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Evaluation of a Fixed Spraying System for Phytosanitary Treatments in Heroic Viticulture in North-Eastern Italy

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Abstract: Modern viticulture cannot be practiced without the use of plant protection products to control diseases like downy mildew, powdery mildew, and pests. In severely sloping vineyards, where mechanization is not possible, pesticide application is realized using spray guns, which is a laborious, expensive, and dangerous application technique. In these vineyards, where viticulture is defined as "heroic viticulture," vine-growers could seriously take advantage of innovation in spray-technique applications. For this reason, several prototypes of a fixed spraying system (FSS) were realized in recent years. Two prototypes of a fixed spraying system were built in 2019 in two different vineyards in the Veneto region (north-eastern Italy). In both vineyards, the fixed spraying systems were used to perform pesticide application during the 2020 season to control downy mildew, powdery mildew, and pests. With this solution, both vineyards were successfully protected, resulting in comparable infection degrees and yields as the ones protected with airblast sprayers and spray guns. This study contributes to assert fixed spraying systems as an innovation that could improve working conditions, safety, timing, and performances of plant protection products' application in heroic viticulture areas.

Keywords: fixed spraying system; steep-slope viticulture; pesticide application; downy mildew; organic viticulture; solid set canopy distribution system

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1. Introduction

Hilly and mountain viticulture present greater difficulties and costs of cultivation than plain viticulture. In Italy, according to the last census of agriculture, the area planted with vineyards in hilly and mountainous areas amounts to 357,000 and 35,800 ha, respectively, representing about 64% of the national area. In most of these vineyards, the cultivation is mechanized, and the production costs are just slightly higher than plain viticulture ones. The situation is different when it comes to viticulture practiced on severe sloping hills or in mountainous areas. A specific name has been given for this type of viticulture by the Centre for Research, Environmental Sustainability, and Advancement of Mountain Viticulture [1]: heroic viticulture. This term applies to vine growing occurring on slopes greater than 30%, in vineyards above 500 m a.s.l. (excluding highlands), or in vineyards on terraces. In such contexts, the cultivation is hardly mechanizable, and consequently, the production cost of the grape is higher, as the majority of growing activities are carried out by hand following traditional agricultural practices.

Commercial vineyards often require intensive crop protection techniques with several pesticide applications. Fungicide treatments against downy mildew, powdery mildew, and botrytis, and insecticide applications against the leafhopper *Scaphoideus titanus* Ball, vector of flavescence dorée, and the grape berry moth *Lobesia botrana* (Denis & Schiffermüller), are the most common treatments.

In heroic vineyards treatments are carried out entirely by hand, using a knapsack mistblower or high-volume sprayer equipped with a spray gun [2] (hereafter: SG). The use of SG in terraced vineyards is laborious and time-consuming. Moreover, since inter-rows are very narrow (no more than 1.5 m) and the operating pressure often exceeds 20 bars [3], this application technique puts the operator into direct contact with the applied solution, resulting in a high risk of pesticide exposure for operators.

Despite the high volumes and high pressures involved, the biological efficiency of the treatments show remarkable variability related to operator precision: some parts of the canopy could be improperly sprayed, while in others, there may be an over-dosage and dripping to the soil of the excess solution [4].

Nevertheless, a fixed spray system (hereafter: FSS) can be suggested also in vineyards where air-blast sprayers (hereafter: ABS) are used, for the protection of difficult rows, like those at the hedge of fields where ABS can hardly operate.

In heroic viticulture, crop protection is one of the most time-consuming activities. According to the estimates of the Prosecco DOCG (*Denominazione di Origine Controllata e Garantita*) Consortium of Conegliano and Valdobbiadene [5], a single pesticide application in severely sloping vineyards requires 4–6 h/ha of work, whereas the same task in plain and highly mechanized plain viticulture requires 0.75–1 h/ha. Improving time-effectiveness could help increase the income of farmers, resulting in better preservation of the viticultural landscape. In severely sloping vineyards, crop protection is also the most cost-intensive operation. In steep slope viticulture, most of the field operations can be done exclusively manually, resulting in a cost difference of +161% compared to plain viticulture [6].

FSSs have already been studied and applied in fruit cultivation, in particular for the control of fungal pathogens in apple [7–9] and cherry orchards [10] as well as for controlling pests [11]. However, most of the previous prototypes used in orchards are not suitable for vineyards, because they are designed to use the existent anti-frost irrigation system, for the distribution of calcium polysulfide solutions [12]. This technique works against the apple scab, but it is not effective against the typical pathogens of the vine, such as downy mildew and powdery mildew, which require the covering of the bunches. For this reason, other types of FSSs have been designed specifically for viticulture. Some prototypes of FSS were built and tested recently in Italy [13–15] and in the USA [16,17], which also have off-field drift potential [13].

Therefore, the FSS for heroic viticulture treatments, rather than being an adaptation of the irrigation system, must be specifically designed to apply the plant protection product as a sprayer and cover the crop canopy with droplets of appropriate number and size, with acceptable off-field drift.

