single union ball valve (Model: 453043S44, Arag S.r.l., Rubiera, RE, Italy). This valve allowed for a quick and easy manual switch between the liquid circuits of the two pumping stations and the air compressor, thus passing mixture or water or air through the spray delivery system. The spraying operations of the PSD-SSCDS follow four steps (Ranjan et al., 2019; Sinha et al., 2020b, 2021), namely: i) filling, ii) recovery, iii) spraying, and iv) cleaning (fig. 2). With the recovery valve shut off (fig. 1; fig. 2a), in the filling step, the spray delivery system was filled with spray mixture at an operating pressure of 0.10 MPa. At this step, as soon as the reservoir was filled, the pumping station was stopped. While a fixed volume of the liquid was stored in the in-line reservoir, the surplus spray mixture in the spray delivery system was purged out, by opening the recovery valve and running the compressed air at an operating pressure of 0.10 MPa (recovery step; fig. 2b). Normally, during field operations, the surplus spray mixture is conveyed into the applicator unit tank. However, in the experimental trials, the recovery valve was unplugged from the tank to facilitate the collection of the mixture. After recovery step, the recovery valve was shut off again and compressed air at 0.31 MPa was passed to deliver the mixture from the reservoir through the emitters (spraying step; fig. 2c). The last step (cleaning; fig. 2d), was performed by running compressed air at 0.31 MPa per 30 s to purge out any mixture left in the reservoir and emitters.

To evaluate the influence of PSD-SSCDS components on the system cleaning performance two reservoir volumetric capacities (235 and 700 mL) in combination with two set of emitters, per each reservoir volumetric capacity (N = 2 and 12), were tested (fig. 3). Emitter sets were selected to test the lowest and highest number of emitters that can be installed to a reservoir without affecting emitters' homogeneity spray distribution (Sahni et al., 2022a).

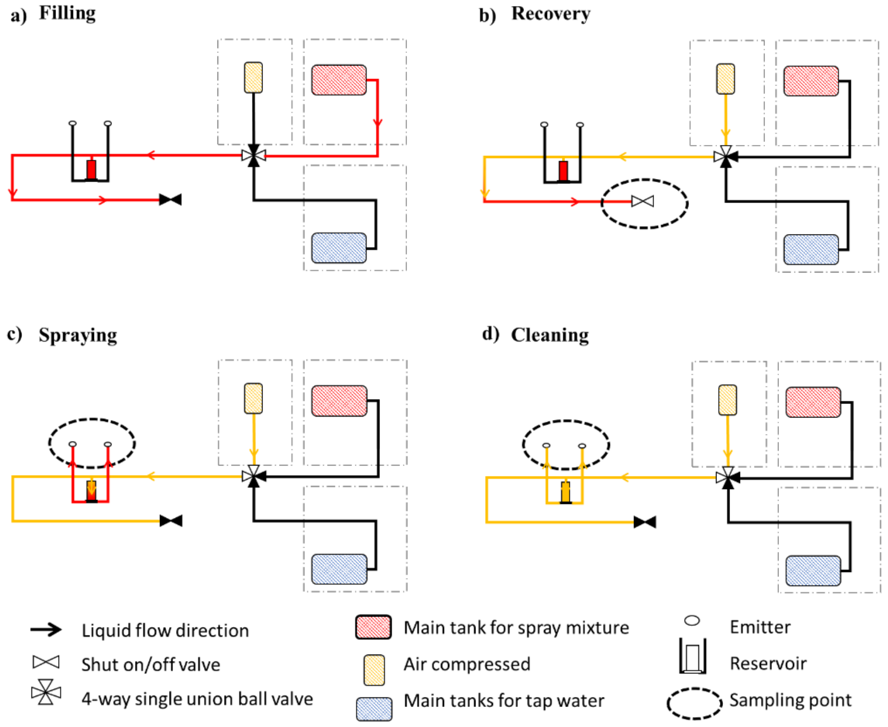

Figure 2. Spraying operational steps of the PSD-SSCDS (not drawn to scale): a) *Filling step*: spray mixture was injected into the system at low-pressure air (recovery valve closed); b) *Recovery step*: surplus mixture was pushed from spray line into collection tank (recovery valve opened); c) *Spraying step*: the mixture was delivered through emitters increasing air pressure (recovery valve closed); d) *Cleaning step*: high-pressure air purged droplets and residual mixture from the emitters (recovery valve closed). Dashed oval indicates liquid sampling points during recovery, spraying, and cleaning steps.

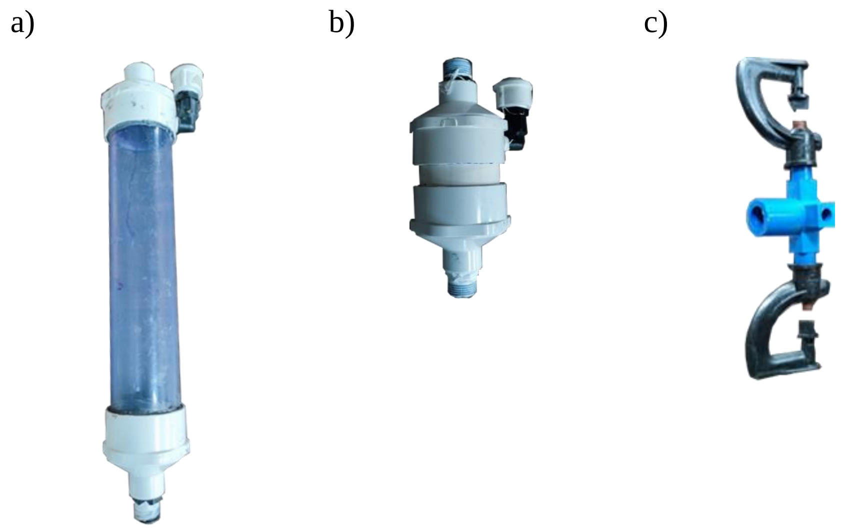

Figure 3. PSD-SSCDS components (not displayed to scale) tested in laboratory for cleaning performance: a) 700 mL reservoir volumetric capacity, b) 235 mL reservoir volumetric capacity, and c) example of modified 90° modular Flat Fan Jain Irrigation emitter.

1.1.1 Cleaning techniques

The PSD-SSCDS cleaning performances were then evaluated comparing five cleaning techniques: four employed an air injection at 0.31 MPa for namely, 30 (*i.e.*, conventional timing), 60, 90, and 300 s, and fifth technique was a combination of air injection and water (hereafter referred to as water rinse). The water rinse technique consisted of performing i) 30 s of air injection at 0.31 MPa followed by ii) water injection in the spray delivery system using pumping station A (fig. 1), iii) water recovery, iv) water spraying, and then v) an air injection for 30 s at 0.31 MPa to realize the air-water-air cleaning sequence. The amount of water injected depended on the reservoir volumetric capacity tested. Thus, considering the liquid needed to fill the reservoir and the surplus liquid into the spray line, 500 (reservoir volumetric size: 235 mL) and 965 mL (reservoir volumetric size: 700 mL) were injected in the spray delivery system.

1.1.2 Sampling methodology

Figure 4 summarizes the workflow of the procedure followed to evaluate the PSD-SSCDS in laboratory setting. This included i) *blank procedure*, to collect eventual residual contamination, inside the PSD-SSCDS before mixture injection, that can interfere during the measurement procedure, ii) *mixture collection*, to collect the reference mixture concentration injected and delivered by the PSD-SSCDS, and iii) *residues collection*, to quantify how much mixture residue was left inside the PSD-SSCDS components after internal cleaning.

The recovery valve and emitters were selected as sampling points to collect the liquid that passed through the spray line and reservoir, respectively. In all cases, 3.78 L capacity plastic bag was placed at the recovery valve outlet to collect all the liquid delivered from that point during recovery step (fig. 2b). Another bag was used to collect all the liquid delivered from the emitters during spraying (fig. 2c) and cleaning steps (fig. 2d). Each of the laboratory trials started with the blank samples collection. The spray delivery system was filled with tap water from pumping station A (filling step) and the surplus liquid in the spray line was purged out from the recovery valve. All the liquid delivered from the recovery valve (water), was sampled accounting for blank samples for the spray line (fig. 2b). After the recovery step, the liquid from the reservoir was first delivered (sprayed) through the emitters (fig. 2c), and residue was purged out (fig. 2d) using compressed air. All the liquid delivered in these steps (spraying and cleaning) was sampled together accounting for blank samples for reservoirs and emitters. The mixture collection step followed the blank procedure. The pumping station B was used in filling step, thus mixture was injected and delivered. Mixture delivered by the recovery valve (recovery step; fig. 2b) was collected. Cleaning techniques (air injection for 30, 60, 90, 300 s, and water rinse) were performed at the last step (cleaning step; fig 2d) during mixture collection procedure. As before, the mixture delivered by the emitters' sampling point was collected by joining the liquid delivered during spraying (fig. 2c) and cleaning steps (fig. 2d). Thus, the collection from the emitters lasted until the air injection technique was run for 30, 60, 90, or 300 s, respectively. For the water rinse technique, the collection of the mixture lasted until the first air injection of this cleaning technique (air injection 30 s). All the liquid delivered in the other steps of the water rinse were not collected as they were out of the scope of this trial. After spray mixture collection the residues collection was carried out. In this step, the pumping station A was used again to inject water in the spray delivery system, to deliver and collect the internal mixture residues left while testing the selected parameters (*i.e.*, PSD-SSCDS components combination and cleaning techniques). The spray mixture residues were sampled separately during the recovery step (from the recovery valve; fig. 2b) and spraying and cleaning steps (from the emitters; fig. 2c, fig. 2d). At the end of each test sampling procedure, the PSD-SSCDS components were cleaned internally (spray line, reservoirs, and emitters) and externally (emitters) three times with tap water to completely remove the residual residues (fig. 4). Thus, the PSD-SSCDS was ready for successive trials. Additionally, a reference sample (50 mL) was collected from the tanks used (pumping station A and B), through plastic vials, before and after blank procedures, mixture collections, and residues collections. In total, three replicates were carried out for each test resulting in the collection of a total of 768 samples.

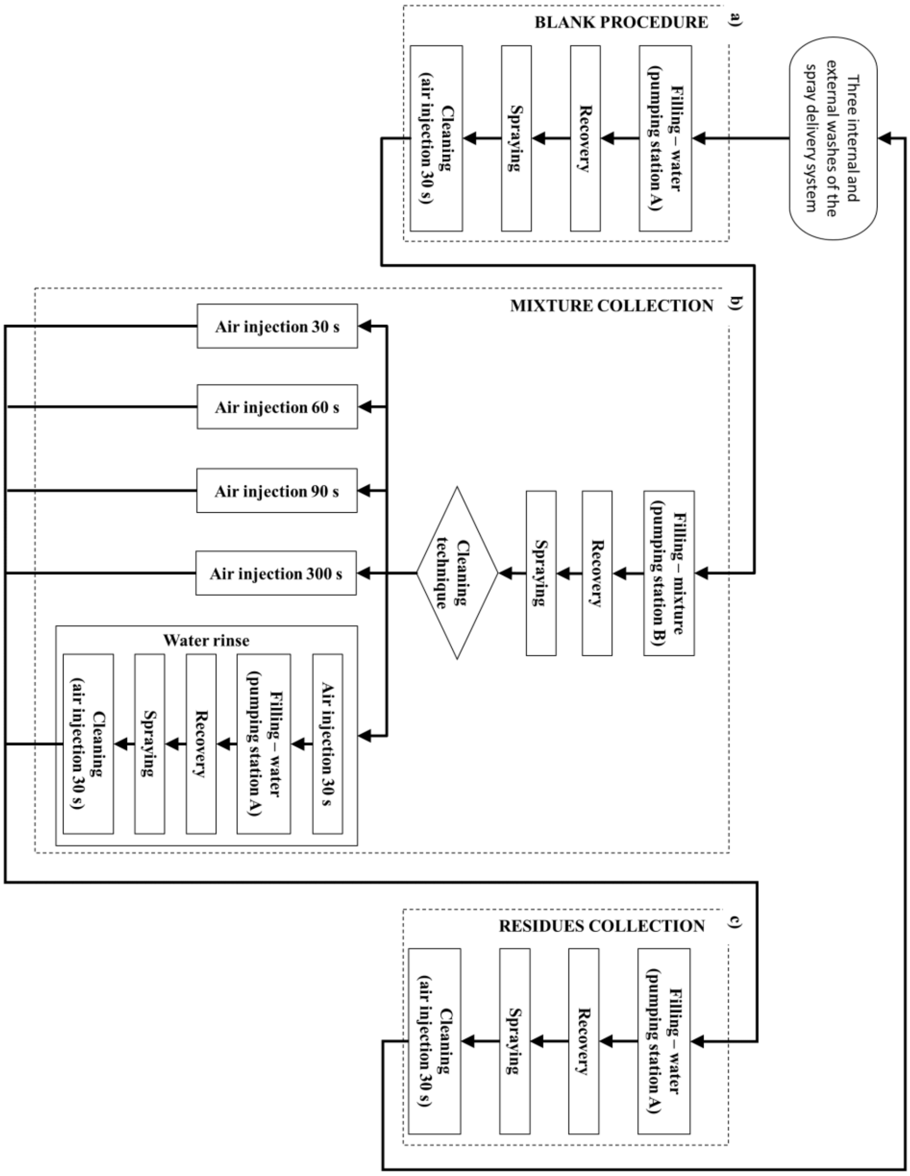

Figure 4. Schematic flow chart of the procedure used to evaluate the cleaning performance of PSD-SSCDS.

