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A NOVEL, AIR-ASSISTED TUNNEL SPRAYER FOR VINEYARDS: OPTIMIZATION OF OPERATIONAL PARAMETERS AND FIRST ASSESSMENT IN THE FIELD

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1. Introduction

Tunnel sprayers for orchards and vineyards have long been recognised as an important tool to reduce both airborne drift and soil contamination [Bera 1985; Bäcker 1991; Siegfried 1991]. Because of their ability to recover and recycle most of the spray fraction that has not been retained by the canopy, these sprayers may make efficient pest control possible even at reduced pesticide dose rates (by 15% to 50%) [Siegfried 1996; Doruchowski 2000].

Despite of these advantages, the number of tunnel sprayers working in European vine-growing farms still is very small. Many factors have played a role in this, including the higher machine cost, lower working speed, and more difficult manoeuvrability as compared to conventional, broadcast sprayers. However, one major problem seems related to unsatisfactory deposition uniformity over the foliage, particularly from those tunnel models lacking any air-assistance system. Insufficient spray penetration in the inside of the canopy, and low deposition on leaf under sides have been reported [Siegfried 1991; Siegfried 1996], and related to higher disease incidence, particularly downy mildew [Viret 2003].

This has led to the proposal of tunnels fitted with centrifugal fans, connected by flexible pipes to the air outlets placed near the nozzles, in the inside of the tunnel [Baraldi 1993; Planas 2002]. However, the use of air-assistance implies that the same volume of air being fed into the tunnel must, at the same time, be discharged to the outside, carrying some fraction of the spray with itself and increasing drift, while reducing the recovery rate. To solve this problem, tunnels fitted with internal axial-flow fans have been proposed [Van de Werken 1991; Molari 2005], working on the “closed loop” system of re-circulating the same volume of air inside the tunnel. Some recent developments have included lamellae separators to prevent fan contamination, and to reduce the risk of damaging the foliage nearest the fan inlets [Ade 2007].

An alternative system may be to use air-droplet separator screens to recover the excess spray that has not been retained by the foliage, while discharging the air to the outside [Bäcker 1991; Panneton 2005]. This avoids the need of placing the fans inside the tunnel, thus preventing both fan contamination and foliage damage. As an additional advantage, the reduced width of the tunnel walls, compared to air-recirculating models, may be important in the perspective of developing two-row and three-row tunnel sprayers, also suited to vineyards with relatively narrow row spacings (2 m and less). Multi-row sprayers are particularly required by professional vine-growing farms and contractors, which need to ensure timeliness of operation and efficient pest control, while reducing application costs per unit sprayed area.

A two-row prototype, based on the air-droplet separator principle, was developed in 2006 in a joint project conducted by the University of Udine and Agricolmeccanica s.r.l. (Torviscosa, Udine). Initial tests were conducted to gather baseline information on machine performance, and more particularly to assess the effects of the main operational parameters (air flow rate, angling of the air jets, and tunnel opening) on the recovery efficiency of the air-droplet separator, both in simulated recovery trials under static or dynamic conditions, and during actual spray application in the vineyard.

2. Materials and methods

2.1 *The prototype tunnel sprayer*

The two-row, prototype tunnel sprayer consisted of two identical spraying units, carried by a tractor-mounted, over-the row structure, while the 1000-litre tank was placed on a separated, trailed unit (Figure 1).

Each of the spraying units consisted of a couple of symmetrical shields (height: 1700 mm; length: 1180

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Fig. 1 - The prototype tunnel sprayer.

