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Effect of Nozzle Orientation on Droplet Size and Droplet Velocity from Vineyard Sprays

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Abstract: Spray drift has become an important issue in pesticide application. Vineyard spraying is particularly interesting to consider, as pesticide droplets are not directed towards the ground but rather towards the targeted crop. The aim of this study was to investigate the influence of nozzle orientation on droplet size and droplet velocity using three different nozzles (IDK, TVI, and TXA) used in vineyards. Two series of measurement were performed in order to assess the effect of the gravity on sprays. Droplet size and one-dimensional droplet velocity characteristics were measured using a phase Doppler particle analyser (PDPA). Two planes, i.e., one horizontal and one vertical, were considered. Results suggest that the nozzle orientation slightly affects the size distribution, which is shifted towards larger droplets when nozzles spray horizontally compared to vertically spray. However, droplet axial velocity distribution is shifted towards lower values. Supposing that the only droplets which can reach the crop are those with an axial velocity greater than 1 m/s and a diameter larger than 100 μm , results showed significant differences according to the nozzle and orientation. More than 98.6% of the spray volume would reach the target whatever the orientation of the IDK nozzle, 78.8% of the spray volume would reach the crop when the TVI nozzle sprays horizontally, while only 16.0% of the spray volume would reach the crop when TXA nozzle sprays horizontally. This paper offers new perspectives in the comprehension and the optimization of the deposition process into the vegetation based from droplet size and velocity profiles from horizontally oriented sprays from flat fan or hollow cone nozzles.

Key words: Droplet size, droplet velocity, nozzle orientation, vineyard sprays.

1. Introduction

Spray drift, defined as the quantity of plant protection product carried out in the treated area by the action of air currents, has become an important issue in pesticide application. Airborne drift is especially an important issue, as pesticide droplet may travel along large distances according to its diameter and initial velocity [1]. Decreasing pesticide-related pollution in vineyards is of paramount importance, due to the high number of applications required per year and the significant risk of off-target contamination. In French vineyards, a large majority of pesticide is applied by using pneumatic sprayers. Up to now, vineyard sprayers do not satisfy the minimum requirements in terms of drift mitigation according to French regulation.

Other technological solutions that could meet the required performances already exist, i.e., air assisted sprayers, but studies on the characterization of potential nozzles are first needed. One way of selecting the more relevant nozzles is to rely on a vertical test bench [2] or on artificial vegetation [3]. A second option consists in phase Doppler particle analyser (PDPA), a non-intrusive optical tool, which has been widely used to study spray droplet characteristics [4-6]. Generally, studies on spray characterization involve nozzles that are spraying vertically downwards, as it is the case for boom sprayers. However, in vineyards or in orchards, the liquid is sprayed horizontally, or even upwards, and may lead to more airborne drift than that in arable crops [7]. That is the reason why it would be worthwhile to assess spray nozzles in horizontal position as well as in vertical position.

The objective of the study was to compare three

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nozzle types when spraying vertically and horizontally, more precisely, to assess droplet size and droplet velocity in these two configurations.

2. Materials and Methods

2.1 Nozzle Characteristics

Three different International Standard Organization (ISO) coded nozzles were selected, namely, an air-induction flat-fan nozzle IDK 90-01 C (Lechler, Germany), an air-induction hollow cone nozzle TVI 80-0050 (Albuz, Coorstek Advanced Material France) and a standard hollow cone nozzle TXA 80-0067 (Teejet, USA). These nozzles were chosen, as they are currently used in France for vineyards application. The spray pressure of each nozzle was chosen such that the three nozzles delivered an identical flow rate of 0.37 L/min (Table 1). The liquid used for all the experiments was tap water. The measurements were performed at room temperature. In vineyards, at early growth stage, pesticide spraying may be performed without air flow assistance. Therefore, no air flow surrounded the spray droplets.

2.2 PDPA Laser Measurements

Droplet size and one-dimensional droplet velocity characteristics of the different spray nozzles (Table 1) have been measured using a PDPA (Dantec, Denmark) at a distance of 0.40 m from the nozzle [8]. This distance between the nozzle exit and the measurement planes corresponds to the distance between spray nozzles and crop in vineyards.

Two series of measurement were performed in order to assess the effect of the gravity on sprays by using a stepwise process according to the sampling grid shown in Fig. 1. During the first series, measurements were performed within a plane at a distance $z = 0.40$ m from the nozzle exit, with nozzle spraying downwards (Fig. 1a). During the second series of measurements, measurements were performed within a plane at a distance $x = 0.40$ m from the nozzle exit, with nozzle spraying horizontally (Fig. 1b).

The nozzle was moved above the measurement volume by an automatic 3D transporter. Phase doppler measurements were carried out following the same

Table 1 Characteristics of the three nozzles studied.