1.1.3 Tracer quantification and data analysis

Tracer concentration (ppm) was quantified using a fluorometer (Model: 10AU, Turner design, San Jose, CA, USA) by comparing the results to a calibration curve in accordance with Sinha et al. (2019). In all cases, dilution of samples was carried out when the sample concentration exceeded the maximum reading threshold of the instrument. Pyranine concentration (*C*, ppm) was calculated according to Eq. (1) previously used by Mozzanini et al. (2024) while evaluating E102 Tartrazine yellow dye tracer concentrations.

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

where, P_{smpl} is the measured concentration of the sample (ppm), P_{blk} is the measured concentration of the sample collected in the blank procedure (ppm), and ε is the volume of dilution factor (dimensionless) equal to 1 if no dilution occurred.

From the Pyranine concentration, the cleaning performance (*CP*, %) was calculated according to Eq. (2).

$$CP = 100 - \left(\frac{P_{smpl}}{P_{mix}} \times 100\right) \tag{2}$$

Where, P_{smpl} is the Pyranine concentration of the sample (ppm), and P_{mix} is the Pyranine concentration of the initial spray mixture (ppm).

1.2 Field trials

The cleaning technique, the sampling procedure, and the reservoir volumetric capacity to be tested at field scale were defined based on the laboratory trials results. Thus, the cleaning technique that foresaw the water rinse was used in the field trials as well as the sampling procedure adopted in laboratory trials (fig. 4). During trials, the water rinse cleaning technique was run per ×1, ×2, and ×3 times to evaluate the effect of subsequent rinses on the cleaning performance. As before, the cleaning technique was performed at the last step (cleaning step; fig. 2d) during mixture collection, between the blank procedure and residues collection (fig. 4).

1.2.1 Vineyard and large-scale PSD-SSCDS characteristics

The field trials were performed at a seventeen-year-old VSP-trained experimental vineyard (Vitis vinifera cv. ‘Chardonnay’) at the Roza farm, Washington State University, Prosser (46°17'19.3" N, 119°44'08.9" W). Vineyard rows were spaced 2.74 m apart with an intra-vine distance of 1.83 m (1,994 vines ha^{-1}).

The PSD-SSCDS used for field-scale trials was composed of one pumping station (pumping station A), an applicator unit, and a large-scale spray delivery system (fig. 1). Pumping station A was used, similar to laboratory trials, to feed the large-scale spray delivery system with tap water. The applicator unit, described by Sahni et al. (2022a), was used to feed the large-scale spray delivery system with spray mixture and compressed air. Briefly, the applicator unit comprised a centrifugal pump (Model: 1538, Hypro, New Brighton, MN, USA) powered by a 3.6 kW gasoline engine (Model: GX 160, Honda Motor Co., Ltd., Minato, Tokyo, Japan), a 189 L tank, and an air compressor (Model: 2475F14G, Ingersoll Rand, Davidson, NC, USA). The large-scale spray delivery system (spray line φ: 25 mm), used for experimental purposes, was the one optimized to perform spray applications in VSP training system (Bhalekar et al., 2024). It consisted of an 81 m loop length with 2-tier emitter configuration. In the top-tier spraying line, modified flat fan emitters (Model: Modified StripNet STR31

1AN, Netafim Ltd., Tel Aviv, Israel) were installed every 5.50 m of row length (14 total), resulting in an installation density of 630 emitters ha^{-1}. A 350 mL reservoir volumetric capacity (fig. 5a) was used to feed two emitters (7 reservoirs in total). In the bottom-tier spraying line, flat fan emitters (Model: Modified 90° modular Flat Fan, Jain Irrigation Inc., USA) were installed every 0.90 m of row length (88 total), resulting in an installation density of 3,960 emitters ha^{-1}. In this case, a 235 mL reservoir volumetric capacity (fig. 5b) fed 8 emitters (11 reservoirs in total). Emitter, reservoir volumetric size, and installation densities were planned to deliver 234 L ha^{-1} every single spray delivery. Thus, per each water rinse ran, considering the liquid needed to fill the reservoirs (5.2 L) and the surplus that is injected in the spray line during the filling step (4.8 L), 10 L of tap water were used. The 235 mL reservoir volumetric size, which had lowest cleaning performance in laboratory trails, was sampled in the field trials as it would present to the worst-case scenario.

a) b)

Figure 5. Reservoirs installed in field as part of PSD-SSCDS: a) 350 mL reservoir that fed the top-tier spraying line, and b) 235 mL reservoir that fed the bottom-tier spraying line.

1.2.2 System cleaning performances

To evaluate the cleaning performances of the system, a 1% suspension of copper oxychloride sulfate (C-O-C-S WDG, Loveland Products Inc., Greeley, CO, USA) was used as spray mixture (Grella et al., 2022d; Mozzanini et al., 2024) to comply with the requirements set by the ISO 22368-1:(2004) (ISO, 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 thus being very close to real field conditions when PPPs are applied. To evaluate the worst-case scenario for an effective cleaning of the PSD-SSCDS, two distances from the injection point, in correspondence of a reservoir each, were selected to sample the liquid delivered through the emitters. Thus, 40.5 m (hereafter referred to as emitter A) and 77.0 m (hereafter referred to as emitter B) from the injection point were selected as sampling points because coinciding to the half and the end of the spray delivery system. The reference spray mixture from the applicator unit tank and the pumping station A, from both the emitters, and the recovery valve were sampled by collecting the liquid through plastic vials (50 mL capacity), plastic bags (3.78 L capacity), and a container (30 L capacity), respectively. In compliance with ISO 22368-1:(2004) (ISO, 2004), three reference samples (50 mL each) were collected from the pumping station A and applicator unit tanks, before and after blank procedures, mixture collections, and residues collections. The three reference samples, per tank, were used to verify that the liquid concentration in each tank did not deviate by more than 5% from the average concentration throughout trials. In total, three replicates were carried out per each trial resulting in a total of 63 samples collected.

1.2.3 Copper quantitation and data analysis

Copper oxychloride samples were shaken vigorously for 10 min (1725 rpm; RX-24 mechanical shaker, W.S. Tyler, Mentor, OH) and examined visually to confirm homogenous suspension. A 5 mL aliquot was spiked with 50 ng terbium (Tb – used as the internal recovery surrogate) and underwent microwave-assisted digestion (Model: MARS 5, CEM Matthews, Charlotte, NC, USA) with concentrated nitric acid (5 mL – Fisher TraceMetal™ Grade, Waltham, MA, USA) prior to inductively coupled plasma – mass spectrometry (ICP-MS) analysis for copper quantification (ISO, 2004). Following the microwave program (10 min ramp to 90˚C, hold 20 min at 90˚C; 800 W, 100%), all samples displayed complete (clear) dissolution of suspended materials (no particulates). The digestate was brought to a 50 mL final volume with ultra-pure deionized water (≥18 MΩ) prior to analysis. The ICP-MS instrument (Model: Agilent 7900-CE; Santa Clara, CA, USA) had a collision reaction cell, which was used in He mode (4.3 mL min^{-1}, OctP RF 200V) to eliminate polyatomic interferences US EPA 6020B (2014) (US EPA, 2014). An 8-point calibration (0.01–5000 ppb, R^2: 0.999) was prepared using a certified reference material (Model: Aristar-BDH, VWR, Radnor, PA, USA) and confirmed with an independent standard produced in compliance with ISO 17034:(2016) (ISO, 2016). An instrument internal standard (^{45}Sc) was applied for the calibration and used to monitor performance. Continuing calibration verification ran at least once per 15 samples indicated good stability (< 5% error), and the sample reporting limit for copper quantification (0.5 ppb) was set at the lowest valid calibrant (relative standard error ≤10%). Assay precision was better than ± 5% for copper quantification, based on replicate analysis of separate sample aliquots (*N=7*), which displayed an average relative percent difference of 1.3% (range 0-5%). All other quality control parameters (blanks, spike controls) were within historical range.

To evaluate the efficacy of the cleaning step, the percentage of field cleaning performance was calculated according to Eq. (2) using copper concentrations. No regulatory limit exists for cleaning performance evaluation of SSCDS. Therefore, the approach described by Mozzanini et al. (2024) was adopted in this study. Thus, the conventional reference threshold value for fixed and semi-mobile sprayers cleaning performance (> 99.67%) was used (ISO, 2014).

1.2.4 Statistical analysis

All statistical analyses were performed using IBM SPSS Statistic (Version 28, Chicago, IL, USA) predictive analytical software. All values were tested for normality using Shapiro-Wilk test and by visual assessment of the Q-Q plots of Z-scores. The datasets were Arcsin transformed to achieve residual normality and homoscedasticity. Residual analyses were also performed. Laboratory trial datasets were analyzed separately according to the sampling point (emitters and recovery valve) to investigate, respectively, the spray line and reservoir specific cleaning performance. To evaluate the performance of the laboratory cleaning technique in relation to the PSD-SSCDS component combinations, a three-way ANOVA was used to test the effects of reservoir volumetric capacity (235 and 700 mL), set of emitters (2 and 12), and cleaning technique (air injection for 30, 60, 90, and 300 s, and water rinse) on the dependent variable 'Cleaning Performance'.

For the field dataset, a two-way ANOVA was used to test the effects of sampling point (emitter A, emitter B, and recovery valve), and number of water rinses (water rinse ×1, ×2, and ×3) on the dependent variable 'Cleaning performance'.

In all cases, the means were compared using a Tukey Honest Significance Difference *post-hoc* test for multiple comparisons to evaluate significant interaction among the factors ($p < 0.05$).

2. RESULTS AND DISCUSSION

2.1 Laboratory trials

Figure 6 reports the average mixture residues concentration (ppm) per each cleaning technique according to the sampling point and tested reservoir volumetric capacity and emitters set combination. For the emitters sampling point, considering all the configurations tested, with respect to the 11.77 ppm obtained on average at 30 s air injection, the mixture residues concentration decreased by 16.35%, 26.98%, 40.21%, and 99.71% when air injection per 60, 90, 300 s, and water rinse were tested, respectively. While sampling at the recovery valve, from the average 103.24 ppm collected at 30 s air injection, different concentration reduction percentages values were achieved, equal to –2.56% (negative value means an increment compared to the reference), 4.58%, 56.51%, and 98.82% for air injection run of 60, 90, 300 s, and water rinse, respectively. The emitter sampling showed decreased residue concentrations with increased air injection timing. Yet the recovery valve showed only a slight increase in residue concentration with respect to 30 s when the 60 s air injection was tested (103.24 vs. 105.79 ppm). This outcome could be explained by the fact that, for the recovery valve (accounting for the PSD-SSCDS spray line), higher air injection timing moved more residues from the injection point along the spray line length but without reaching the reservoir and being delivered through the emitters. In fact, increasing the air injection timing by 90 and 300 s, with respect to 60 s, reduced the residue concentration by 7% and 57.53% on average, respectively. Thus, increasing air injection timing expelled more liquid through the emitters decreasing the residues of the spray line (*i.e.*, recovery valve).

The three-way ANOVA, conducted on laboratory datasets (emitters and recovery valve sampling points), reported that the cleaning performance was significantly affected by the reservoir volumetric capacities (235 and 700 mL) and the cleaning techniques (air injection for 30, 60, 90, and 300 s, and water rinse). The factors were significative in interaction only when mixture residues were sampled at the emitters (table 1). When mixture residues were sampled at the recovery valve only, the cleaning technique by itself affected the performance. For the latter, no significant interactions among fixed factors tested were observed. Additionally, for both datasets, the emitter set did not result in significantly different cleaning performance. Thus, data suggested that the PSD-SSCDS internal cleaning performance is not influenced by the number of emitters installed to a reservoir. The results underlined that the unique component influencing the cleaning performance was the reservoir unit and its volumetric capacity. On average, considering all the cleaning techniques, the 700 mL reservoir had an increase of 1.11% in cleaning performance compared to the 235 mL reservoir. As expected, the cleaning technique adopted plays a key role in determining the cleaning performance. Considering that the water rinse cleaning technique was able to considerably reduce the mixture residue concentrations (fig. 7), it derives that it achieved the best cleaning performance. From the pure mixture concentration (500 ppm; pumping station B), using the water rinse cleaning technique, it was possible to achieve cleaning performance (mean ± standard error) equal to 99.99 ± 0.01% (emitters) and 99.76 ± 0.02% (recovery valve). Thus, 499.95 and 498.80 ppm were removed, respectively (fig. 7).

The higher effectiveness of water rinse was reported also in previous studies conducted on internal and external cleaning evaluation of conventional sprayers (Balsari and Marucco, 2017) and, by using Tartrazine yellow dye tracer in HSD-SSCDS (Mozzanini et al., 2024). Additionally, the use of water rinses for both internal and external sprayer cleaning is also suggested by the BMP guidelines (TOPPS–Water protection Project, 2017). While Doerpmund et al. (2011) suggest the combination of air and water, as a cleaning technique enhancing the internal cleaning performance of PAE.