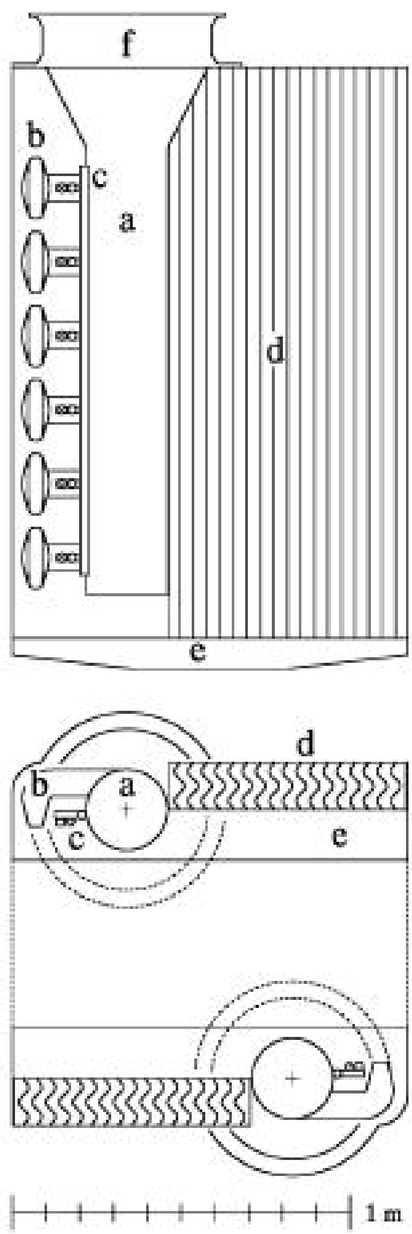

Fig. 2 - Schematic views of the prototype. Top: from the (inner) side; below: from the top. (a) main air duct; (b) air outlets; (c) nozzles; (d) air/droplet separator; (e) basin; (f) fan.

mm), each including (Figure 2):
- an axial-flow fan (diameter: 600 mm), driven by an hydraulic motor;
- a vertical air duct (height: 1700 mm; diameter: 250 mm), fitted with six air jets (total outlet section: 61.2 cm^2), spaced at 216 mm intervals;
- a vertical boom with six hydraulic nozzles;
- an air/droplet separator panel, fitted with vertical lamellae (height: 1700 mm; length: 670 mm; thickness: 150 mm; pitch: 40 mm), designed to separate the excess spray, not deposited onto the canopy, and to capture its liquid fraction while discharging the air flow to the outside;
- a recovery basin, connected to the recycling system of the sprayer, to convey the recovered liquid back to the tank.

The distance both between the tunnel units, and between the shields in each unit, could be adjusted by means of hydraulic actuators to fit the row distance of the crop (between 1.8 m to 3.6 m), and the width of the vine canopy (up to 1.0 m tunnel opening, as measured between the basins, Figure 3). Both the main air duct and the air outlets could be rotated in the horizontal or vertical plane, respectively, to adjust the directions of the outcoming air flows, relative to the canopy and/or the separator panel.

The tractor-mounted, main structure of the sprayer also included: the main circuit's diaphragm pump, fitted with a constant pressure regulator; the membrane pump of the recycling circuit, connected to the tank; suction filters before each pump; and a hydraulic power system, driven by the tractor's P.T.O. and used to operate the fans and the hydraulic actuators on the over-the-row structure.

In this first prototype, the transmission ratio from the oil pump to the hydraulic motors of the fans could not be changed (a flow rate controller might be added in a later version, if required). The fan's rotational speed could only be adjusted by changing the speed of the P.T.O. operating the hydraulic system.

2.2 *Air flow rate and air velocity*

Preliminary tests were performed to assess the air flow rate of the fans, and the air velocities in the inside of the tunnel. All measurements were performed on the left tunnel, after directing the air outlets horizontally towards the opposite separator wall (0° angling in Figure 3).

After adjusting the tractor's P.T.O. at 350, 450 and 540 rpm, the corresponding rotational speeds of the fans were measured using a Photo Tachometer (DT-2236, Metermaster NZ Ltd., Auckland, New Zealand). The air flow rate was then assessed using a Pitot probe (Swema 2000, Swemaman, Stockholm, Sweden), to determine the mean air velocity across the section of a pipe (diameter: 0.60 m; length: 2.00 m), connected to the suction side of the fan [ISO-FDIS, 1999]. The resulting air flow rates were 0.73 m^3/s, 1.02 m^3/s, and 1.20 m^3/s per fan (at fan speeds