The aim of the study was to compare the biological performance of FSS prototypes with the farmer standard spray-application techniques in two peculiar areas of the Veneto region: the Prosecco DOCG Consortium area of Conegliano and Valdobbiadene, a United Nations Educational, Scientific, and Cultural Organization World Heritage Site [18], and the Soave Consortium area, recognized by the Food and Agriculture Organization as a Globally Important Agricultural Heritage Site [19]. The two vineyards selected for the study present different training systems, vine varieties, crop protection methods (conventional and organic agriculture), and geological and meteorological conditions. Therefore, the FSS was designed and tested to meet the specific needs of two different agronomical contexts.

2. Materials and Methods

2.1. Experimental Areas

Experimental trials were performed in two different vineyards. The first vineyard was in Vidor (Treviso, Italy 45°53′9.29′′ N, 12°3′18.59′′ E, 147 m a.s.l., Scandolera Wineries), within the Prosecco DOCG Consortium area. Vines were in linear trellis, and crop protection was conventional. The FSS was mounted in a steep vineyard (slope 35%) of the Glera vine variety, the principal vine of Prosecco DOCG wine. The area chosen for the trial was a 750 m^2 vineyard where vines are trained to the local traditional "doppio capovolto" (Figure 1a) linear training system. The spacing of the vines was not regular, ranging from 2.50 × 1.00 m to 3.20 × 1.40 m, due to irregular terracing soil conformation. The age of the plants varied from 2 to 40+ years old, but most of them were 15/20 years old. The area chosen for the trial had six rows, each one 45-m long, plus a 50-m long row for the untreated control plot (hereafter: UTC).

(**a**) (**b**)

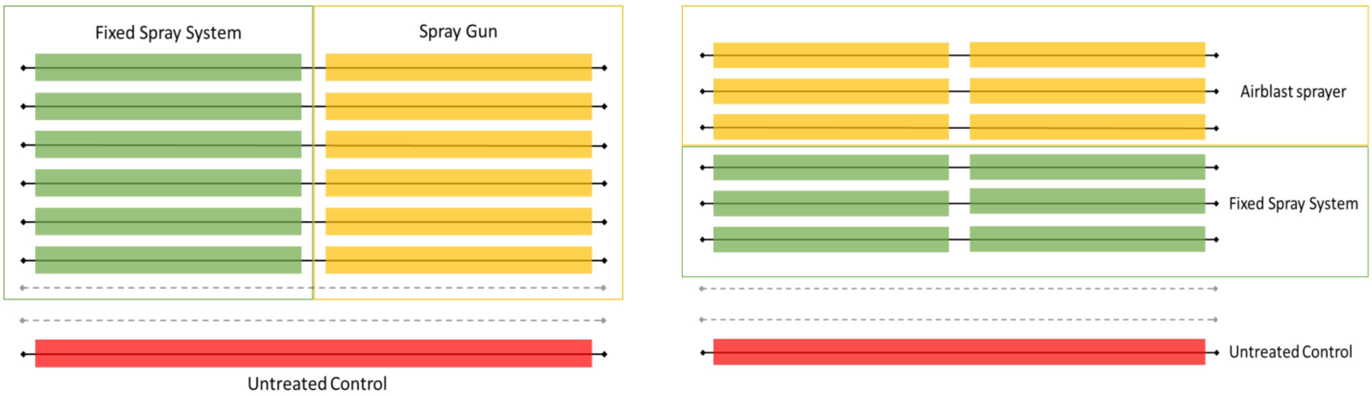
Figure 1. Training systems in experimental vineyards: (**a**) Vidor "Doppio capovolto" training systems, (**b**) Soave "Pergola veronese" training system.

The second vineyard was in Soave (Verona, Italy 45°27′45.39′′ N, 11°13′59.40′′ E, 347 m a.s.l. Coffele vineries), within the Soave DOC Consortium area. Vines were in Pergola trellis, and crop protection was according to organic farming protocol. The area chosen for the trial was a plain 2000-m^2 wide, organic vineyard. The FSS was mounted on a vineyard of the Garganega vine variety trained to the local traditional "Pergola Veronese" (Figure 1b) trellis training system with vines spaced 3.50 × 1.00 m. The area chosen for the trial had six rows, each one 85-m long, plus a 60-m long row for UTC.

2.2. Experimental Design

In Vidor, the FSS was compared with SG. The experimental area was split into two plots: each one of the six rows had half of its length treated with the FSS, and the other half treated with a SG (Figure 2a). This splitting without plot randomization was mandatory due to technical-constructive reasons related to the FSS structure. A UTC was included.

In Soave, the FSS was compared with ABS. For the same reasons as above, also in Soave, the experimental area was split into two non-randomized plots (Figure 2b). A UTC was included.



(**a**) (**b**)

Figure 2. Experimental design in the Vidor vineyard (**a**) and in the Soave vineyard (**b**).

2.3. Fixed Spraying Systems

The FSS was designed taking into account the results of previous experiments carried out on vineyards [14] and orchards [7,20,21]. According to these findings, the general layout of the plant included a lower line and an upper line arranged to spray separately the fruit zone and the upper canopy, to ensure good coverage of the leaves since the most relevant pathogens were located on the downsides (e.g., downy mildew). For this purpose, the general layout of the FSS was designed as follows (Figure 3).