As for water rinse, the air injection timings were capable of reaching higher cleaning performances for the emitter with respect to the recovery valve. This result suggests that the most difficult component to clean was the spray line probably due to the higher contact surface with respect to the reservoir and emitters (~ +28.6%). The conventional 30 s of air injection achieved a cleaning performance equal to (mean ± standard error) 97.64 ± 0.14% and 79.35 ± 0.28% for emitters and recovery valve, respectively. By increasing the air injection timing to 60 and 90 s, the cleaning performances observed were equal to (mean ± standard error) 98.04 ± 0.12% and 98.26 ± 0.10% for emitters and 78.84 ± 0.23% and 80.33 ± 0.24% for recovery valve. Only by increasing the timing up to 300 s was it possible to observe higher performance using air, which equaled to (mean ± standard error) 98.53 ± 0.10% and 91.03 ± 0.44% for emitters and recovery valve, respectively. For the emitter sampling point (fig. 7a), the different cleaning techniques tested for the 700 mL reservoir volumetric capacity, resulted all statistically different between them, suggesting the strong influence of the technique used to improve the cleaning performance. The same outcome was observed for the 235 mL reservoir. For recovery valve sampling point (fig. 7b), it resulted that running the air injection for 30 s (*i.e.*, conventional cleaning technique) would obtain the same cleaning performances as running the air injection for 90 s, but as mentioned before, longer air injections would further improve the cleaning performance.

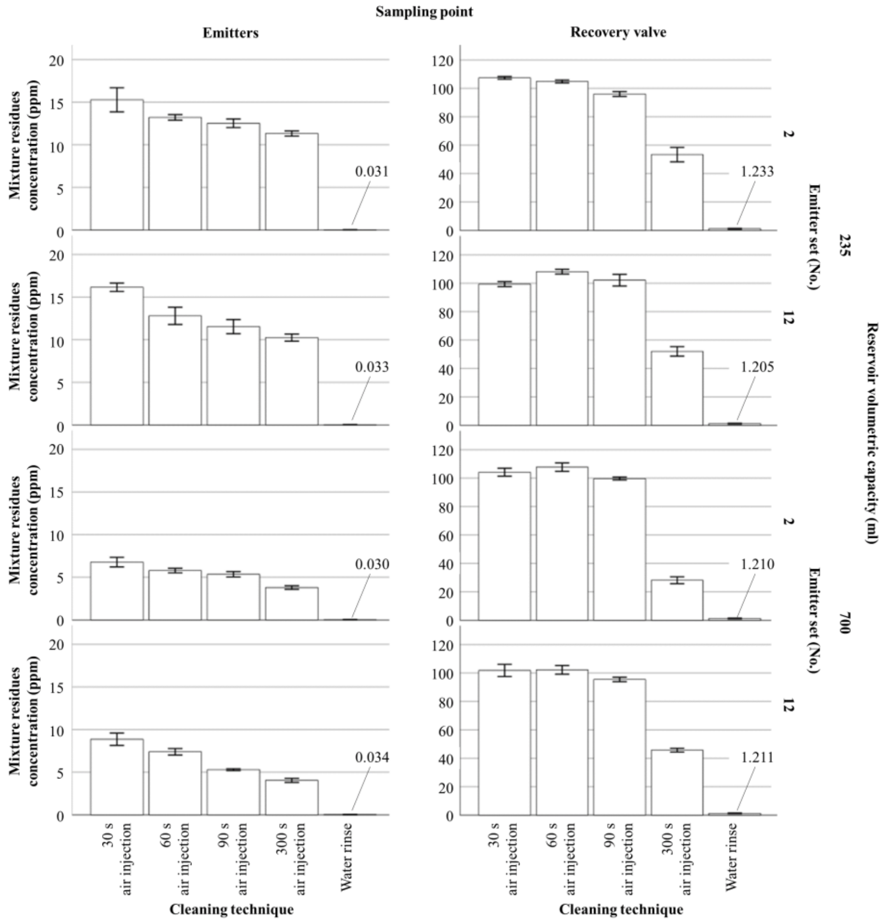

Figure 6. Mixture residues concentration (mean ± standard error) for tested cleaning techniques according to the sampling point and reservoir volumetric capacity combination.

Table 1. Results of the three-way ANOVA ($p < 0.05$) for the cleaning

performance of the emitters and recovery valve sampling point.

	Emitters			Recovery valve		
	DF	*p* > (F)	Signif. [a]	DF	*p* > (F)	Signif. [a]
Main effect						
Reservoir volumetric capacity (A)	1	1.51E-65	***	1	0.07	NS
Emitter set (B)	1	0.21	NS	1	0.26	NS
Cleaning technique (C)	4	3.51E-138	***	4	1.35E-176	***
Interactions						
A × B	1	0.09	NS	1	0.28	NS
A × C	4	5.62E-25	***	4	0.13	NS
B × C	4	0.13	NS	4	0.30	NS
A × B × C	4	0.58	NS	4	0.11	NS

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

a) b)

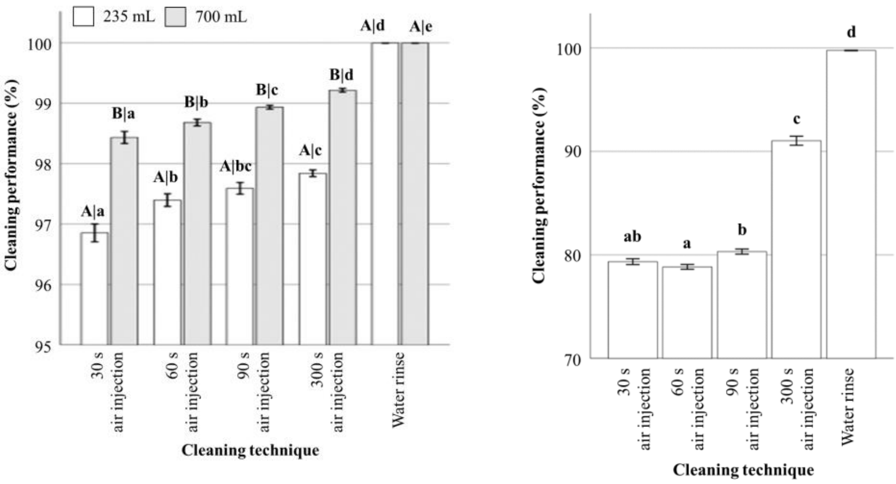

Figure 7. Cleaning performance (mean ± standard error) of a) emitters, according to the two reservoir volumetric capacities tested, and b) recovery valve sampling points. For emitters, different uppercase letters indicate significant differences between reservoir volumetric capacity per each cleaning technique, whereas lowercase letters indicate significant differences between cleaning techniques tested per each reservoir volumetric capacity. For the recovery valve, different lowercase letters indicate significant differences between the cleaning techniques tested.

2.2 Field trials

All sampling point locations showed different values of copper concentration (ppm), yet they all followed the same trend lines (fig. 8). Considering the sampling points (emitter A, emitter B, and recovery valve), the different copper concentration values highlight that the most difficult component to be cleaned was the emitters. On average, the copper concentration in the emitters (791.37 ppm) and recovery valve (43.21 ppm) after ×1 water rinse decreased by 86.96% (emitters) and 95.30% (recovery valve) for ×2 water rinses, and by 96.79% (emitters) and 97.94% (recovery valve) for the ×3 water rinses. In addition, the copper concentration for the recovery valve, accounting for the spray line, decreased faster while running water rinses suggesting that this PSD-SSCDS component is easier to clean compared to the emitters. This is further confirmed in that the spray line with a ×2 water rinse (*i.e.*, 20 L of tap water) would be already enough to comply with the ISO threshold (value > 99.67%) (ISO, 2014).

Copper oxychloride is well known for being sticky (*i.e.*, difficult to remove), and being a suspension, it is difficult to be properly mixed (Grella et al., 2022d; Mozzanini et al., 2024). Even if the copper is deposited into the spray line between the steps that occurred for mixture delivery, the regular and straight-shaped pipe with no corners could be easily cleaned by water. On the contrary, the funnel shape of the reservoirs led to a higher deposition of copper inside the reservoirs itself requiring more water rinses to be properly removed.

The two-way ANOVA indicated that the number of subsequent water rinses done after mixture delivery significantly affected the cleaning performance of the PSD-SSCDS [F2,18 = 7.362; p = 4.61E-03]. On the contrary, no significance was observed for the sampling point as well as for the interaction between the two fixed factors considered (sampling point and number of water rinses). The mixture concentration after ×1 and ×2 water rinses showed an equal cleaning performance of (mean ± standard error) 93.67 ± 2.21 and 99.19 ± 0.38% (emitter A), 89.99 ± 5.16% and 98.67 ± 0.99% (emitter B), and 99.55 ± 0.09 and 99.97 ± 0.01% (recovery valve) (fig. 9). The ×3 water rinse led to a performance equal to (mean ± standard error) 99.80 ± 0.11%, 99.68 ± 0.17%, and 99.99 ± 0.01% for emitter A, emitter B, and recovery valve, respectively. Yet there was no significant difference between the ×2 or ×3 water rinses, meaning a ×2 rinse would suffice for cleaning the PPE. Despite this, results obtained from the field trials showed that, for the tested PSD-SSCDS, the water rinse run ×3 times in a row (involving 30 L of water in total) was able to overcome the ISO 16119-4:(2014) threshold (fig. 9; ISO, 2014) with a 99.82% cleaning performance. This result is even higher than those obtained using cleaning agents while testing conventional sprayers (Marucco et al., 2010), and close to the cleaning performance achieved by Mozzanini et al. (2024) while testing a high (–0.16%) and low (–0.11%) HSD-SSCDS emitter density layout. Previous research also underlined that multiple water rinses were necessary to reach the internal cleaning performance of a PAE (Doerpmund et al., 2011).

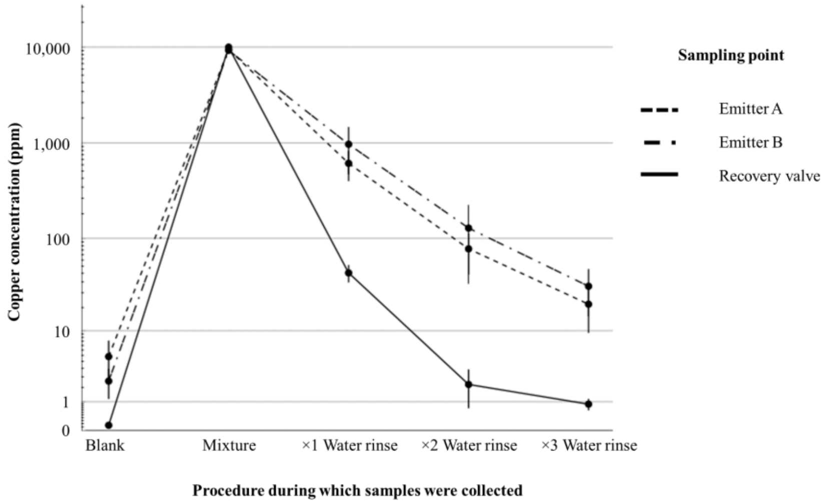

Figure 8. Copper concentration (mean ± standard error) after specific sampling procedure (blank, mixture, ×1, ×2, and ×3 water rinses) per each of the sampling point considered (emitter A, emitter B, and recovery valve). Values in the y-axis are reported in logarithmic scale.

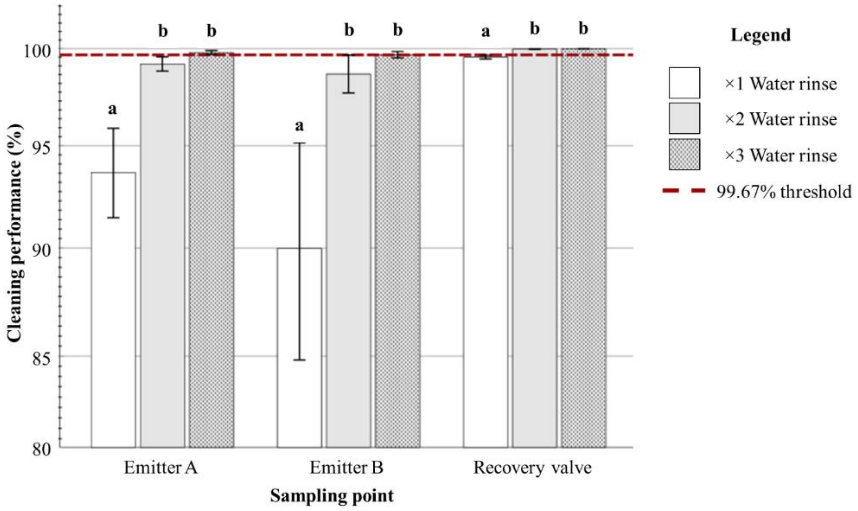

Figure 9. Cleaning performance (mean ± standard error) at each sampling point (emitter A, emitter B, and recovery valve) after the number of water rinses (×1, ×2, and ×3). Red dashed line represents the threshold, above which the cleaning performance is higher than 99.67% in compliance with EN/ISO 16119-4 (ISO, 2014). Different letters denote significance differences among water rinse numbers within each sampling point considered (emitter A, emitter B, and recovery valve) ($p < 0.05$).

2.3 Practical implications of water rinse cleaning technique

According to the field trial results, to reach and overcome the cleaning performance requirements set by the ISO standard (ISO, 2014), a PSD-SSCDS would require substantial modification. In particular, clean water in a dedicated tank as well as a dedicated pump would be needed to run the water rinses. Also, the loop spray line/s conventionally installed in PSD-SSCDS needs to be modified by installing at its end a three-way union ball valve to switch the flow from the main spray mixture tank to an additional auxiliary dedicated tank that would be needed to recover the remnants (water and mixture residues) generated during the water rinse cleaning process. During the PSD-SSCDS field trials, each ×1 water rinse needed 10 L of water, accounting for 5.2 L and 4.8 L used to clean the reservoirs/emitters, and the spray line, respectively. By running the ×3 water rinse, consideration for the amount of contaminated water generated must be calculated for the total volumetric need of these two additional tanks.