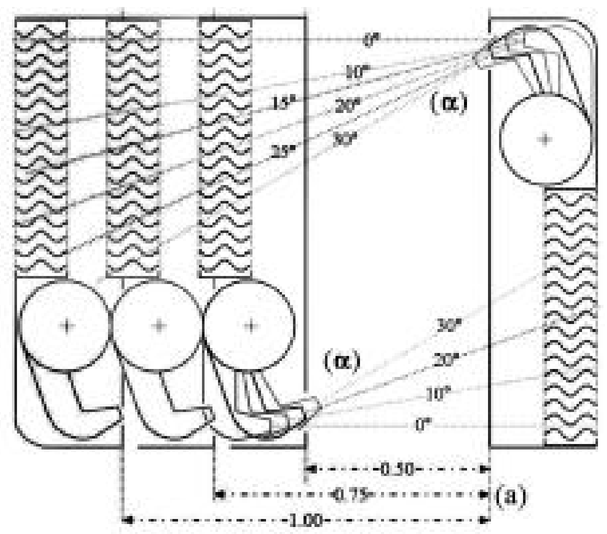

Fig. 3 - Definition of some setup parameters used in this study: (a) tunnel opening and (α) angling of the air outlets.

of 36.1, 46.8 and 52.4 rev/s, respectively).

The air velocity in front of the air outlets was measured on a vertical line, equidistant from the tunnel walls, at 0.10 m intervals between 0.10 m and 1.60 m height over the basin level. Nine series of measurements were made, using a propeller anemometer (HHF23, Omega Engineering, Inc., Stamford, Connecticut, U.S.A.), after adjusting the P.T.O. speed at 350, 450 or 540 rpm, and the inner tunnel opening at 0.50 m, 0.75 m or 1.00 m (measured between the basins at the base of each shield, Figure 3). This meant that the horizontal distances between the measurement points and the tips of the outlets were 0.35 m, 0.475 m, and 0.60 m, respectively, depending on tunnel opening.

2.3 *Static tests*

The spray recovery rate of various configuration of the prototype was evaluated on the basis of laboratory tests, performed with water only under static conditions, and in the absence of vegetation.

The sprayer was fitted with 12 Albuz ATR brown hollow cone nozzles (Very Fine BCPC spray quality at 10 bar), and the total flow rate was 7.92 l/min (at 10 bar pressure) in all experiments. Before each test, the nozzle output was checked by measuring the amount of water collected after four minutes in graduated cylinders, connected to the nozzles by flexible pipes. The spray recovery rate was measured by collecting the water flow from the tube of the recycling system, previously disconnected from the tank. This involved: starting the sprayer, and waiting until the water flow from the recycling pipe became steady; placing the end of the tube in a container (volume capacity: 50 l), so as to collect the water flow; after four minutes, removing the tube's end, and measuring the volume of water collector using graduated cylinders. In each test, the machine was let to spray for at least five minutes before taking the first measurement, in order to completely soak all inside surfaces.

The spray recovery rate (R, in %) was then calculated as:

$$R = V_r /(t\, q)$$

where: V_r, in l, is the recovered volume of water; t, in min, is the spraying time; and q, in l/min, is the total nozzle flow rate.

Four different tests were performed. Test No. 1 was a factorial experiment, in which the following settings were compared:

– tunnel opening: 0.50 m, 0.75 m and 1.00 m;
– outlet angling: 10°, 20° and 30°; both air booms were symmetrically rotated towards the centre of the tunnel (Figure 3);
– fan speed: 36.1 rev/s, 46.8 rev/s and 52.4 rev/s (giving air flow rates of 1.46 m^3/s, 2.05 m^3/s, and 2.40 m^3/s, respectively, from the two fans of the tunnel).

In test No. 2, the effect of different outlet orientations (10°, 15°, 20°, 25° and 30°) was further analysed at medium fan speed and at three tunnel openings as above.

In test No. 3, the fans were shut off, and this adjustment was compared with the medium fan speed (46.8 rev/s), in order to assess the effect of air-assistance on the spray recovery rate. Six measurements were performed (two fan settings combined with three tunnel openings as above).