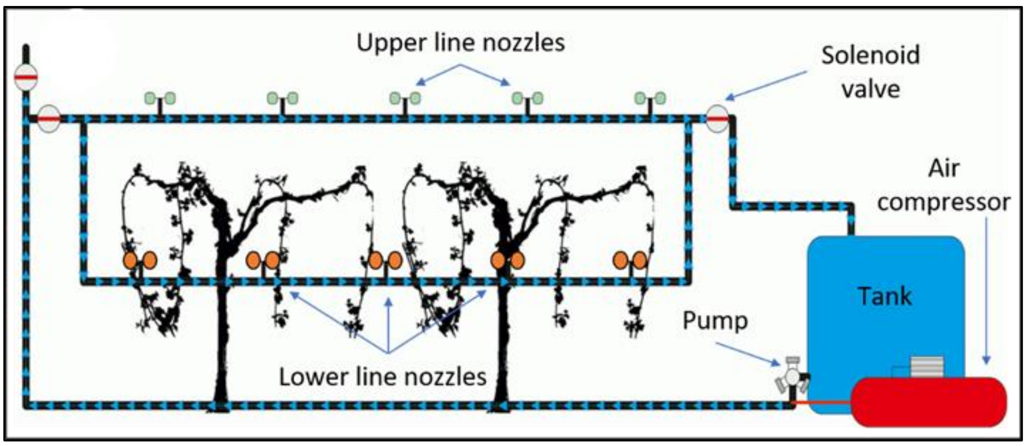


Figure 3. Scheme of the fixed spray system.

A polyethylene tank, with a 1-m^3 capacity, was placed at the head of the vineyard and equipped with an electric-driven three-membrane pump, with a 40-L-min^{-1} capacity; a general supply tubing Ø 25 mm connected the tank with a manifold from which the pipes direct to the individual rows branch off. The piping that feeds each row was in turn divided into two separate lines, one for the spraying of the foliage from above, the other for the clusters, and the lower part of the vegetation from below. Due to the different locations of the two lines, they were fitted with different types of nozzles, each one provided with an anti-drop valve calibrated to open when the pressure exceeded 2 bar: the lower line was equipped with TeeJet TXR800053VK hollow cone nozzles, with a flow rate of 0.21 L/min @ 3 bar, oriented 45° upwards to target the fruit zone and the lower part of the canopy; the upper line, installed about 50 cm over the top of the canopy, holds micro-sprinklers spraying downwards. The specific components differ between the two versions of the plant installed in the experimental vineyards and will be described in detail at the end of this section. At the end of the row, the tubes converge into a transverse pipe, which returns to the tank, thus reproducing the functionality of a normal hydraulic closed circuit, like the ones that are normally used on the tractor-driven sprayers.

The whole tubing was also fed with compressed air with the function of emptying the lines and the nozzles after spraying. All pipes were supplied individually and isolated from the others through solenoid valves placed at both the ends of the individual row pipes; the operation sequence of the valves was controlled by a programmable logic controller (hereafter: PLC).

The operational steps of the spraying process are:

1. the agrochemical mixture is circulated at low pressure in the system, with the solenoid valves of the row to be treated open, until the liquid completely fills the line; this step takes about 100 s;
2. once the pipeline is fully replenished, the PLC closes the solenoid valve located at the end of the row; the pressure rises suddenly at 6 bar, the anti-drop valves open, and the nozzles start spraying, with virtually no delay between the opening of the first and last nozzle; after 15 s, the PLC opens the terminal row valve: the pressure drops immediately below 2 bar, anti-drop valves close, and the mixture flows through the collecting tube back to the tank;
3. at the end of spraying, the pump is switched off and a solenoid valve lets compressed airflow at low pressure (<0.2 bar) into the supply line, thus emptying the mixture into the tank; after 70–80 s, the air pressure in the nozzle line increases due to the closing of the end-of-row valve, and the residual mixture in the nozzles is sprayed on the foliage;
4. steps 2 and 3 are repeated for each row.

2.4. Application of Pesticides

The application of pesticides in Vidor was carried out using the FSS or SG. The use of the SG is the traditional application technique of pesticide in the Prosecco DOCG area because the majority of vineyards there are planted on terraces in sloping hills. The application of pesticide carried out with the FSS and the one performed with the hand SG were both set to deliver a 1000 L/ha volume of phytosanitary solution, in line with the mean volumes used in the area for pesticide application on vineyards. The SG method was set to spray at 20 atm of pressure, while the FSS was set to spray at 6 atm of pressure in the lower line and 3.5 atm in the upper line. The details of pesticide applications are listed in Tables 1 and 2.

Table 1. Dates, product names, rates, and active ingredients, and target of plant health treatments realized in theVidor vineyard during 2020.