This rinse water also requires proper disposal to avoid point source pollution. Considering the total water used for the water rinse, two fractions can be individuated. The first fraction is the one that goes to the reservoirs and therefore to the emitters, meanwhile, the second one is the remaining mixture in the loop spray line. It derives that, following the BMP suggestions provided for conventional PAE regarding the on-site management of cleaning and mixture residues, the first fraction in the case of the PSD-SSCDS can be appropriately managed directly in the field as well. Thus, after a spray application, the contaminated washing water (i.e., diluted PPP) can be applied to the crop canopy (TOPPS-Water protection Project, 2017; Schulze Stentrop, 2019). It’s worth noting that this management of the first fraction would drive to deliver serial dilution of PPP which would be likely intercepted by the canopy instead of the ground. Differently, the second fraction, represented by the remnants collected from the recovery valve and stored in the auxiliary dedicated tank, needs to be properly managed using dedicated devices. To date, devices based on different functioning principles are available to manage the PPP contaminated remnants at the farm site to dispose the PPP without threats to the environment and humans. Briefly, these devices can be divided into four main categories according to their working principle. The simplest and cheapest available on the market are represented by devices based on physical principles, mainly evaporation (e.g., Heliosec, Osmofilm, Remdry) and biological (e.g., biobed, biobac, and phitobac systems). More advanced, complex, and expensive systems are those based on physical-chemical principles, and photocatalytic degradation techniques (De Wilde et al., 2007; TOPPS-Prowadis Project, 2014; TOPPS-Water protection Project, 2017). The adoption of these systems is highly dependent on the farm's investment capabilities and on the amount of remnants to be managed along the growing season (Debaer and Jaeken, 2006; De Wilde et al., 2007; TOPPS-Prowadis Project, 2014; TOPPS-Water protection Project, 2017; Pauwelyn and Vanwijnsberghe, 2019). However, to date, very simple, and economical systems that allow to manage huge volume of remnants at the farmyard are available (Grella et al., 2019). In these trials, 30 L of water was used for cleaning, of which 48% was collected as remnants and 52% was delivered by emitters (remnants management in the field). In this case, the volume used for the internal cleaning of PSD-SSCDS was 50% less than those previously used by Mozzanini et al. (2024) for the internal cleaning of HSD-SSCDS (60 L). It has to be mentioned that the PSD-SSCDS was featured by 2.8 times fewer emitters ha-1 than the HSD emitter layout. Even if a higher amount of water was used to clean the HSD-SSCDS, no remnants were produced because the water is concurrently used as propeller for the delivery of PPP and cleaning agent. In the latter case, all the contaminated water is managed in the field without any remnants collected in a dedicated auxiliary tank like for PSD-SSCDS.

The time occurring between the mixture delivery and the cleaning plays a key role in the decontamination success of sprayer internal surfaces. Trials conducted on conventional sprayers demonstrated that the more the spray mixture is left drying the more difficult it would be to remove it from the sprayer's external surface (Doruchowski, 2019). Grella et al. (2022d) demonstrated that when the cleaning is carried out within 1 hour from the end of spray application, instead of after 24 hours, higher would be the cleaning performance. This demonstrates the importance of cleaning a PAE just after the PPP spray application and this information can be potentially inferred to the SSCDS. Based on the prior literature, the water rinse step during PSD-SSCDS internal cleaning has to be carried out right after the mixture delivery to prevent clogging and effectively clean the system. However, if the cleaning is performed right after the mixture delivery, PPP foliar wash-off can occur due to the in-field management (canopy spray application) of the first fraction of water used for the cleaning. Thus, the definition of time that occurs between the mixture delivery and the cleaning, plays a key role in the decontamination success of sprayer internal surfaces without affecting the biological efficacy of the treatment due to possible PPP wash-off. Thus, a possible solution for the PSD-SSCDS optimal cleaning could be to perform cleaning right after the mixture delivery with a ×1 water rinse to reach an average system cleaning performance equal to 94.40% and then after a few hours, perform the ×2 water rinses to refine the cleaning procedure (potentially reaching an average cleaning performance equal to 99.88%). The two-step cleaning procedure is designed to minimize the risk of foliar PPP wash-off. As supported by Bondesan et al. (2023), which compared the PPP biological efficacy achieved with a conventional airblast sprayer and two HSD-SSCDS layouts, tested with an application rate in all cases equal to 500 l ha-1, it was demonstrated that the PPP biological efficacy remained consistent across all examined plant parts, irrespective of the spraying technology employed. Notably, despite the HSD-SSCDS employing a higher water volume than the PSD-SSCDS (Sinha et al., 2020b) and exhibiting promising biological efficacy results to a conventional sprayer (Owen-Smith et al., 2019; Sahni et al., 2022b; Bondesan et al., 2023), the relatively low water volumes used by the PSD-SSCDS during the water rinse are unlikely to compromise the PPP biological efficacy. Thus, the proposed two-step cleaning procedure would prevent the PSD-SSCDS from clogging through the first water rinse. Then, after a waiting period during which the PPP on the canopy and leaves would dry, and the active ingredient would become less susceptible to removal, the last two water rinses would be performed to meet the regulatory cleaning performance standards (ISO, 2014). It would be expected that at each water rinse the delivered liquid would be retained by the vine leaves with a limited wash-off phenomenon. This procedure would need to be ad hoc field validated through season-long pest management to test possible interactions between water usage and the PPP biological efficacy.

3. CONCLUSIONS

The following are the conclusions from this study:

1. The PSD-SSCDS was able to overcome the cleaning performance threshold of the EN/ISO standard used as a reference for the cleaning evaluation trial (ISO, 2014).
2. Combining air injection and water rinse after spray mixture delivery significantly enhanced cleaning performance (99.88%) in laboratory setup of PSD-SSCDS. Field trials emphasized the need for a modified cleaning step during spray applications with PSD-SSCDS. Three water rinses as a modification addressed challenges such as cross-contamination, components clogging, and runoff effects, ensuring operator and environmental safety with system cleaning performance > 99.67%. The study highlighted considerations for adding new components to the PSD-SSCDS, managing remnants, and determining the timing of water rinses. Contrary to the laboratory results, emitters were difficult to clean in the field setup pointing out the aspect that PSD-SSCDS components behave differently according to the spray mixture injected and its chemical properties.

Further discussions are warranted to adapt existing standards (EN/ISO 16119-4:2014; ISO, 2014) to the unique challenges posed by this novel PAE in the market. These data will support further development and adoption of systems that are in compliance with ISO standards and assist decision makers with their implementation.

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Nomenclature

BMP	Best management practices
HSD	Hydraulic spray delivery
ICP-MS	Inductively coupled plasma – mass spectrometry
PAE	Pesticide application equipment
PPP	Plant protection product
PSD	Pneumatic spray delivery
SSCDS	Solid set canopy delivery system
VSP	Vertical shoot positioning

Chapter V

Session 3: PAE inspection harmonised test methods for PAE not included in ISO EN 16122

Proposal of a methodology for the functional inspection of a fixed spray delivery system

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Abstract

A Fixed Spray Delivery System (FSDS) is a new pesticide system derived from a drip irrigation system. Briefly, it consists of a series of emitters (nozzles) - mounted on a pipeline positioned within the plant canopy - and a pumping station, that can be either fixed or mobile. The FSDS can be used for applying pesticide in bush and tree crops and offers several advantages for farmers such as the possibility to spray at the most appropriate conditions (e.g., low wind speed, right temperature/humidity, and immediately after a rain, etc.), the drastic reduction of tractors use and of related manpower. The adoption of this system could be of primary importance in steep slope areas, where it can represent an alternative to conventional spray application techniques, it can mitigate workers' exposure to pesticides (e.g., when spray application is carried out manually due to inaccessibility of the area with tractors) and avoid safety risks for tractor drivers (e.g., where spray applications are carried out using sprayers connected to tracked tractors and risk of overturning is high). FSDS operates at a pressure and flow rate close to the drip irrigation one, resulting in reduced energy use, compared to conventional Pesticide Application Equipment (PAE), and significantly contributing to carbon footprint mitigation. Due to these positive aspects, the interest in FSDS increased across EU Countries. Since these systems are PAE, they shall comply with the EU Directive on the Sustainable Use of Pesticides (2009/128/EC), article 8, and shall be subjected to a periodical mandatory inspection for their functionality. At present, no specific EN or ISO Standards concerning the requirements and methods for the functional inspection of FSDS are available. Trying to cover this gap, a

first draft proposal about the components of this system that deserves to be subjected to functional inspection has been made. Furthermore, the required functional limits for the different components and the methods to carry out their inspection were investigated and proposed. The present document is intended to provide a first draft set of technical indications about the steps to be followed for carrying out a functional inspection of FSDS. When possible, the harmonized standard EN ISO 16122 for general (part 1) and specific (part 4) components were followed.

1. Introduction

EU policy through the EU Green Deal and the Farm to Fork Strategy has recently highlighted the need to change agricultural practices (Von der Leyen 2019). New technologies are then necessary to optimize spray applications, reduce risks for end-users, and ensure food and environmental safety. In bush and tree crops, spray applications are traditionally carried out by using air-assisted sprayers, but due to their poor technology and inadequate adjustments, most of the spray mixture delivered does not match the canopy, driving spray drift to be a significant issue (Cross et al. 2001; Grella et al. 2017; 2022). As orchards and vineyards are moving towards minimizing the size and density of canopies (Robinson 2007), spray application systems without air assistance have been considered. However, spray application optimization could be achieved also by optimal timing of treatment and by developing pesticide application equipment (PAE) that can operate independently of weather conditions, such as after rain events in which soils are wet and impassable for heavy equipment (tractors and sprayers in general). One promising alternative to conventional PAE is the fixed spray delivery system (FSDS), which plays a key role in achieving environmental, food, and human safety goals while maintaining treatment efficacy (Owen-Smith, Wise, and Grieshop 2019). There are numerous advantages linked to FSDS use such as the drastic reduction of tractors, reduction of manpower, and the possibility of spraying in steep-sloped areas. Noteworthy, besides spray application, FSDS can also be used as an irrigation, frost prevention, and cooling system (Caravia et al. 2017; Costa et al. 2019; Mozzanini et al. 2023). Typically, an FSDS comprises a canopy delivery system, a pumping station, and a cleaning system. The canopy delivery system consists of polyethylene pipelines and emitters permanently positioned at predetermined locations throughout the field rows and crop canopy. The pumping station, which can be mobile, like a conventional airblast sprayer, or fixed, is located outside the field and consists of a spray tank and a pump. The pumping station ensures that the spray mixture is delivered, through the canopy delivery system, regardless of the emitter location. The cleaning system let to deliver the spray mixture and clean the components avoiding cross-contamination between spray applications. The type of cleaning system defines the two main FSDS groups: Pneumatic Spray Delivery (PSD) and Hydraulic Spray Delivery (HSD). In PSD-based FSDS compressed air, provided by an air compressor, is used in two separate stages: first to deliver the spray mixture and second to clean pipeline and emitters (Sahni et al. 2022). In HSD-based FSDS clean water, provided through tap or rainwater supplies, is used at low pressures to simultaneously deliver the spray mixture and clean the canopy delivery system (Dale Threadgill 1985). Due to its many benefits, nowadays FSDS is rapidly raising interest in the EU. In Italy, for example, more than 200 ha of HSD-based systems were already installed in commercial apple orchards. As FSDS is a type of PAE, in the EU it will have to comply with the periodical mandatory inspection of sprayers in use. Regarding this, no EN or ISO Standards concerning the requirements and methods for the periodical mandatory inspection of FSDS are available. Thus, authors believe it is necessary to provide specific advice on how to carry out the periodical mandatory inspection of FSDS. To this extent, when possible, the harmonized Standard EN ISO 16122 for general (parts 1) and specific components (part 4) could be followed. The FSDS inspection should be divided into i) pre-inspection, ii) inspection, and iii) test report sections.

2. Pre-inspection of fixed spray delivery systems

The pre-inspection refers to all the preliminary operations made by the inspector at the beginning of the inspection process and mainly consists of visual tests. Due to the impossibility of being moved, pre-inspection of FSDS fixed components shall be carried out directly in the field (Fig. 1a). Only mobile pumping stations shall be inspected directly to the workshops and according to the conventional EN ISO 16122:2015 requirements (Fig. 1b).

In general, during the pre-inspection the inspector shall verify that:

The FSDS (*i.e.*, pumping station and canopy delivery system) has been properly cleaned checking filters and other internal and external components giving special consideration to areas of contamination to which the inspector could be exposed;

The components and test adapters used for the inspection shall work properly, not cracked and be equipped with the required protection/safety systems;

If present, the moving parts shall work correctly;

The FSDS shall not show visible liquid leaks, excessive abrasions, permanent deformations, cuts, cracks, and/or significant corrosion or damages in general.

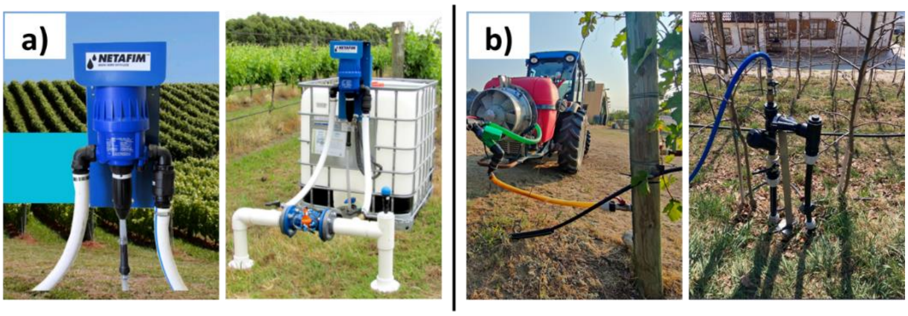

Figure 1. Examples of a) fixed and b) mobile pumping station of a fixed spray delivery system.