In test No. 4 the separator panels were made ineffective by covering their inner or outer side with plastic foils, so as to simulate a tunnel sprayer with full containment walls, and to assess the effect of the spray separating system on the recovery rate.

Air temperature was 10°C to 17°C during all the above tests, with 73% to 88% relative humidity, and 0.2 to 0.4 m/s wind speed.

2.4 *Dynamic tests*

Further tests were performed with the tunnel sprayer in motion at 6.23 km/h forward speed along a 250 m long, smoothly paved lane. Tunnel opening was adjusted at 0.50 m, and the fan speed was set to the maximum (52.4 rev/s). Outlet orientation was initially set at 25° (with both air booms symmetrically rotated towards the centre of the tunnel, Figure 3). Preliminary visual observation suggested that the spray and air flows generated by the nozzles and air outlets were, by some extent, being deflected backward by the additional flow of air, entering the tunnel from the front opening owing to motion. This was causing a relatively small, but clearly visible loss of droplets from the rear opening. In order to compensate for this effect, additional runs were made after rotating either the front or rear outlets towards the back or the front of the tunnel, in steps of 5°, and repeating the procedure until no further improvement in the spray recovery rate was recorded.

The measuring procedure was the same as de-

Tunnel opening, m		0.50		0.75		1.00	
Height range	PTO rpm	mean	C.V.	mean	C.V.	mean	C.V.
(a) 0.1 to 1.6 m	350	6.4	31	5.7	30	5.1	30
	450	8.8	24	7.9	25	6.9	25
	540	10.2	24	9.3	27	8.6	30
(b) 0.4 to 1.4 m	350	7.6	8	6.7	10	6.0	10
	450	9.9	9	9.0	10	7.8	11
	540	11.6	10	10.8	10	10.0	12

TABLE 1 - Mean air velocities in the inside of the tunnel.

scribed above, except for the following. Two separate containers (volume capacity: 20 l each) for liquid recovery were used, and placed in a metallic frame, fitted in the back of the tank trailer. After the water flow from the recycling pipe had become steady, the sprayer was put in motion; liquid recovery was started as soon as the forward speed of the sprayer had stabilised, and was stopped after two minutes. The same was done during a second run in opposite direction, using the second container. At the end of both runs, the volume of water collected was measured, and the spray recovery rate was assessed.

2.5 *Field tests*

During 2007, the tunnel sprayer was used for pesticide application in a commercial vineyard estate, located in San Martino al Tagliamento (PN, N.E. Italy). The vineyard (cv: Merlot) was trained to a spur-pruned low cordon. Standard canopy management was performed, including side and top trimmings, and vertical shoot positioning using movable catch wires, which helped to limit the canopy width to 0.5 m or less at all growth stages.

Seven spray applications were made between April 3 (before bud break) and July 11 (full foliage development). Forward speed was 6.23 km/h, and the air flow rate was 2.17 m^3/s per row. Tunnel opening was kept as small as possible, depending on canopy width (55 cm to 65 cm); the number of open nozzles was adjusted between two and six per side, depending on canopy height. Thus, the sprayed volumes ranged from 219 to 555 l/ha (TABLE 5).

After each application, six vines were randomly chosen in the vineyard for the assessment of the leaf area index (LAI); all their leaves were counted, and one leaf every five was taken. The area of the leaves sampled was measured with an area meter (Model LI-3100C, LI-COR Inc.). Based on the number of leaves per vine and their mean area, the total leaf area (S, in m^2) was estimated for each sample vine.

The leaf area index (LAI) was then calculated as:

$$LAI = S / (x\ b)$$

where: x, in m, is the planting distance between the vines length (0.8 m); and b, in m, is the row spacing (2.4 m).