Date	Product Name	Rate/ha	Active Ingredient	Target
2 May	Polyram DF Dimethomorph Sulfur	1500 g 400 mL 3000 mL	Metiram Dimethomorph Sulfur	Downy and powdery mildew Downy and powdery mildew Powdery mildew
14 May	Polyram DF Dimethomorph Sulfur	1500 g 400 mL 3000 mL	Metiram Dimethomorph Sulfur	Downy and powdery mildew Downy and powdery mildew Powdery mildew
21 May	Sercadis Enervin TOP	150 mL 2500 g	Fluxapyroxad Ametoctradin + metiram	Powdery mildew Downy mildew
1 June	Sercadis Zorvec Zelavin	150 mL 1500 mL	Fluxapyroxad Oxathiapiprolin	Powdery mildew Downy mildew
12 June	Lieto SC Quantum Score 25 EC	450 g 500 mL 200 mL	Cymoxanil + zoxamide Dimethomorph Difenoconazole	Downy mildew Downy and powdery mildew Powdery mildew and black rot

Table 1. *Cont.*

Date	Product Name	Rate/ha	Active Ingredient	Target
23 June	Enervin Duo Vivando Kestrel	1000 mL 200 mL 400 mL	Ametoctradin + dimethomorph Metrafenone Acetamiprid	Downy mildew Powdery mildew Leafhoppers
6 July	Lieto SC Vivando	450 g 200 mL	Cymoxanil + zoxamide Metrafenone	Downy mildew Powdery mildew
14 July	Ridomil GOLD R WG Zorvec Zelavin Brionflo 100 SC Kestrel	5000 g 300 mL 1000 mL 400 mL	Metalaxyl + copper oxychloride Oxathiapiprolin Cyazofamid Acetamiprid	Powdery mildew Downy mildew Downy mildew Leafhoppers
21 July	Ridomil GOLD R WG Champ 20 Sulfur	5000g 1000 g 3000 mL	Metalaxyl + copper oxychloride Copper hydroxide Sulfur	Powdery mildew Downy mildew Powdery mildew
30 July	Curame bordeaux Mavrik smart Zolvis	5000 g 300 mL 4000 g	Copper sulfate + cymoxanil Tau-fluvalinate Sulfur	Downy mildew Leafhoppers Powdery mildew

Table 2. Operating parameters used in every pesticide application in the Vidor vineyard during 2020.

Thesis		Nozzle Type	Number of Nozzles	Operating Pressure (bar)	Air Pressure (bar)	Flow Rate @ 3.0 bar (L min^{-1})	Forward Speed (km h^{-1})	Volume Rate (L ha^{-1})
FSS	Upper line	Netafim Coolnet Pro mod. 075	1 nozzle every 0.8 m	3.5	8	0.43	-	1000
	Lower line	TeeJet TXR TXR800053VK (hollow cone)	A couple every 1.2 m	5—5.5	8	0.21	-	
SG	-	TeeJet TXA8004VK (hollow cone)	1	20	-	1.58	2.5	1000

The application of pesticides in Soave was carried out using the FSS or ABS (Florida NAZA 600 L at 25 bar), both set to deliver a 750 L/ha volume of phytosanitary solution, in line with the mean volumes used in the area for pesticide application on vineyards. The details of pesticide applications are listed in Tables 3 and 4. Since in organic farming most of the active substances are forbidden, only copper- and sulfur-based fungicides, and only authorized insecticides, were used during the field trial, according to Commission Regulation (EC) No 889/2008 [22].

Table 3. Dates, product names, rates, active ingredients, and the target of plant health treatments realized in the Soave vineyard during 2020.

Date	Product Name	Active Ingredient	Rate/ha	Target
2 May	Mexiram Hi Bio Tiovit Jet	Copper hydroxide Sulfur	1.5 Kg/ha 3 kg/ha	Downy mildew Powdery mildew
9 May	Mexiram Hi Bio Tiovit Jet	Copper hydroxide Sulfur	1.5 Kg/ha 3 kg/ha	Downy mildew Powdery mildew
14 May	Mexiram Hi Bio Tiovit Jet	Copper hydroxide Sulfur	1.5 Kg/ha 3 kg/ha	Downy mildew Powdery mildew
21 May	Mexiram Hi Bio	Copper hydroxide	1 Kg/ha	Downy mildew
29 May	Tiovit Jet Mexiram Hi Bio	Sulfur Copper hydroxide	3 kg/ha 1.5 Kg/ha	Powdery mildew Downy mildew