3. Inspection of fixed spray delivery systems

This second section lists the test methods, procedures, and instruments to carry out the inspection of FSDS. Many of the requirements already listed in the EN ISO 16122:2015 are applicable to this type of PAE, but for those not reported, specific methods of verification are proposed.

1. Leaks and drips

There must be no liquid leaks.

1.1 – Static leaks

Method of verification - visual test:

- The tank of both mobile and fixed pumping stations shall be filled with water up to its nominal volume. With the pump not running, a visual inspection shall be carried out to detect any leaks from the tank, the pump, and its hydraulic system.

- For large capacity tanks, (>3000 l) water filling can be reduced to not less than half the nominal tank volume, provided that a further inspection of the tank is carried out in order to detect any cracks, holes, or other damage which may cause leakage.

1.2 – Dynamic leaks

Method of verification - visual test:

- Leak-test when not spraying – with the pumping station running, without spraying liquid, at a pressure equal to the maximum pressure that can be used by the system, there shall be no leaks of any kind.

Leak-test when spraying – while spraying liquid at a pressure equal to the maximum operating pressure recommended by the pumping system manufacturer, or by the distribution system manufacturer if lower, there shall be no leaks of any kind.

1.3 – Spraying and dripping on parts

Regardless of the distance between the canopy delivery system and the pumping station, no liquid shall be sprayed directly on the pumping station itself.

2. Pumping station pump

2.1. – Pump capacity

The pump capacity shall be suited to the needs of the FSDS and be at least equal to or greater than 70% of the nominal pump capacity indicated by the pump manufacturer.

Method of verification – functional test:

- The pumping station tank shall be filled with clean water up to half of its nominal volume. A properly sized, clean filter shall be placed on the suction side of the pump according to the pumping station instruction handbook. The measurement must be carried out with the nominal rotational speed of the pump recommended by the manufacturer of the pumping station;
- There shall be no leakage or air ingress from any connection;
- Connect the measuring device (e.g., flowmeter) as close as possible to the pump outlet or at a position provided by the pumping station manufacturer;
- In case of multiple pump outlets, the measuring device shall be connected to each outlet separately or all together at the same time;
- Water discharged from the measuring device shall be fed back into the tank of the pumping station;
- The flow must be measured without any forced back pressure from the measuring device and at a pressure between 0.8 (± 0.02) and 1 (± 0.02) MPa, or if lower, the maximum working pressure of the pump.

2.2 – Backflow for agitation

The pump backflow to ensure tank agitation shall be at least equal to the value indicated in the FSDS instruction handbook. The tank of the pumping station shall be filled with clean water up to half of its nominal volume. A filter, of adequate size and clean, shall be positioned on the suction side of the pump according to the instructions of the manufacturer of the FSDS

Method of verification – functional test:

- With the nominal pump rotation speed recommended by the pumping station manufacturer;
- When spraying liquid at the maximum working pressure recommended by the pumping station or the canopy delivery system manufacturer (the higher of the two values shall be chosen);
- With the canopy delivery system spraying;
- The flow rate returned to the tank can be measured by connecting the measuring device on all backflow/agitation lines separately or simultaneously to determine the total flow rate returned to the tank. The measured values shall then be recorded. Excess liquid (not recovered by the measuring device) is returned to the tank.
- Alternatively, it is possible to calculate the total return backflow (B_F) by subtracting from the measured pump capacity (P_C; l min^{-1}) the total discharge from the pumping station (not recovered by the measuring device) which is returned to the tank (T_D; l min^{-1}).

2.3 – Pulsations

The pulsations shall not exceed ± 10 % of the working pressure.

Method of verification – functional test:

- With the nominal pump rotation speed recommended by the pumping station manufacturer;
- Where is installed the pressure gauge (by using the calibrated test pressure gauge or the pressure gauge of the pumping station if the requirement listed in §5.1 – Pressure gauges is accomplished);
- With the intended working pressure.

3. Spray mix agitation

3.1 – Hydraulic

Clearly visible agitation shall be maintained:

- When spraying at the maximum working pressure as recommended by the sprayer or nozzle manufacturer (whichever is the lower);
- With the largest nozzles mounted on the pumping station;
- With pump rotation speed as recommended by the pumping station manufacturer;
- With the tank filled to half its nominal capacity.

Method of verification – visual test

3.2 – Mechanical

A clearly visible agitation shall be maintained when the agitation system is working as recommended by the pumping station manufacturer, with the tank filled to half its nominal capacity.

Method of verification – visual test

4. Spray liquid tank(s)

4.1 – Pumping station lid

The tank shall be provided with a lid that shall be well-adapted and in good condition. It shall be tightly sealed to prevent leakage and shall avoid unintended opening, and if a vent is fitted in the lid, it shall prevent spillage.

Method of verification – visual test

4.2 – Filling hole

The filling hole of the pumping station tanks shall be provided with a strainer in good condition.

Method of verification – visual test

4.3 – Tank content indicator

The volume of liquid in the pumping station tank shall be clearly readable from where the tank is filled.

Method of verification – visual test

4.4 – Induction hopper

If present it shall prevent any object greater than 20 mm in diameter from entering the pumping station tank, shall properly function and not leak.

Method of verification – functional test

4.5 – Pressure compensation

The pumping station shall be equipped with a pressure compensation device to avoid over- and under-pressure in the tank. The canopy delivery system and the cleaning system shall be equipped with a pressure compensation device to avoid over- and under-pressure to ensure even liquid distribution along the spray line/s (e.g., pressure regulators, pressure compensating drippers, air vents).

Method of verification – visual test.

4.6 – Tank content emptying

It shall be possible to completely empty the tank (e.g., valve or tap) and collect the liquid without contamination of the environment and without the potential risk of exposure of the operator.

Method of verification – visual test.

4.7 – Tank filling

If the FSDS cleaning system is used also to fill the pumping station, or other systems are adopted, backflow prevention systems, to prevent liquid from returning to the water source, shall be installed (e.g., non-return valve).

Method of verification – functional test.

4.8 – Cleaning device for plant protection product containers

If provided, the cleaning device for plant protection product containers shall function.

Method of verification – functional test.

4.9 – Cleaning systems

The pumping station tank and FSDS cleaning systems shall properly function.

Method of verification – visual test.

5. Measuring systems, controls, and regulation systems

All devices for measuring, indicating and/or adjusting the pressure and/or flow rate shall properly function.

The valves for switching on/off the spray shall properly function. In addition, it shall be possible switching on/off all nozzles simultaneously. It shall be possible to operate the control valves during spraying from the operator`s position and the instrument displays shall be readable from this position.

Method of verification – visual and functional test.

5.1 – Pressure gauges

The pumping station, canopy delivery system, and cleaning system shall be equipped with a pressure gauge. The pressure gauges shall be installed in easy-to-reach positions to facilitate their readability by the operator. The scale of analogue pressure gauges, such as their dimension, shall be suitable for the working pressure used by the FSDS.

- The pumping station shall be equipped with a pressure gauge – diameter not less than 63 mm;
- The cleaning system shall be equipped with a pressure gauge – diameter not less than 40 mm;
- The canopy delivery system shall be equipped with a minimum of two pressure gauges – diameter not less than 40 mm. One pressure gauge shall be installed at the topmost part of the spray line. The second shall be installed at the bottommost part of the spray line. The pressure gauge scale shall provide graduation at least every 0.02 MPa. In addition, pressure gauge accuracy shall be ±0.02 MPa for working pressures ≤0.2 MPa, and ±10.0 % of the real value for pressures at ≥0.2 MPa and above.

Method of verification – functional test.

- Pressure gauges shall be tested mounted on their FSDS main components or on a test bench by comparison with a calibrated test pressure gauge.
- Measurements shall be carried out with both increasing and decreasing pressures. In each case, the accuracy of the FSDS

pressure gauges shall be checked at a minimum of 4 equally spaced points within the relevant working pressure range.

5.2 – Flowmeters for controlling the spray volume rate

The flowmeter for controlling the volume rate injected in the pumping station and the one installed on the FSDS circuit (between the pumping station and the canopy delivery system) shall be accurate.

Method of verification – functional test.

- The accuracy of the flowmeters for controlling the volume rate injected in the pumping station and the one installed on the FSDS circuit shall not exceed ±5.0 % of the value measured by the test device.

5.3 – Pressure adjusting devices

All devices for adjusting pressure shall maintain a constant pressure in the whole system with a tolerance of ±10.0 % at constant setting and shall return within 10 s to the original working pressure ±10.0 % after the sprayer has been switched off and on again.

Method of verification – functional test.

- Test shall be carried out using the working pressure given by the manufacturer.
- Use two pressure gauges as testing material (selected according to §5.1 Pressure gauges). One shall be installed at the pumping station and the second at the bottommost part of the canopy delivery system.
- Check the values given by the two pressure gauges.

5.4 – Direct injection systems

If present, shall not show leaks in general, shall prevent backflow through the chemical pathway or through the water inlet of the dosing unit, and have a mixing chamber on the outlet side. In addition, the injection rate of the chemical shall not deviate from what is set on the dosing device by more than ± 10 %.

Method of verification – functional test.

- Operate the direct injection system at the most used setting indicated by the owner/farmer.
- Use clean water in the direct injection system during the measurement of the flow rate.
- Calculate the dosing rate as a percentage by dividing the direct injection system flow rate (B) by the difference between the measured flow rate of the total discharge of the complete system (pump flow rate + direct injection system flow rate) after the mixing device (A; l min^{-1}) and B.

6. Lines

Lines shall not show excessive bending, corrosion, or abrasion through contact with surrounding surfaces. Lines shall be free from defects such as excessive surface wear, cuts, or cracks.

Method of verification – visual test.

7. Filters

FSDS shall be equipped with a filter per each main component (pumping station, canopy delivery system, and cleaning system) to prevent damage due to debris or impurities. It shall be possible, with the pumping station tank filled to its nominal volume, to clean filters without any spray liquid leaking out, except for those present in the canopy delivery and cleaning systems. Filters shall be in good condition and the mesh size shall correspond to what is listed in the FSDS instructions handbook.

Method of verification – visual and functional test.

8. Canopy delivery system

8.1 - Dripping

After being switched off there shall be no continuous dripping from nozzles 5 s after the spray jet
has collapsed.

Method of verification – visual test.

8.2 – Nozzles (emitters)

- All nozzles shall be provided with an anti-drip device;
- Nozzles spray pattern shall match, as much as possible, the canopy area/crop to cover;
- Nozzles spacing and their orientation shall be uniform along the spraying lines;
- Nozzles body spacing, orientation, and configuration shall correspond to the manufacturer's design specifications;
- It shall not be possible to modify unintentionally the nozzle position in working conditions;
- Nozzles (emitters) flow rate shall be accurate.

Method of verification – visual and functional test.

- Nozzles spray pattern shall match the brand-new nozzles one;
- Also, canopy delivery system;
- The average flow rate of at least three nozzles (emitters) per row shall be measured with a measuring device (e.g., cylinder) to calculate the average value of a single nozzle. The three nozzles shall be selected randomly on each row: at the topmost, medium,

and bottommost parts of the spray line. The test shall be performed with nozzles mounted on the canopy delivery system and with the pressure range given by the FSDS or nozzles manufacturer. Nozzle flow rate shall not exceed ±15 % of the nominal flow rate indicated by the nozzle manufacturer for the maximum working pressure of the FSDS instruction handbook.

8.3 – Pressure drop

The pressure drops between the top- and bottommost part of the canopy delivery system, while spraying, shall not be higher than ± 10 %. In addition, the canopy delivery system shall be equipped with one or more vents based on the layout design.

Method of verification – visual and functional test.

- Test shall be carried out using the working pressure given by the manufacturer.
- Use two pressure gauges as testing material (selected according to §5.1 Pressure gauges). Pressure gauges shall be installed on the top and bottommost parts of the canopy delivery system.
- Check the values given by the two pressure gauges.

8.4 – Backflow prevention

To prevent liquid from returning to the water source and pumping station, the canopy delivery system shall be installed with a non-return valve.

9. Autonomous application units

If provided (e.g., travel speed robots, drive systems) shall properly function.

Method of verification – functional test.

4. Test report

A Test report shall report the results of both pre- and main inspections carried out and shall be given to the owner of the FSDS. The test report shall list the following minimum information:

- Place of execution of the tests (field where the FSDS is installed and test station);
- Name, contact details, and company name of the inspector who carried out the inspection and, where different, of the company providing the service (testing organization);
- Date of the inspection;
- Details of the owner of the FSDS (name, address, etc.…);
- FSDS manufacturer;
- FSDS serial number and other identifications per each main component;
- Year of construction;
- Type of FSDS (mobile, with mobile pumping station. Conversely, it can be defined as fixed);
- Any malfunction of the FSDS (even if the malfunction is a result of the FSDS design);
- Any information on malfunctions of the FSDS useful to identify the corrective actions work required;
- Result of the periodical mandatory inspection (results of all inspections performed, both visual and functional).

National or local regulations may give additional requirements for reporting inspections.

5. Conclusions

The present paper represents a first draft of how to perform the periodical mandatory inspection for FSDS, and for that reason, many parts need to be further defined and verified. The number of nozzles (emitters) flow rate to be inspected in this kind of PAE shall be defined considering also the time requested to perform this activity and the huge number of nozzles present in one hectare. In addition, to inspect FSDS, inspectors must move to the field at which the system is installed leading to an increase in the cost of the inspection activity. It is then of primary importance to agree on a solution to limit and simplify, as much as possible, the FSDS inspection activities in order to reduce its cost but at the same to guarantee the maintenance of its functionality as well as the environmental and operator protection during the time.