3. Results and discussion

3.1 *Air velocities inside the tunnel*

The mean air velocities in the middle of the tunnel changed proportionally to the P.T.O. speed, while

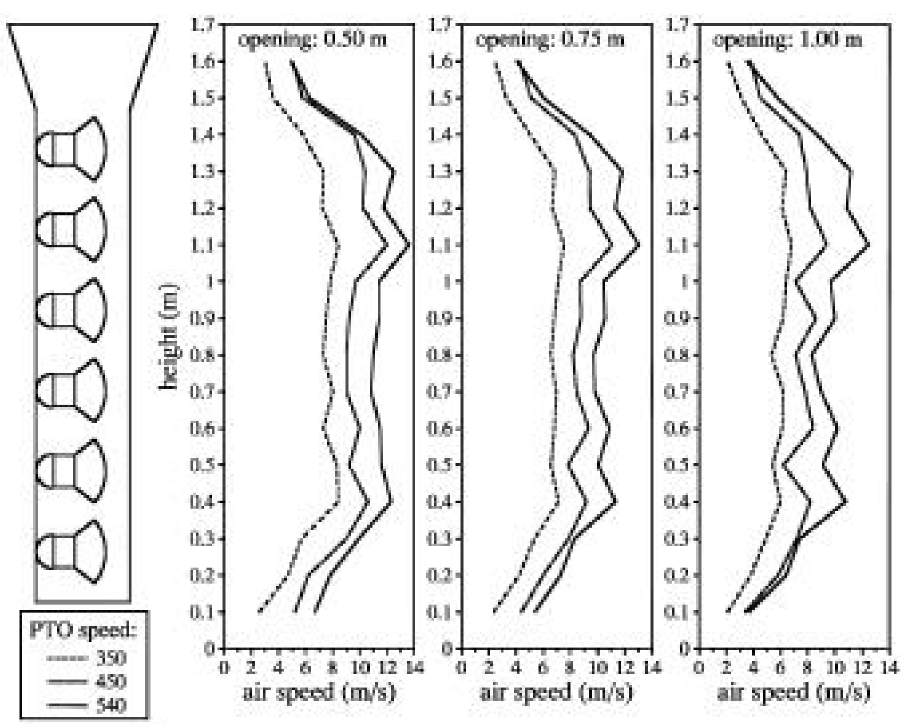

Fig. 4 - Air velocities in the middle of the tunnel at different openings and P.T.O. speeds. On the left, the position of the air outlets is shown.

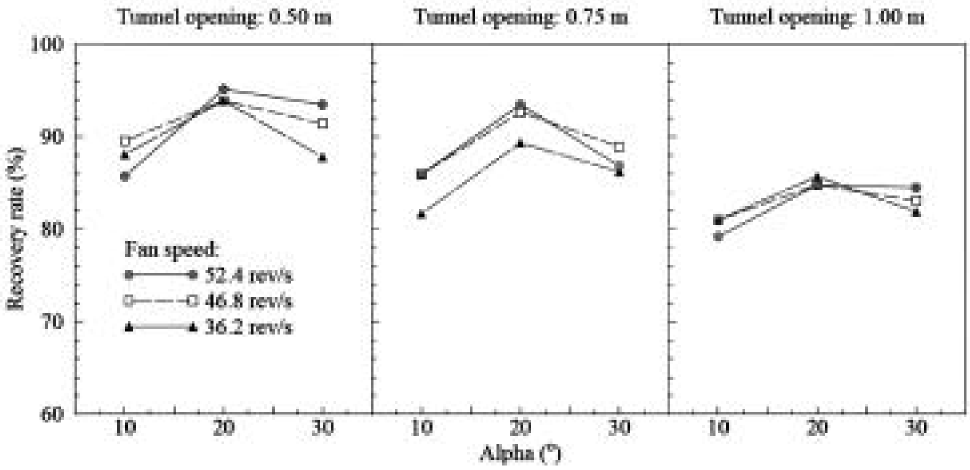

Fig. 5 - Static test No. 1: effect of tunnel opening, fan speed and outlet orientation on spray recovery rate.

showing only a small decrease at increasing openings of the tunnel (corresponding to different distances from the air outlets; TABLE 1).