Table 3. *Cont.*

Date	Product Name	Active Ingredient	Rate/ha	Target
3 June	Tiovit Jet Mexiram Hi Bio	Sulfur Copper hydroxide	3 kg/ha 1.5 Kg/ha	Powdery mildew Downy mildew
5 June	Tiovit Jet Mexiram Hi Bio	Sulfur Copper hydroxide	3 kg/ha 1.5 Kg/ha	Powdery mildew Downy mildew
8 June	Tiovit Jet Mexiram Hi Bio	Sulfur Copper hydroxide	3 kg/ha 1.5 Kg/ha	Powdery mildew Downy mildew
15 June	Tiovit Jet Mexiram Hi Bio	Sulfur Copper hydroxide	3 kg/ha 1.5 Kg/ha	Powdery mildew Downy mildew
25 June	Microthiol Disperss Mexiram Hi Bio	Sulfur Copper hydroxide	4 kg/ha 0.5 kg/ha	Powdery mildew Downy mildew
7 July	Microthiol Disperss Neemik Ten	Sulfur Azadirachtin	6 kg/ha 2.6 L/ha	Powdery mildew Leafhoppers
15 July	Microthiol Disperss	Sulfur	8 kg/ha	Powdery mildew
28 July	Mexiram Hi Bio Microthiol Disperss	Copper hydroxide Sulfur	400 g/hl 800 g/hl	Downy mildew Powdery mildew
18 August	Poltiglia Disperss Microthiol Disperss Surround Wp	Bordeaux mixture Sulfur Kaolin	2 kg/ha 4 kg/ha 15 kg/ha	Downy mildew Powdery mildew

Table 4. Operating parameters used in every pesticide application in the Soave vineyard during 2020.

<table>
<tr><th colspan="2">Thesis</th><th>Nozzle Type</th><th>Number of Nozzles</th><th>Operating Pressure (bar)</th><th>Air Pressure (bar)</th><th>Flow Rate @ 3.0 bar (L min^{-1})</th><th>Forward Speed (km h^{-1})</th><th>Volume Rate (L ha^{-1})</th></tr>
<tr><td rowspan="2">FSS</td><td>Upper line</td><td>NETAFIM Gyronet 58 SR</td><td>1 nozzle every 2.5 m</td><td>6</td><td>10</td><td>0.83</td><td>-</td><td rowspan="2">750</td></tr>
<tr><td>Lower line</td><td>TeeJet TXR TXR800053VK (hollow cone)</td><td>A couple every 1 m</td><td>6</td><td>10</td><td>0.21</td><td>-</td></tr>
<tr><td>ABS</td><td>-</td><td>TeeJet TXB8003VK (hollow cone)</td><td>6</td><td>20</td><td>-</td><td>1.18</td><td>5.3</td><td>750</td></tr>
</table>

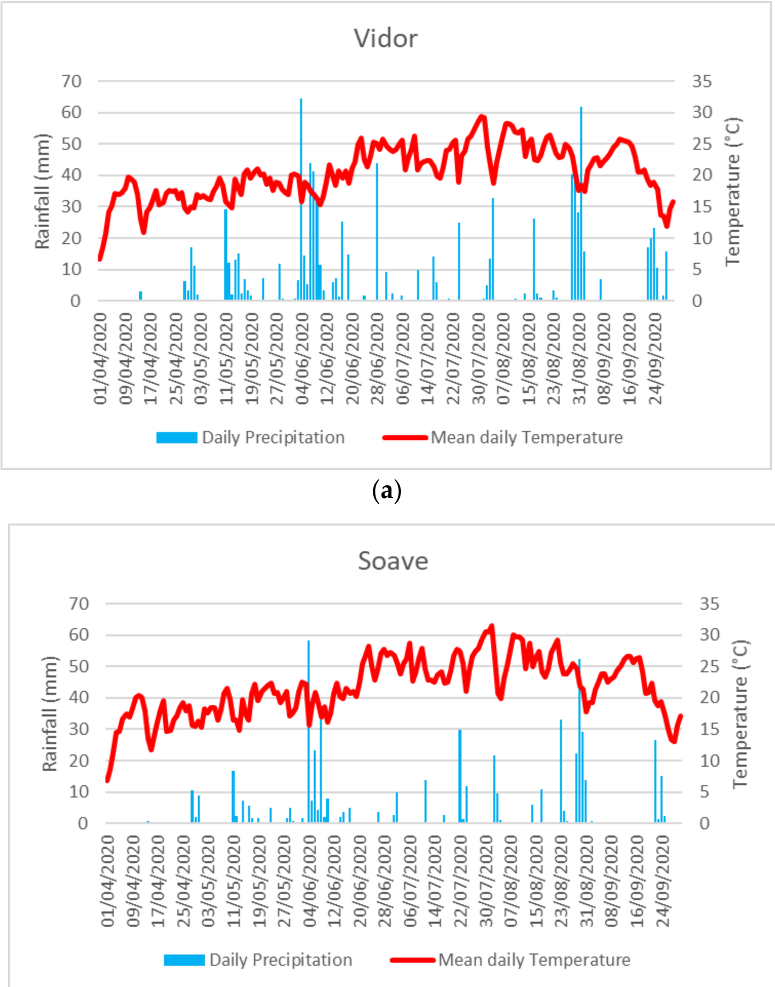
2.5. Meteorological Data

Figure 4 shows the mean daily temperature and precipitation in the two vineyards in the 2020 growing season recorded at meteorological stations located inside or very near the vineyards. In Vidor, the total amount of precipitation between 1 April 2020 and 30 September 2020 was 916.6 mm, and the number of rainy days was 59 (a rainy day was considered a day when the amount of rainfall was over 1 mm). In Soave, the total amount of precipitation in the same period was 546.2 mm, and the number of rainy days was 45.