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Chapter VI

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Quantifying canopy deposition and ground losses of fixed spray delivery system layouts for trellised vineyards

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Summary

A fixed spray delivery system (FSDS), a pesticide application technique based on a modified irrigation system, is raising interest among farmers for spray applications in 3D crops. This vineyard field study compared the spray performance of four hydraulic-based FSDS layouts (L1, L2, L3, and L4) combining three emitter types with different emitter densities (number of emitters per row length). Tartrazine dissolved in water (10 g L^{-1}) was used as testing liquid. Spray deposition and ground losses were assessed by sampling vine leaves and by placing Petri dishes on the ground, respectively. Samples were analysed using spectrophotometry.

The dataset analysis showed a statistically significant effect of layout on mean deposition and ground losses. In general, layouts with a higher emitter density (L2, L4) should promote depositions, but in the hydraulic-based FSDS, result in lower canopy deposits. The emitter density and layout are the key factors affecting the spray performance of a hydraulic-based FSDS.

Keywords**:** spraying equipment, innovative sprayers, solid set canopy delivery system, layout design, pesticide application equipment, emitter density, spray performance

1. Introduction

The need for changing agricultural practices has been reinforced by EU policy, as outlined in the EU Green Deal and the Farm to Fork Strategy. Among others, one of the aims is to reduce pesticide use by 50% by 2030. One possible solution to meet this aim is to employ new application technologies. Traditionally, orchards and vineyards have relied on air-assisted sprayers for plant protection product (PPP) delivery, but in some cases due to inadequate pesticide application equipment (PAE) adjustment and outdated technology, a significant portion of the spray volume is lost off-target, leading to concerns about spray drift (Grella *et al.*, 2022). With the current trend towards minimizing canopy size and density, there is potential to explore PAE without air assistance. Conversely, there is an increasing demand for flexibility in treatment timing, prompting the study of PAE capable of operating independent of soil conditions (e.g., in wet conditions post-rainfall), especially in a heavily sloped landscape (e.g., heroic viticulture) where the only options are handheld PAE. One promising alternative to conventional PAE are hydraulic-based fixed spray delivery systems (FSDS). Hydraulic-based FSDS mainly consist of a network of irrigation polyethylene pipelines and emitters installed along the crop rows (in the field), and a pumping station (outside the field). FSDS have the potential to apply PPPs in an environmentally and human friendly way while ensuring the biological efficacy of treatments (Owen-Smith *et al.*, 2019; Sinha *et al.*, 2020; Bondesan *et al.*, 2023). In Italy, a hydraulic-based FSDS for Guyot-trained vineyards is currently under evaluation. Previous studies focused on i) characterizing the irrigator emitter to be used for PPP delivery (Mozzanini *et al.*, 2022, 2023), and ii) verifying the homogeneity distribution among emitters and the internal cleaning performances (Mozzanini *et al.*, 2024). Since the FSDS emitter positioning into the field (*i.e.*, layout) can be customized to suit specific crops and training systems, four FSDS layouts, resulting from combining three emitter types and two emitter densities (number of emitters per row length), were compared. Spray deposition and ground losses were evaluated in a vineyard at full growth stage.

2. Material and Methods

2.1 Fixed spray delivery system components and operational steps

Hydraulic-based FSDS consist of three main components: i) a mobile pumping station (placed outside the field) – connected to the pipelines of the distribution system and consisting of a tank, a pump, and a hydraulic circuit; ii) a distribution system – composed of pipelines connected with the pumping station, and emitters, installed in the canopy in a specific layout (see §Field location and tested layouts). From the emitters the liquid is delivered onto the crop canopy; iii) a water supply system – connected to the pipelines of the distribution system and directly connected to the tap water system. A double check valve (Arag S.r.l., Italy) between the tap water and the distribution system prevents liquid backflow. The water supply system allows three operational steps: first, to pressurise the system before injecting the spray mixture, second to convey the spray mixture injected by the pumping station into the main pipelines and up to the emitters, and third, once the spray mixture is delivered, to clean the entire hydraulic circuit of the distribution system at the end of the application. The three main components were connected to each other by a three-way single union ball valve (Arag S.r.l., Italy) to switch easily between the circuits of the three main components. A flowmeter (Polmac S.r.l., Italy) was installed at the pumping station outlet to measure the exact spray mixture volume injected in the distribution system. In addition, filters were installed between each component to prevent from clogging.

The three operational steps, to perform a spray application with the FSDS (all at 0.30 MPa), are fully detailed in Mozzanini *et al.* (2024). Briefly as a first step, the distribution system was pressurized by feeding it with tap water (from the water supply system) and water was delivered for 10 s. Second, in the filling step, the water supply system was shut-off and the spray mixture was injected from the pumping station in the distribution system. The flowmeter switched automatically off as soon as the predefined spray mixture volume was injected. This step lasted, according to the layout, 91 (L1 and L3) and 38 s (L2 and L4). Third, spraying and cleaning step, the pumping station was shut-off and the water supply system injected pure water in the distribution system for 420 (L1 and L3) and 300 s (L2 and L4). Water pushed all the spray mixture along the pipelines and through the emitters, until the mixture was completely delivered and the remaining water cleaned all the components in the meantime. Finally, the distribution system remained filled with clean water.

2.2 Field location and tested layouts

Field trials were conducted in Grugliasco, Turin, Italy (45° 3' 54.6" N, 7° 35' 28.9" E), in a twelve-year-old Guyot-trained vineyard (Vitis vinifera cv. 'Barbera', row distance of 2.80 m, intra-vine distance of 0.80 m resulting in 4 464 vines ha^{-1}). The inclined point quadrat technique (Palleya and Landers, 2017) was used to characterize the vine canopy before trials execution. Measurements were taken between 0.40–2.20 m above ground level (AGL). The vineyard had an average height of 2.01 m and a canopy width of 0.50 m. Other vegetation characteristics calculated at the BBCH 89 ‘Berries ripe for harvest’ vine growth stage were: 1.54 m average height of the vegetative stripe, 14.48 % gaps, 1.64 leaf area index, 3.98 leaf area density, and 4 073 m^3 tree row volume, calculated at the BBCH 89 ‘Berries ripe for harvest’ vine growth stage. Each layout (Table 1), one per experimental plot, consisted of two pipelines, placed respectively at 1.50 (middle line) and 2.50 m (top line) AGL, installed and running 31.0 m for a single vineyard row. Each line was fitted with a different number and type of emitters based on the results achieved by Mozzanini *et al.* (2023). Emitters used in the present study were StripNet®, VibroNet®, and MistNet® nozzles coupled with a Pulsar® kit (Fig. 1a; Netafim Ltd Co., Israel) able to pressure compensate the emitters. Emitter working principles and specifications are reported in previous studies conducted by Mozzanini *et al.* (2023). Briefly, the different types of emitters are able to provide the same nominal flow rate (0.20 L min^{-1} at 0.20–0.40 MPa working range) but with a different spray pattern and droplet size characteristics, namely long-range flat fan (StripNet®, very coarse/extremely coarse), large umbrella-shape (VibroNet®, coarse/very coarse), and small umbrella-shape (MistNet®, fine droplet size spectra). Layout L1 combined StripNet® and VibroNet® emitters. The middle line was composed of 78 VibroNet® emitters, 39 on each side of the canopy wall (0.8 m distance between emitters), installed in pairs. Each nozzles orifice was placed 0.16 m from the middle of the row, with the emitter body parallel to the ground (Fig. 1b). The top line had 21 emitters, consisting of three emitters (one StripNet® and two VibroNet®) installed every 4.50 m (seven locations in total). The StripNet® emitter was installed vertically, while the 2 VibroNet® emitters, as for the middle line, were installed parallel to the ground, and with the nozzle orifices opposite to each other. The layout had a total flow rate (at 0.30 MPa) of to 19.8 L min^{-1} and the emitter installation density was 12 774 emitters ha^{-1}. Layout L2 (Fig. 1b) used VibroNet® for both lines, with 78 emitters installed in pairs on each line placed as in the L1 middle line. The layout flow rate and emitter installation density were equal to 31.2 L min^{-1} and 20 128 emitters ha^{-1}, respectively. Layout L3 was similar to L1 but had MistNet® emitters instead of VibroNet® (again combined with StripNet®). Finally, layout L4 was similar as L2 but again with MistNet® emitters instead of VibroNet®. The flow rates and emitter densities of L3 and L4 were the same as for L1 and L2, respectively.

Table 1. *FSDS layouts main characteristics: emitter type and number per line and overall flow rate.*

FSDS layout	Top line (2.50 m AGL)			*Middle line (1.50 m AGL)*		Flow rate (L min^{-1})
	StripNet®	VibroNet®	MistNet®	*VibroNet®*	*MistNet®*	
L1	7	14	-	*78*	-	19.8
L2	-	78	-	*78*	-	31.2
L3	7	-	14	-	*78*	19.8
L4	-	-	78	-	*78*	31.2

a) **b)**

Fig. 1. Emitters tested and combined in order to obtain the four FSDS. a) From left to right StripNet®, VibroNet®, and MistNet® nozzles coupled with Pulsar® kit, and b) example of the VibroNet® emitter installed in layout L2.

2.3 Canopy deposition and ground losses

A water solution of E102 Tartrazine (85 % w/w – Andrea Gallo di Luigi S.r.l., Italy) at a concentration of 10 g L^{-1} was used as spray mixture. In each layout 10 L of spray mixture was injected corresponding with an application rate equal of 1 152 L ha^{-1} (spray mixture only). Then, in the spraying/cleaning step 37.8 (L1 and L3) and 78.0 L (L2 and L4) of water were injected, leading to a total application rate (spray mixture + water delivered) of 5 507 and 10 138 L ha^{-1}, respectively. Spray mixture volume and concentration were set based on Mozzanini *et al*. (2024).

In each layout, three distances from the injection point at 5.8 m (R1), 13.8 m (R2), and 25.8 m (R3) were identified (Fig. 2). At +1.5, 0, and -1.5 m from each of those, following the standardized methodology ISO22522 (2007), nine sampling positions were selected, for each distance, in the canopy at three heights above the ground level (0.8, 1.4, and 2.0 m), and in three positions across the canopy (two externals and one internal). A coded bag was used to collect a single leaf sample from each canopy sampling position for spray deposit quantification. Also, at each defined sampling distance, ground losses were quantified by placing on the ground, transversely to the row and aligned with the canopy used for deposit assessment, an array of seven paired plastic Petri dishes (diameter 90 mm; Aptaca S.r.l., Italy): under the canopy (0 m) and each 0.25 m up to 0.75 m in the inter-rows at the right and left of the canopy. Meteorological data (wind speed, wind direction, air temperature, and humidity) were monitored throughout the trials with a weather station.

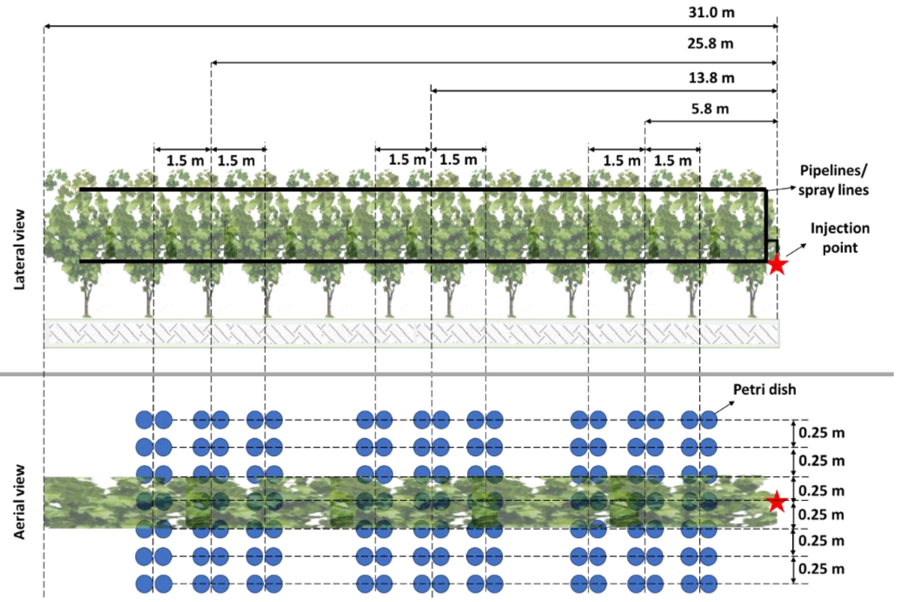

Fig. 2. Sampling methodology adopted for canopy deposition and ground losses assessment per each FSDS layout tested (figure drawn not in scale).

2.4 Data analysis

Sample concentrations were determined using a UV-1600PC VWR spectrophotometer (WVR International, USA) by measuring their absorbance at 427 nm wavelength. Results were compared to a calibration curve. Dilution of samples was carried out if necessary (*i.e.*, Tartrazine concentration of the samples out of the optimal instrument reading range). The spray canopy deposit and ground losses (C), were calculated according to *Eq.* (1) in order to obtain the deposit amount per surface unit (µL cm^{-2}).

$$C = \frac{(P_{smpl} - P_{blk}) \times V}{0.5 \times (P_{start} + P_{end}) \times A} \quad (1)$$

Where P_{smpl} is the measured absorbance of the sample (dimensionless), P_{blk} is the measured absorbance of the tap water provided by the water supply system (dimensionless), V is the volume of dilution liquid (μL; deionised water) used to extract the tracer deposit from the samplers, P_{start} and P_{end} are the absorbance value of the spray mixture concentration sampled from the pumping station main tank before and after each trial, respectively (dimensionless), A is the area of the sampler exposed to the spray (cm^2).