The results proved that it was possible to adjust the fan speed so as to obtain average air velocities in the range of 5 m/s to 10 m/s on the row of vegetation, independently of the tunnel opening, as required by different widths of the vine canopies. This range of air velocities was considered suitable for improving spray deposition on vine canopies, as suggested by previous research work [Pergher 2005; Pergher 2006].

The air velocity profiles were relatively uniform in the height range of 0.4 m to 1.4 m height (Figure 4), approximately in front of the five upper outlets. This was the result of an interaction between the air currents generated by nearby outlets, which were by some extent channelled, and forced to move horizontally across the tunnel. At the ends of the air boom, on the other hand, the air fluxes were relatively free to expand upwards or downwards, and this may explain the decrease in the air velocity. This happened even in front of the lowest outlet (Figure 4), probably owing to the relatively large opening between the basins at the bottom of the tunnel, and did only little affect the uppermost outlet, placed near the tunnel roof.

This may suggest that, in a future version of the prototype, an additional couple of air outlets may be placed at the bottom and possibly at the top of the air booms, in order to better confine the air fluxes in the inside of the tunnel, and to maintain a constant air speed along the full range of the canopy height.

3.2 *Static tests*

The maximum recovery rate in static test No. 1 (95.1%; Figure 5) was recorded after adjusting the distance between the tunnel's walls at the minimum, 0.50 m, the outlet orientation at 20°, and the fan speed at the maximum (52.4 rev/s).

The reduction in the recovery rate at increasing distances between the tunnel's walls was largely expected. However, this effect was very small at the 0.75 m tunnel opening, while clearly visible at the 1.00 m distance (maximum recovery: 93.5%, and 85.7%, respectively).

The spray recovery rate was little affected by the fan speed adjustments. Only at the 0.75 tunnel opening, the minimum fan speed resulted in a slight reduction in spray recovery. This was indeed a good result, since it suggested that it would be possible, during spray application in the vineyard, to choose the correct air flow rate in order to obtain sufficient penetration into the vine canopy, without affecting the spray recovering and recycling potential of the sprayer.

Also the effects of different outlet orientations were comparably small. In general, the best angling of the air outlets was 20°, so as to point towards the middle of the opposite separator panel. At 10° inclination, in fact, part of the spray plume was not completely captured by the separator panel, but visibly escaped through the front and rear openings of the tunnel. On the other side, the 30° inclination of both air booms towards the centre of the tunnel visibly increased the turbulence of the air flows, particularly at the minimum distance between the shields (0.50 m, Figure 5), and this may have reduced droplet penetration through the separating panels.

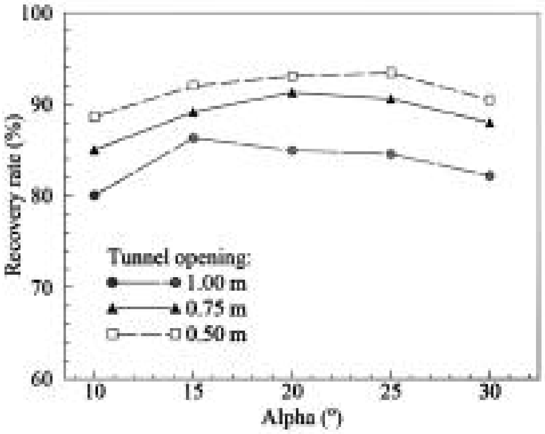

Fig. 6 - Static test No. 2: further analysis of the effect of outlet orientation.

Tunnel opening, m	Recovery rate, %	
	No fan	Medium fan speed
0.50	74.6	94.2
0.75	71.7	92.5
1.00	61.8	84.7

TABLE 2 - Static test No. 3: no fan versus medium fan speed (46.8 rev/s).

Tunnel opening, m	Outlet orientation, degrees	Recovery rate, %		
		panels covered at the inside	panels covered at the outside	panels not covered
0.50	25	77.7	79.9	93.3
0.75	20	70.6	72.0	92.1
1.00	15	60.6	62.1	86.3

TABLE 3 - Static test No. 4: effect of separator panel covering.