2.6. Evaluation of Disease Symptoms and Arthropods Abundance

In 2020, the phytosanitary status of leaves and bunches was monitored in both sites, and disease symptoms were evaluated for the spray-application techniques under comparison (FSS, SG, and ABS) and for UTC.

In Vidor, the damage from downy mildew was assessed first on leaves at the time of veraison (BBCH 80; 30 July 2020) and then on bunches at the time of harvest (11 September 2020). In Soave, the evaluation of the leaf damage was assessed at the time of veraison, and the damage on bunches was assessed at the time of harvest (26 September 2020).



(**a**)

(**b**)

Figure 4. Mean daily temperature and precipitation in the Vidor (**a**) and Soave (**b**) vineyards in 2020.

To evaluate the performance of the pesticides, the response of the plants to downy mildew disease was analyzed regularly at each growth stage (BBCH-identification keys of grapevine), following the developmental scale described by Lorenz et al. (1994). We scored 100 leaves and 100 bunches picked randomly from 10 central plants of each plot and estimated the percentage of affected organs (disease incidence) and the percentage areas of leaves and bunches showing disease symptoms (disease severity). For the evaluation of the damage in each site, 50 leaves/bunches were sampled randomly from central plants of each plot. The first and the last rows of the vineyards were excluded from sampling to create a buffer zone between the experimental areas and the surrounding vineyards. In Vidor, four plots for FSS and SG, and the UTC, were sampled. In Soave, due to the different arrangement of the FSS, three plots for FSS and ABS, and the UTC, were sampled. Disease severity (infection degree (ID)) was calculated using a scale of eight classes (0–7) with the Townsend–Heuberger formula [23]:

$$ID\% = \frac{\sum n \times v}{N \times V} \times 100, \quad (1)$$

with n = number of leaves/bunches per each class, v = value of the class, N = number of leaves/bunches sampled, and V = value of the higher class of the scale.

The percentage incidence of disease (Ic) was calculated as the percentage of total organs sampled showing symptoms of disease.

In addition to fungal pathogens, mites and leafhoppers occurring in vineyards were also monitored. The abundance of the predatory mite *Kampimodromus aberrans* (Oudemans) and its prey the mite pest *Eotetranychus carpini* (Oudemans) were quantified on 100 leaves per the spray-application techniques and collected in every plot in both vineyards. The leaves were then observed under the stereoscope, and the mite numbers were quantified. Samples were taken at 10-day intervals between 11 June and 28 August in Vidor, while, in Soave, the samples were taken from 19 June to 24 September.

To quantify the abundance of the leafhopper pests *Scaphoideus titanus*, *Zygina rhamni* (Ferrari), *Erasmuneora vulnerata* (Fitch), and *Empoasca vitis* (Göethe), a yellow sticky trap (12×20 cm) was placed in every plot in both vineyards. The traps were replaced regularly, and the leafhoppers captured were quantified. In Vidor, the collection of traps was accomplished every ten days from 2 July to 28 August, while, in Soave, the collection was done every 30 days from 10 July to 12 September.

The quantification of the yields was performed in a similar way in the two sites. In Vidor, 10 plants per plot were chosen randomly, and the bunches were divided into two classes: first quality bunches (damage classes 1–2) and second quality bunches. In Soave, since the vineyards are fairly bigger than in Vidor, 20 plants per plot were harvested. Given the heterogeneous nature of the plants and the presence of failed plants, we decided to determine the yield as "kilograms of grapes per vine."

2.7. Data Analysis

The non-parametric one-factor analysis (Kruskal–Wallis test; post hoc: Conover test; $\alpha = 0.05$) was used to evaluate significant differences in disease severity (Ic) between the spray-application techniques and the UTC in both vineyards.

Data on the abundance of leafhoppers in Vidor collected before the first insecticide application (July 12) was analyzed using the non-parametric one-factor analysis (Kruskal–Wallis test; $\alpha = 0.05$) to evaluate the abundance of leafhopper populations before the insecticide application. Data collected after the first insecticide application were analyzed with the Friedman two-way non-parametric repeated measure analysis of variance ($\alpha = 0.05$) to test the effect of insecticide application using different spray-application techniques on leafhopper populations. Data on the abundance of leafhoppers observed in Soave and collected after insecticide application were analyzed using a Friedman two-way non-parametric repeated measure analysis of variance ($\alpha = 0.05$). The populations of leafhoppers in UTC in both vineyards were not assessed, because insecticide treatments in the Veneto region are mandatory to control grapevine flavescence dorée and its vector *Scaphoideus titanus* [24]. Different analyses were performed on different leafhopper species. In all analyses, the numbers of leafhoppers belonging to the different species observed on each sticky trap were considered as dependent variables (with repeated measures made at different sampling dates, in case of post-treatment sampling), while the spray-application technique was considered as an independent variable.