The ratio (%) between canopy deposits and ground losses for each layout was also calculated to identify which layout resulted in the most efficient spray delivery.

2.5 Statistical analysis

All statistical analysis was performed using IBM SPSS Statistic (Version 28, USA) 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 canopy deposit and ground losses. Residual analysis was also performed. Dataset derived from canopy deposit and ground losses were analyzed separately. A two-way ANOVA was used to test the effects of the independent variable sampling height above the ground and FSDS layout on the dependent variable canopy deposit. A one-way ANOVA was used to test the effects of the independent variable FSDS layout on the dependent variable ground losses. In all cases, means were compared using Duncan's *post hoc* test for multiple comparison ($p < 0.05$).

3. Results and Discussion

3.1 Canopy deposit and ground losses evaluation

Results indicated that in the hydraulic-based FSDS the higher amount of spray mixture deposited in the top region of the canopy. This trend was more evident in the layouts installed with StripNet® emitters (L1 and L3), suggesting its stronger potential of providing a more uniform and targeted spray distribution in the top portion of the canopy with respect to VibroNet® or MistNet® (Fig. 3a). Considering the canopy penetration capability results (Fig. 3b) the spray liquid was able to deposit in the three depths investigated (both the two externals and one internal). The two-way ANOVA indicated a strong interaction between sampling height AGL and FSDS layout main effects (Tab. 2). In general, the highest deposition (±SEM) was observed for layout L1 (0.46 ± 0.03 μL cm^{-2}), followed by L3, L2, and L4, with values of 0.21 ± 0.02, 0.15 ± 0.01, and 0.07 ± 0.01 μL cm^{-2}, respectively.

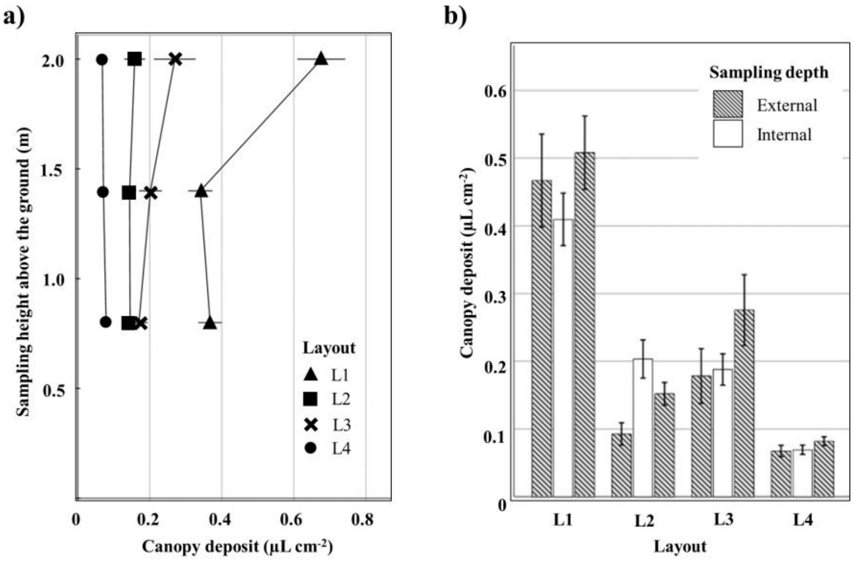

Fig. 3. Mean spray deposition (µL cm^{-2}) of each layout according to a) the sampling height above the ground (0.8, 1.4, and 2.0 m); b) the sampling depth (externals and internal canopy portions).

Table 2. Result of the two-way ANOVA (p < 0.05) for canopy deposits (µL cm^{-2})

	DF	p > (F)	Signif. [a]
Main effect			
Sampling height above the ground (A)	2	4.51E-06	***
Layout (B)	3	3.76E-37	***
Interaction			
A × B	6	5.13E-07	***

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

Regarding ground losses, the lowest values (±SEM) were recorded for L3 with 2.99 ± 0.34 µL cm^{-2} followed by L2, L4 and L1, with values equal to 4.12 ± 0.40, 4.70 ± 0.37, and 5.28 ± 0.52 µL cm^{-2}, respectively (Fig. 4). The one-way ANOVA indicated that FSDS layout has a significant effect [F3,500 = 5.554; *P* = 9.35E-04]. As expected, being a fixed spray system targeting the liquid over the row, ground losses were highest under the row in the ±0.50 m zone from the row midpoint. This outcome is in line with previous findings (Ballion & Verpont, 2023).

The overall results indicated that the emitter spray pattern, and consequently the emitters density, as well as the emitter location into the canopy, are key factors influencing the spray delivery. The difficulty in achieving a consistent canopy deposition was observed with the layout L2 and L4, even using a high emitter installation density layout. This outcome is in contrast with Sharda *et al*. (2015) highlighting the difference between pneumatic and hydraulic-based FSDS. In general, a layout using emitters with a spray pattern that matches the canopy characteristics has to be preferred to maximize the spray deposition on the canopy. In fact, the ratio between canopy deposit and ground losses were only 9%, 4%, 7%, and 1% for layouts L1, L2, L3, and L4, respectively. This means that most of spray mixture delivered is lost to the ground. In general, the low canopy deposit obtained was due to an excessive wash-down effect caused by the large volume of water applied during the spraying/cleaning step. In fact, among layout tested, in L2 and L4 the volume delivered was higher than the one used in L1 and L3 (+106%) which led to an over-dilution of the spray mixture collected by the Petri dishes (*i.e.*, tracer inside the Petri dishes was spilled and diluted by water used in spraying/cleaning step because the maximum capacity of the Petri dish was in many cases exceeded). Results clearly underline that the total amount of liquid delivered is excessive. A possible solution to increase canopy deposition by reducing the wash-down effect, is to decrease the overall flow rate of the whole FSDS. This is further suggested by the higher canopy deposits obtained in L1 and L3 with respect to L2 (+67.3, and +28.6%), and L4 (+84.8, and +66.7%) layouts. One option is to drastically reduce the number of emitters installed and optimize the spraying/cleaning step (*i.e.*, minimum water amount needed to clean the system). In fact, the canopy deposit values obtained from trials are in line with those obtained by Biglia *et al.* (2022) using an uncrewed aerial spray system (UASS) in the same vineyard plot at low application rates (250 L ha^{-1}). Furthermore, using UASS authors obtained lower ground losses compared to FSDS. Additionally, results are far from those obtained by using ground-based sprayer application and this is further suggested by the amount of ground losses measured in FSDS.

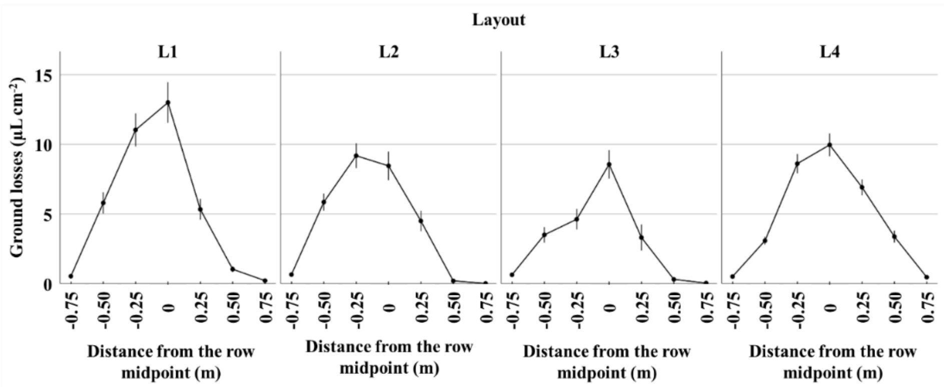

Fig. 4. Mean ground losses (µL cm^{-2}) of each layout tested at seven sampling distances from the row midpoint (0, ±0.25, ±0.50, and ±0.75 m).

4. Conclusion

The 2-tier layouts L1 and L3, among the ones tested, gave the best results both in terms of higher canopy deposition and better canopy deposit and ground losses ratio. Anyway, the overall low canopy deposit indicates that further FSDS optimization is needed to improve the spray application using fixed system in order to increase canopy deposit and decrease ground losses. Based on these outcomes, Netafim company developed the StripNet X® nozzle. This is a new specific nozzle for FSDS installed in vineyards, characterized by a spray pattern better matching the vine canopy allowing to decrease the emitter installation density. Trials aiming to test different FSDS layouts, equipped with StripNet X® nozzles, are ongoing at the DiSAFA facilities. Different layouts will be compared for their spray performance at different vine growth stages and canopy densities.

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Final considerations and future perspectives

General discussion

In the first study (Mozzanini et al., 2023a), which is pivotal to the overall research, three irrigators (hereafter called emitters) normally installed in irrigation systems to perform over-head irrigation and frost/freeze protection in vineyards and apple orchards, were evaluated to be adopted as HSD-FSDS emitters (*i.e.*, nozzles to deliver PPPs). The studied emitters were selected for their capability to overcome pressure drop issues over long installation distances. First, the activity focused on the analysis of the emitter parameters influencing the spray performance (droplet size spectrum, horizontal spray pattern, flow rate) to compare them with conventional agricultural nozzles used for PPP delivery. Second, the outcomes obtained and additional field trials aimed to identify promising emitter installation configurations and spacings (i.e., layouts), to be further tested in a Guyot-trained vineyard.

The trials carried out in the workshop investigated the flow rate of the emitters at four operating pressures to test its pressure compensating capabilities, and therefore maintaining a fixed flow rate of 0.20 l min^{-1} at least between the operating pressures declared by the manufacturer (0.25 – 0.40 MPa). The data collected demonstrated that at the operating pressure adopted in the field (0.30 MPa), this emitter would maintain an average flow rate of 0.206 ± 0.03 l min^{-1}, and thus close to the nominal one. Considering the overall tested emitters and pressures, the results highlighted that even if the operating pressures tested exceeded the optimal pressure range, emitters delivered on average 0.209 ± 0.03 l min^{-1}. It is noteworthy that pressures of 0.20 and 0.50 MPa represented testing values outside the manufacturer's recommended range. Therefore, from one side overapplications could occur if operating pressures are higher than 0.40 MPa (in the worst case a +4.5% at 0.50 MPa was recorded for the single-sided flat fan emitter), on the other side the emitters flow rate varied always less than ±5% from the one declared by the manufacturer, thus complying with the ISO 16119-4 requirement as requested for conventional agricultural nozzles (ISO, 2014).

The droplet spectra parameters measured for the double-sided (VMD = 453.1 ± 37.9 μm) and circular (VMD = 338.1 ± 6.8 μm) emitters aligned with those of air inclusion nozzles tested under field and laboratory conditions (Van de Zande et al., 2008; Grella et al., 2017). Their cumulative curves moved between the 'coarse' and 'extremely coarse' ASABE spray quality classification thresholds (ASABE S572, 2009). Therefore, results demonstrated their potential to be used as a spray drift reducing technology (SDRT) and potentially reduce drift phenomena. Conversely, the single-sided emitter cumulative curve classified in the 'medium' spray quality threshold (VMD = 266.3 ± 40.6 μm), thus resulting closer to conventional agricultural nozzles (Van de Zande et al., 2008; ASABE S572, 2009; Ferguson et al., 2015).

Since the HSD-FSDS is a fixed technology installed along the crop rows and doesn't move as conventional ground-based sprayers do, the horizontal spray pattern evaluation was the key to determining the best layout to minimize spray overlap and produce a homogeneous spray distribution along a row. Per each emitter type the horizontal spray pattern was characterized from the lateral (max spraying distance from the spraying source) and aerial point of view (sprayed liquid recovered at different sampling points from the spraying source). It was then observed that both flat fan emitters produced a long-range triangular shape pattern that would have been the potential optimal one to spray the vine row canopy from the top. The circular emitter, on the other side, produced an irregular shape that would potentially have improved the vine row canopy penetration if used to deliver a liquid from the row side if installed with the emitter body parallel and at a certain height above the ground. Considering a vine row width of 0.52 m (full growth stage) was therefore estimated that if the single- and double-sided flat fan emitters were used to deliver a liquid over them, they would potentially deposit 90.70% (single-sided) and 85.70% (double-sided), with potential ground losses equal to 9.30% (single-sided) and 14.30% (double-sided). Next, adopting a similar procedure to that used by other authors while evaluating the horizontal spray distribution in boom sprayers (Holterman et al., 2018; Zwertvaegher et al., 2022), multiple spray patterns for the same emitter type were graphed one next to each other and areas superimposed along 15.0 m. Based on the superimposition area analysis the homogeneity of spray distribution was defined through the coefficient of variation (CV) of the spray distribution in the target zone. It was estimated that the spray homogeneity along a row would have been reached by spraying the top and side canopy areas through dedicated spray lines. For the top canopy area, a first spray line composed of one double-sided flat fan in combination with a circular emitter installed every 7.50 m, reached a CV equal to 7.3%. For the side canopy area, a second spray line with circular emitters spaced every 3.0 m reached a CV equal to 6.3%. To further confirm the workshop finding the spray coverage capabilities were tested in the field (full growth stage) per each of these types. The final optimized HSD-FSDS layout proposed was composed of 2 separate spray lines (2-tier layout) to spray both the top and side canopy areas further confirming, as previously proposed, the need of a 2-tier layouts for HSD-FSDS designed for vineyard (Sinha et al., 2020a). Results confirmed the workshop proposed spacing and emitters combination to spray the top canopy area with emitters installed at 0.50 m above the canopy. The resulting emitter density equaled 520 (double-sided) and 1040 (circular) emitters (one circular emitter per each canopy side and installed parallel to the ground with the emitter tip at 0.18 m far from the row midpoint) per hectare in a typical 2.50 m inter-row vineyard layout. Conversely, to spray the side canopy area, the circular emitter spacing was optimized and reduced to 0.80 m, and as done for the top canopy area, it was proposed to install emitters at both the canopy sides, with the emitter body parallel with the emitter tip at 0.18 m far from the row midpoint, but at 1.50 m above ground height. For this second spray line, the resulting emitter density equaled 8000 emitters ha^{-1} in a typical vineyard layout. The overall activity demonstrated (i) the suitability of the emitters to be used to apply PPPs complying with the thresholds set for conventional agricultural nozzles, (ii) that the emitters were able to potentially reach the performances of such spray drift reducing technologies (SDRT). This study set the base for further field trials aimed at the comparison with sprayers equipped and adjusted, with spray drift reducing technologies and techniques, respectively.