Outlet orientation		test conditions	Recovery rate, %
front air boom (degrees, backwards)	rear air boom (degrees, forwards)		
25	25	static	95.0
25	25	dynamic, at 6.23 km/h forward speed	83.8
5	25		87.4
0	25		86.7
0	30		79.6

TABLE 4 - Dynamic tests: effect of outlet orientation.

Test no. 2 allowed a more complete analysis of the effects of outlet orientation (Figure 6). In fact, the best angling was different, depending on the distance between the air outlets and the opposite separator panel, and was 15°, 20° or 25° for openings of 1.00 m, 0.75 m and 0.50 m, respectively. This was consistent with the fact that, for a given angle of inclination, the air flow would impact the separator panel in slightly different points, depending on the distance between the shields. In general, the best setup was always obtained when the air jets were orientated towards the middle of the spray capture panel.

Test No. 3 showed that air-assistance was important to improve the recovery rate. In the no-fan treatment, in fact, part of the droplets did not even have sufficient energy to reach the separator panel at the facing tunnel wall, and were mainly lost through the opening at the bottom of the tunnel. As a consequence, the recovery rate was decreased at 61.8% to 74.6%, depending on tunnel opening (TABLE 2).

Test No. 4 showed that a similar reduction could be expected from a tunnel sprayer fitted with air-assistance and full containment walls (60.6% to 79.9%; TABLE 3). More particularly, covering the separating panels with plastic foils in the inside reduced the spray recovery by 16% to 26% approximately, depending on the distance between the shields (0.50 m or 1.00 m, respectively). This meant that 16% to 26% of the total delivered spray volume was lost through the tunnel's front, back and bottom openings. Placing the plastic foils in the outside did not prevent the separation effect completely, but resulted in the loss of 14% to 24% of the spray volume anyway.

3.3 *Dynamic tests*

The dynamic tests performed with the sprayer in motion at 6.23 km/h showed that the orientation of the air outlets, and particularly the front ones, needed to be differently adjusted, in order to compensate for the effect of the additional flow of air, entering the tunnel from the front opening. In fact, the symmetrical rotation by 25° of both air booms towards the centre of the tunnel, giving a 95.0% recovery under static conditions (static test No. 2), resulted in a substantially lower recovery rate (83.8 %; TABLE 4) at 6.23 km/h forward speed. This was associated with a relatively small, but clearly visible loss of droplets from the rear opening.

The best adjustment found in these tests was with the front outlets rotated by 5° (towards the centre of the tunnel, or backwards relative to the 0° orientation, as defined in Figure 3), and the back outlets rotated by 25° (forwards, Figure 3). This resulted in a recovery rate of 87.4% (TABLE 4). Thus, complete compensation of the effect of motion was not possible.

It was considered unnecessary to further analyse this effect, i.e. for tunnel openings or forward speeds different from those tested (0.50 m, and 6.23 km/h). In fact, the best orientation of the air outlets under field conditions will be affected by the presence and density of vegetation, so that, in general, the optimum setting will have to be determined in the field. Under practical conditions, visual assessment of the droplet loss from the rear tunnel opening might be sufficient to suggest how to adjust the outlet angling. Alternatively, a better confinement of the spray cloud might be obtained by differently managing the air currents in the inside of the tunnel. For instance, additional air jets might be used, and placed on each side of the front opening so as to form a sort of shield before the nozzles, and to prevent external air to enter the tunnel, as suggested by some Authors [Baldoin 2008].