The effect of pesticide application using different spray-application techniques on mite populations was evaluated using a Friedman two-way non-parametric repeated measure analysis of variance ($\alpha = 0.05$) on the number of predatory and pest mites observed in the two vineyards. Different analyses were performed on different mite species. In all analyses, the numbers of mites per leaf belonging to the different species were considered as dependent variables with repeated measures made at different sampling dates, while the spray application technique was considered an independent one. The non-parametric one-factor analysis (Kruskal–Wallis test; post hoc: Conover test; $\alpha = 0.05$) was used to evaluate significant differences in yield between the spray-application techniques in both vineyards, analyzing separately 1st quality bunches from 2nd quality bunches.

3. Results

3.1. Vidor

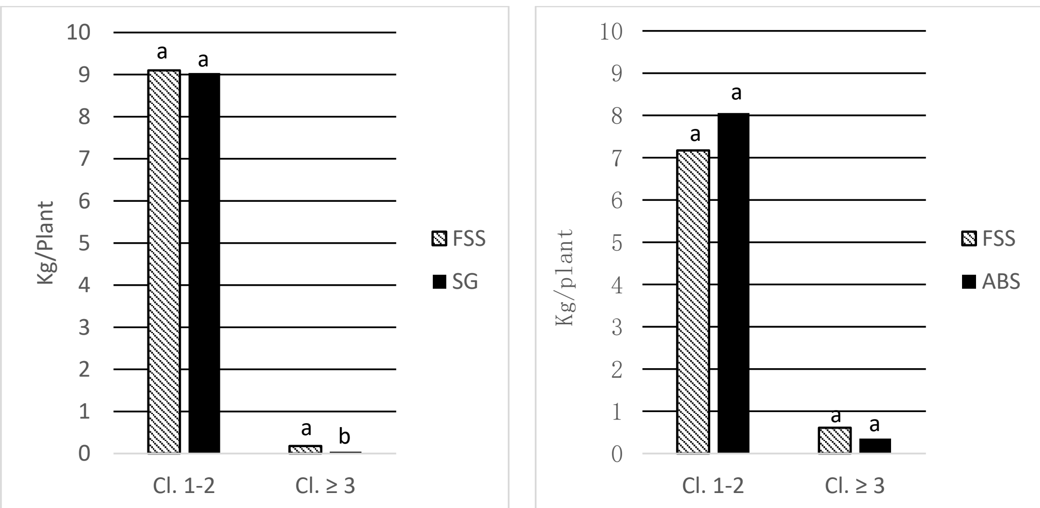
The incidence and severity obtained by sampling the four plots for each spray application technique were analyzed with the Kruskal–Wallis test. The comparison was made between FSS, SG, and UTC. The results in Table 5 show a significantly different incidence (Ic) on SG, compared to FSS and UTC. The analysis of severity (ID) also showed significant differences between the three application techniques.

Table 5. Infection of grapevines with downy mildew in the Vidor vineyard: comparison between the two spray-application techniques and the untreated control. Damage index on 23 July 2020 was applied to leaves and, on 11 September 2020, was applied to bunches. Different letters indicate significant statistical differences. * = *p*-value < 0.05; ** = *p*-value < 0.01.

Pathogen	Evaluation Day	Application Method	Incidence (ID) (%)	Severity (Ic) (%)
Downy mildew	23 July 2020	Fixed spray system	25.5 a	9.07 b
		Spray gun	13.00 b	3.07 a
		Untreated control	42.47 a	29.80 c
		p-value	0.0181 *	0.0072 **
Downy mildew	11 September 2020	Fixed spray system	4.00 a	1.35 b
		Spray gun	4.00 a	0.85 a
		Untreated control	44.00 b	21.00 c
		p-value	0.0053 **	0.0089 **

The results of the incidence and severity on bunches resembled those on leaves. The incidence and severity were significantly different according to the Kruskal–Wallis test. Incidences on FSS and SG were not significantly different, while UTC had a significantly higher percentage of affected bunches. The severity results replicated the situation on the leaves, distinguishing significant differences between all three application techniques (Table 5).

The yield of 1st quality bunches (Cl = 1–2) showed no significant differences between FSS and SG, settling around 9 kg/plant. The yield of 2nd quality bunches (Cl > = 3) showed significant differences between the two spray methods, with a lower quantity of 2nd quality bunches in SG than in FSS (Figure 5a).



(**a**) (**b**)

Figure 5. Grape yield in Vidor (**a**) and Soave (**b**) vineyards calculated as kg/plant of vines harvested. Class 1–2 bunches were 1st quality bunches (portion of bunch damaged < 5%); class ≥ 3 bunches were 2nd quality bunches (portion of bunch damaged ≥ 5%). Different letters within each class indicate significant statistical differences.

In this vineyard, the presence of the leafhoppers *S. titanus, Z. rhamni*, and *E. vitis* and the mites *K. aberrans* and *E. carpini* were observed (data not shown). The Kruskal–Wallis test on the population of *Z. rhamni* (*p*-value = 0.546) and on the population of *E. vitis* (*p*-value = 0.090) on June 22 showed no significant differences between FSS and SG. Just one *S. titanus* was captured during 2020 (on 2 August), so the analysis was not performed for this species. The post-treatment Friedman test on the population of *Z. rhamni* (*p*-value = 0.179) and on the population of *E. vitis* (*p*-value = 0.654) showed no significant differences between FSS and SG. The presence of the mite pest *E. carpini* was observed at a low level. However, the Friedman test revealed that the *E. carpini* density was slightly higher in SG than FSS (*p*-value = 0.014). No differences between spray systems emerged on *K. aberrans* populations (*p*-value = 0.414).