In the second study (Mozzanini et al., 2023b), the double-sided flat fan emitter (StripNet) was further investigated for its potential to be used as an HSD-FSDS emitter for PPP application evaluating its potential as SDRT (Mozzanini et al., 2023a). The study aimed to test the potential use of a spray line, equipped with StripNet emitter, to spray from the top of the canopy (0.50 m above the canopy top) in Guyot-trained vineyard and semi pedestrian-trained apple orchard cases. The study compared first, the spray coverage at different distances from the spraying source (*i.e.*, the emitter), and second, compared the spray coverage obtained by the emitter and a sprayer equipped with SDRT. Regardless of the leaf surface, and in accordance with the fact that the liquid was sprayed from the top canopy area, the highest spray coverage was reached at the top canopy area both for the vineyard (nearly 33%) and apple orchard (nearly 40%). Conversely, the medium and low canopy areas were characterized by lower values. Despite this outcome, with respect to the vineyard case (10.02%), the apple orchard had higher mean spray coverage (28.67%), underlining the capability of the spray to better penetrate apple tree canopies. Furthermore, the StripNet emitter resulted in a more uniform spray coverage along the canopy height just for the apple orchard case. Results were close to other coverage evaluation studies aimed at both HSD- and PSD-FSDS layout evaluations (Sharda et al., 2015; Otto et al., 2018; Mozzanini et al., 2023a; Bhalekar et al., 2024), thus suggesting from one side that a 1-tier HSD-FSDS layout could potentially be a suitable solution for the apple orchard case (semi pedestrian-trained) and, from the other side, the vineyard would need a 2-tier layout to reach a homogeneous spray coverage and increase the potential spray deposits into the grape band.

Regarding the comparison between the StripNet emitter and the conventional sprayers equipped with SDRT comparison, even if, with respect to the conventional sprayers, the overall spray coverage achieved with the double-sided emitter was lower for both the crop tested (-10% for apple orchard and -27.31% for vineyard), the top canopy area spray coverage resulted in equal values (vineyard case) or even three times higher (apple orchard case). It must be mentioned that the activity was carried out with water sensitive papers (WSP) only, thus further trials were planned to evaluate the canopy deposit as well. In this context, the activity and the related outcomes were presented in chapter six.

In the third study (Mozzanini et al., 2024a), the 2-tier HSD-FSDS layout proposed by Mozzanini et al. (2023a) was field installed and first tested to evaluate its capability to deliver along the spray lines a homogeneous PPP quantity. One of the challenges of the fixed spray systems, and for the HSD-FSDS in particular because is not equipped with reservoirs like the PSD-FSDS, is to deliver the same PPP amount along a row in which is installed and, more extensively, into the field.

The average spray mixture homogeneity among the sampled emitters showed a CV equal to 6.71%, thus reaching similar results to conventional PAEs equipped with direct injection systems (Vondricka and Lammers, 2009; Dai et al., 2019) and uniformly delivering the spray mixture to the crop canopy as conventional sprayers do. In the same study, being the HSD-FSDS a pesticide application technology, the internal cleaning performance was evaluated to verify compliance with the set environmental and sprayer performance mandatory threshold (ISO, 2014).

Results showed that in the worst-case scenario, with respect to the 99.67% threshold value (ISO, 2014), it is possible to achieve a +0.26% internal cleaning performance. Therefore, the HSD-FSDS achieved higher cleaning performances with respect to conventional cleaning methods adopted for sprayers such as cleaning agents or triple water rinse (Marucco et al., 2010; Doerpmund et al., 2011). Thus, the HSD-FSDS resulted fully capable to be properly cleaned after delivering a spray mixture. In the same study, two linear regression models were also developed to estimate spraying/cleaning step duration and pure water consumption according to the total HSD-FSDS flow rate.

The conducted activities (emitter characterization, homogeneity distribution along the line, and cleaning performance) set the groundwork for the HSD-FSDSs optimization.

In the fourth study, considering the EU regulations with which pesticide application technologies must comply, and to further enlarge the performance baseline of FSDSs in general, the cleaning performance was also evaluated for the PSD-FSDS. Differently from the HSD-, where the “propeller” used (*i.e.*, water) resulted in the key element to achieve compliance with the regulatory threshold, for the PSD-FSDS the only combination of air injection and water rinses, since laboratory trials, resulted the only optimal cleaning technique to clean the spray delivery system. In general, the air injection itself, even if increased up to 300s (always at 0.31 MPa), didn’t lead to overcome the 99.76% threshold value (ISO, 2014). Only when air injection was combined with water rinse it was possible to achieve, at the laboratory scale, a PSD-FSDS internal cleaning performance equal to 99.88%. Field trials emphasized the need for a modified cleaning step and, after spray mixture delivery, only three successive water rinses, with respect to the 99.67% threshold value (ISO, 2014), reached a +0.15% internal cleaning performance, getting close to the performance achieved by the HSD-FSDS (99.93%; Mozzanini et al., 2024a). The three water rinses would address challenges such as component clogging, cross-contamination, and runoff effect, ensuring operator and environmental safety. It has to be considered that, to overcome this ISO threshold, the PSD-FSDS should be equipped with additional components to (i) hold the clean water to perform water rinses, and ii) collect the remnants from the recovery valve after each water rinse, therefore leading from one side to increase the number of tanks needed to perform a spray application with a PSD-FSDS (one each to hold the spray mixture, clean water, and collect the remnant), and from another the need to define a proper practice for remnant management (e.g., Heliosec, Remdry, biobed). Considering the outcomes achieved, from which was estimated a huge consumption of water if the suggested operations were followed, it was also discussed the possibility of adapting (lower) the existing regulatory threshold to this novel pesticide application technology.

In the fifth chapter, since the FSDSs are starting to be installed across the EU, especially in the North-Est of Italy, to meet the need for specific regulations referred to FSDSs, a first FSDSs' inspection methodology draft was proposed to comply with the Directive of the EU for the sustainable use of pesticides (European Community, Directive

2009/128/EC; https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0128), and, in particular, the periodical mandatory inspection for the FSDSs functionality requirement. To further contribute to closing the legislative gap on this novel pesticide application technology, since no specific EN or ISO Standards concerning the requirements and methods for their functional inspection are available, a first draft proposal about the components of this system that deserve to be subjected to functional inspection has been presented. The paper, that is based to the actual standards used for the conventional sprayers performance evaluation, is intended to provide a first draft set of technical indications about the steps to be followed for carrying out a functional inspection (*i.e.*, a series of checking and limits to evaluate the FSDSs performances).

In the sixth study, the spray performance of the first HSD-FSDS 2-tier layouts equipped with the emitter characterized by Mozzanini et al. (2023a) was field-evaluated. In general, as previously obtained by the workshop and the preliminary field trials (Mozzanini et al., 2023a; 2023b), it was observed higher deposits in the top canopy area with values, in the best case scenarios, equal to 0.68 and 0.26 μL cm^{-2}. Moreover, the layouts that gave better results spraying PPP from the top of the canopy were the ones equipped with the StripNet emitters. In addition to the previous outcome, it was noticed that layouts characterized by lower flow rates achieved higher mean deposits (0.46 and 0.21 μL cm^{-2}). The obtained results were close to the values achieved by the first experiment conducted by previous authors (Sinha et al., 2020b) and far from the ones achieved using a PSD-FSDS (Bhalekar et al., 2024). The ground losses obtained further suggested that the HSD-FSDS needs to be optimized to reduce the significant wash-off effect observed. Despite this outcome, it has to be noticed that the highest ground losses were obtained in correspondence to the plant trunk and seemed restricted to the row nearby. Therefore, as observed also by other authors, this pesticide application technology, with respect to conventional sprayers, has a considerable advantage in limiting drift (Shina et al., 2020a; Ballion and Verpont, 2023). The trial revealed the need for some technology refinements to reduce the water volume used during spraying applications, and thus the wash-off effect. To achieve this goal some suggestions, such as the overall flow rate reduction, emitter reduction, and pipeline re-sizing, were proposed. It was also highlighted the need to develop a specific emitter for the HSD-FSDS using, due to its characteristics, the StripNet emitter model tested over the years as a baseline.

In conclusion, from the combination of laboratory and field trials aimed at (i) the emitter characterization, (ii) HSD-FSDS field spray homogeneity performance evaluation, (iii) HSD- and PSD-FSDS compliance evaluation to the actual sprayers' internal cleaning threshold and remnant management recommendations, (iv) the drafting of an inspection methodology to check the FSDS performances across years after their installation and use, and (v) spray performance evaluation of different 2-tier layouts, the HSD-FSDS technology was engineered and improved from a "Experimental proof of concept" (technology readiness level – TRL 3) to a "Technology validated in a relevant environment" (TRL 5). Yet further trials, presented in the following chapter, need to be done to fully promote the HSD-FSDS full-scale commercialization and to cover research gaps.

Conclusions and future research directions

The FSDS has recently emerged as a novel field of study in spray research, offering intriguing possibilities for pest management in agriculture. Historically, the focus of research on this spray application technology has been limited and primarily compared its spray performance with conventional ground-based sprayers. This comparison is crucial since ground-based sprayers have been a long-standing spraying technology in agriculture, therefore this has to be still the reference but, since FSDSs are designed, and a suitable technology, to spray in sloped areas, other novel technologies, such as uncrewed aerial spray systems (UASS), and "more" traditional ones, such as hand-held sprayers, must be included.

A second FSDS key area of investigation has been the emitters. Nowadays valuable options have been defined for two major crops (apples and grapes), different training systems (spindle and semi-pedestrian for apples, and pergola, Guyot and vertical shoot positioning for grapes), and type of FSDS (HSD- and PSD-FSDS). In this context, the next gap to be covered will be the evaluation and optimization of this pesticide application technology for other crops such as citrus (only a preliminary study has been conducted in China), other trellised 3D perennial crops (e.g., apricots, plums, blueberries, cherries), and further apples and grapes training systems.

The next gaps to be covered involve a better understanding of the environmental factors influencing the FSDS, such as wind speed and direction, to define how these novel pesticide application technologies could reduce spray drift with respect to conventional ones. To do so, a season-long spray drift evaluation, carried out according to the reference ISO standard methodology (ISO 22866:2005), is necessary to define the environmental pros of this technology. Moreover, the operator and bystander's exposure while operating with FSDS need to be investigated. Therefore, while performing drift evaluations, studies must likely consider also these aspects.

The FSDS stands out for its rapid application capability. The current FSDS prototype can cover a hectare in just a few minutes, highlighting its potential for pest control. This speed allows quicker spray applications matching the best PPP efficacy window, possibly reducing application times and rates. This efficiency is particularly beneficial if reduced risk compounds and bio-PPPs are used, thus underling the potential for FSDSs to be used in organic and IPM strategies. To this extent, multi-year season-long biological efficacy evaluations must be carried out to define the pros and cons of this novel pesticide application technology. Recent preliminary studies have indicated potential successful FSDS applications in grapes and apples but further biological efficacy trials need to be carried out and, up to now, that's the next path to study to demonstrate the capability of this novel technique to protect crops as expected.

Also, a series of additional studies need to be carried out to highlight the FSDSs' multiple uses such as conditioning (*i.e.*, cooling down the crop and fruit temperature in summer) or frost/freeze damage prevention in early spring. If the FSDS were proven to be a multipurpose technology, this would justify the farmer's investment especially if the system itself could also be operated automatically, remotely and/or in combination with decision support systems better matching the right short time-window when it is strategically to protect the crop against plant diseases (PPP delivery), and high (conditioning), and cold temperatures (frost damage prevention).

In summary, while FSDS offers substantial promise for modern agriculture, the system's optimization, adaptation to different crops, and understanding of its interaction with environmental factors are areas ripe for further research and development.

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Related to: General introduction, Aim and thesis structure, Final considerations, and future perspectives; the specific references related to Chapter I, Chapter II, Chapter III, Chapter IV, Chapter V, and Chapter VI are reported at the end of each paper/chapter

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Appendix B (Auxiliary research contribution)

Paper published in a peer-reviewed international journal

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Biglia, A., Comba, L., Eloi Alcatrão, L., Sopegno, A., Messina, C., Mozzanini, E., Bloise, N., Guglieri, G., Grella, M. (2023) Comparison between 60° and 30° hollow cone nozzles for targeted UAV-spray applications in vineyards. Precision Agriculture '23, pp. 67-73. At 14th European Conference on Precision Agriculture 2023. ISBN: 978-90-8686-393-8. https://dx.doi.org/10.3920/978-90-8686-947-3_6

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