3.4 *Field tests*

Spray recovery in the vineyard was 77% at beginning of season (April 3, before bud break) to 34% on July 11 (full foliage development; TABLE 5). The decrease in recovery rate during the season is common for most tunnel sprayers [Bäcker 1991; Siegfried 1996; Planas 2002; Ade 2007]. In fact, as the leaf area

Trial Date (2007)	LAI	Tunnel opening, m	Recovery rate, %	Open nozzles per side	Volume sprayed, l/ha	Nozzle type
3 April	0.00	0.60	77	3	319	ATR brown
3 May	0.33	0.55	40	2	219	ATR orange
9 May	0.53	0.60	47	3	323	ATR orange
21 May	0.46	0.60	47	3	323	ATR orange
31 May	0.61	0.60	50	4	444	ATR orange
8 June	0.96	0.65	40	5	555	ATR orange
11 July	1.79	0.65	34	6	433	ATR yellow

TABLE 5 - Amount of spray recycled by the tunnel sprayer in 2.71 ha Merlot vineyard during 2007.

index of the crop increases, more volume of spray is retained by the canopy, leading to a reduction in the amount of spray available for recovering. However, the prototype tunnel sprayer gave a relatively constant recovery rate between May 3 and June 8 (40% to 50%), despite an increase in the LAI by nearly three times (from 0.33 to 0.96).

The work capacity of the tunnel sprayer averaged 2.0 ha/h, with 22.5% of total time lost for turning manoeuvres and tank refilling.

4. Conclusions

The tunnel sprayer fitted with lamellae separators was efficient in recovering a large portion of the spray both under static and dynamic conditions.

The maximum potential recovery under static conditions was 95.1% or 93.5%, at 0.50 m or 0.75 m tunnel openings, respectively, but clearly decreased at 1.00 m. This suggested that better performances are to be expected when using the tunnel sprayer in vineyards with relatively thin canopies, and in VSP (vertical shoot positioned) training systems such as Guyot or Low Spur Cordon.

Under dynamic conditions, the spray recovery rate decreased, owing to the effect of the additional flow of air, entering the tunnel from the front opening at 6.23 km/h forward speed. Adjusting the orientation of the air outlets to 5° backwards (front air boom) and 25° forward (rear boom) could partially compensate for this effect, resulting in a recovery rate of 87.4%. This suggested that the prototype could be possibly improved by increasing the air flow rate of the fans, or by using additional air jets to shield the front opening from the incoming air flux.

The recovery rate during spray application in the vineyard was maximum before bud break (77%), but still very good during the growing season of the vines (34% to 50%), and was relatively little affected by the LAI development. These values were similar, and in many cases even better, as compared with those reported in the literature from tunnel sprayers both without air-assistance [Bäcker 1991; Siegfried 1991; Siegfried 1996], or fitted with centrifugal fans [Baraldi 1993; Planas 2002].

These preliminary tests were also useful to set up the tunnel sprayer for further analyses, particularly in order to assess the spray distribution over the foliage, penetration into the canopy and coverage of the under side of the leaves. The objective of further research will be to determine whether the new air-assistance system, developed for this sprayer, will be efficient in improving spray distribution uniformity, which has often been reported as unsatisfactory from most models of experimental or commercial tunnel sprayers proposed so far [Siegfried 1996; Viret 2003; Planas 2002].

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Summary

Tunnel (recycling) sprayers have long been recognised as an important tool to reduce drift losses. Depending on the crop and the growth stage, tunnel sprayers may recycle up to 60% of the spray volume, thus enabling the farmers to control pests even at reduced PPP dose rates. However, the introduction of tunnel sprayers in Italian vine-growing farms has been hindered so far by high machine cost, low working speed, and often unsatisfactory uniformity of deposition, generally related to the difficulty of correctly managing the air currents inside the tunnel. Recently, a new prototype, air-assisted shielded sprayer has been developed by the University of Udine and Agricolmeccanica s.r.l. The two-row, tractor-mounted sprayer uses a lamellae separator wall, placed in front of each nozzle boom, to recover the excess spray which has not deposited on the canopy. Initial tests have been conducted to analyse the effects of the main sprayer settings (air flow rate, distance between the shields, and orientation of the air outlets) on spray recovery. Maximum recovery rate was 95.1% under static conditions. The sprayer was then used for spray application in the vineyard during the 2007 season, showing high reliability and work capacity. The recovery rate was 34% to 77% under field conditions, depending on the leaf area of the crop and other factors.

Keywords: Recovery rate, Air Flow Rate, Static Tests.