3.2. Soave

Nearly no leaf damage was detected for most of the season on every thesis. On the other hand, some damage was detected on bunches due to powdery mildew and grey mold after veraison. As for Vidor's vineyard, the analysis of the incidence data (Ic) of powdery mildew on bunches showed significant differences between theses: FSS was less affected than ABS and UTC. The Kruskal–Wallis test performed on the ID showed no differences between the spray methods. Table 6 shows that the average level of infection at harvest (26 September 2020) was fairly low.

Table 6. Infection of grapevines with powdery mildew and grey mildew in Soave vineyard: comparison between the two spray-application techniques and the untreated control. Different letters indicate significant statistical differences. * = *p*-value < 0.05.

Pathogen	Evaluation Day	Application Method	Incidence (ID) (%)	Severity (Ic) (%)
Powdery mildew	26 September 2020	Fixed spray system	4.00 a	2.85 a
		Airblast sprayer	6.66 b	3.04 a
		Untreated control	6.67 b	3.61 a
		p-value	0.0456 *	0.8068
Grey mildew	26 September 2020	Fixed spray system	27.33 a	10.38 a
		Airblast sprayer	34.04 a	13.06 a
		Untreated control	32.00 a	16.28 a
		p-value	0.3932	0.2019

The Kruskal–Wallis test on the incidence (Ic) and severity (ID) of botrytis symptoms on bunches showed no differences between FSS, ABS, and UTC at the time of harvest (Table 6).

The yield of 1st quality bunches (Cl = 1–2) showed no significant differences between ABS and FSS, with a yield of 8.05 kg/plant for ABS and a yield of 7.21 kg/plant for FSS. The yield of 2nd quality bunches (Cl > = 3) showed no significant differences between the two spray methods (Figure 5b).

Leafhoppers *E. vulnerata, S. titanus, Z. rhamni*, and *E. vitis*, and the predatory mite *K. aberrans*, were observed in this vineyard (data not shown). The Friedman test found no significant differences in leafhopper populations between FSS and ABS (*p*-value = 0.533). No differences between spray systems emerged on *K. aberrans* populations (*p*-value = 0.654).

4. Discussion

During 2020, different pest management strategies showed similar results in both vineyards equipped with the FSS.

In Vidor, the major disease was downy mildew. On leaves, the incidence of downy mildew was higher in FSS and UTC than in SG. However, considering the severity of the damage (Ic), it can be seen that the disease was present in several plants of the FSS, but the damage was not as severe as in the UTC (Table 5). This is the reason why the damage on leaves appears to be less critical in FSS than in UTC. Focusing on bunches' damage, the FSS provided efficient protection against diseases, despite the fact that the SG had a higher canopy penetration potential thanks to a higher operational pressure (6 bar and 20 bar, respectively). Several previous studies on FSSs and solid set canopy delivery systems (SSCDS) determined a lower canopy penetration capability of FSSs and SSCDS than ABS, in particular regarding the lower surface of leaves [25,26]. We empirically observed that the FSS had a lower capability of reaching the lower surface of the leaves, and this can explain the higher incidence of downy mildew on leaves (Table 5). However, the use of systemic active ingredients, and the position of bunches, which are easier to be reached from the lower line of nozzles, allowed achievement of the same ID (%) and yield as in SG.

In Soave, the damage on leaves and bunches due to fungal infections were quite low, even if only active ingredients allowed in organic agriculture were used. The bunches damage index (ID%) showed that the FSS was able to manage the infection of powdery mildew better than the ABS (Table 6). However, the damage caused to bunches by two severe hailstorms, which both occurred after the end of the treatments (on 15 August and 2 September), led to a severe late grey mildew infection. This infection caused so much damage to the UTC that no bunches were spared at the moment of harvesting. It is likely that this high level of damage was related to the plot position at the edge of the vineyard, which was much more exposed to the hailstorm than other plots.

No differences among spray systems were found on arthropods occurring in vineyards highlighting that FSSs are efficient as standard methods for insecticide application against leafhoppers, which are major grapevine pests [27–29], and no differences on side-effects on beneficial predatory mites emerged [30].

5. Conclusions

After a season-long study, FSS biological performances were comparable to those of commercial spraying application techniques in both sites. However, to achieve those results, it is necessary to perform accurate pruning in the early stages of growing, possibly twice in sturdy vines. The financial feasibility is, instead, doubtful, mainly because expensive nozzles for air-blast sprayers were used. At the moment, this makes the cost of the prototype too high for standard commercial vine-growers, even if it can be markedly reduced by involving industrial stakeholders, mainly for the production of nozzles specific for FSSs.

Further research is needed to confirm the biological and hydraulic efficiency of a FSS over years. This will also help to evaluate the economic feasibility of the FSS and the chance of this new technology gaining importance in the market of agricultural sprayer systems.

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