Nozzle brand	Spray pressure (kPa)	Spray
Lechler IDK 90-01 C	260	Air induction flat fan spray
CoorsTek TVI 80-0050	1,000	Air induction hollow cone spray
Teejet TXA 80-0067	570	Hollow cone spray

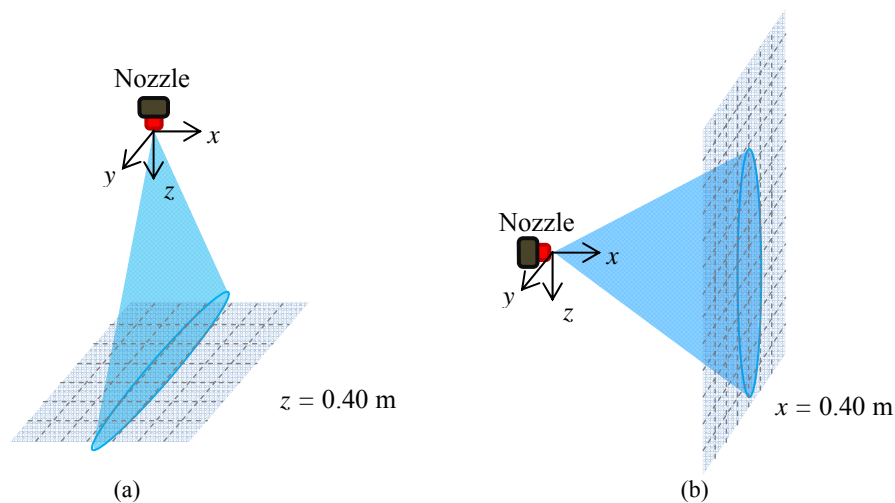


Fig. 1 Experimental set up.

In Fig. 1a, plane $z = 0.40$ m (vertical spray); in Fig. 1b, plane $x = 0.40$ m (horizontal spray).

method for all nozzles, as the reflection scattering mode was selected. In each measurement point, the time depending on the nozzle was required to get enough droplets to stabilize either the Sauter mean diameter (ratio between the volumetric and surface area of the particles assumed to be spherical) and the axial velocity values.

Table 2 describes the total number of measurement points (along x and y axes), measurement duration in each point and the total droplet number within the plane $z = 0.40$ m when the nozzle is spraying vertically. In post-processing, the mean values for the diameter and velocity in various spray positions were recorded.

Table 3 describes the total number of measurement points (along z and y axes), measurement duration in

each point and the total droplet number within the plane $x = 0.40$ m when the nozzle is spraying horizontally.

Note that when the spray is horizontal, the position of the lowest measurement point was determined with difficulty, as the axial velocity of some droplets tended to zero, which means droplets tended to fall vertically. In this case, a droplet could be measured several times in the vertical plane.

3. Results and Discussion

The number distribution and volume distribution by size classes, namely, $< 100 \mu\text{m}$, $100\text{--}500 \mu\text{m}$ and $> 500 \mu\text{m}$, for the three nozzles were presented in Figs. 2 and 3, respectively. The first line corresponds to vertical spraying ($z = 0.40$ m), whereas the second line

Table 2 Total number of measurement points, measurement duration in each point and total droplet number when nozzle sprayed vertically.

Nozzle brand	Total number of measurement points	Measurement duration in each point (s)	Total droplet number
Lechler IDK 90-01 C	126 (7×18)	90	13,854
CoorsTek TVI 80-0050	98 (7×14)	45	3,035
Teejet TXA 80-0067	98 (7×14)	20	16,699

Table 3 Total number of measurement points, measurement duration in each point and total droplet number when nozzle sprayed horizontally.

Nozzle brand	Total number of measurement points	Measurement duration in each point (s)	Total droplet number
Lechler IDK 90-01 C	270 (15×18)	90	25,927
CoorsTek TVI 80-0050	234 (13×18)	60	10,191
Teejet TXA 80-0067	255 (15×17)	30	22,104

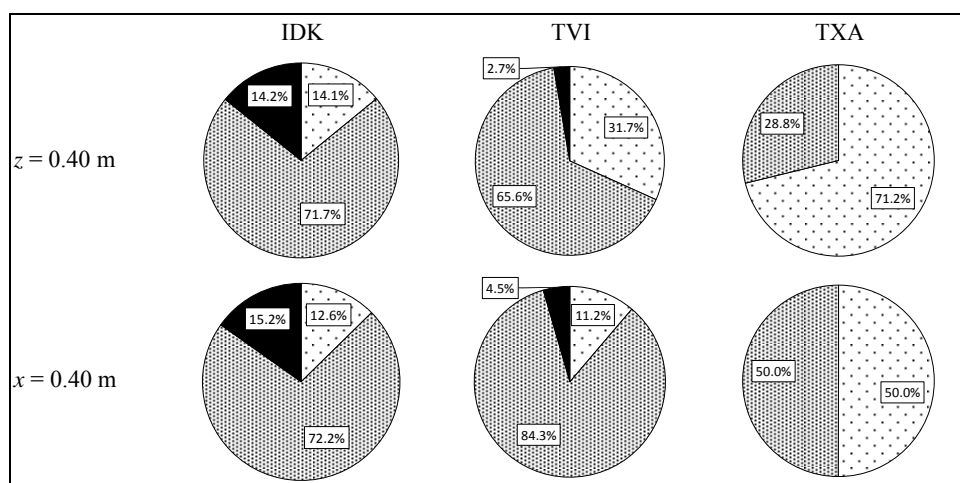


Fig. 2 Number distribution by size classes for the three nozzles in both nozzle orientations.

$\cdot\cdot\cdot$: $d < 100 \mu\text{m}$; $\times\times\times$: $100 \mu\text{m} \leq d \leq 500 \mu\text{m}$; \blacksquare : $d > 500 \mu\text{m}$.
Vertical spraying: $z = 0.40$ m; horizontal spraying: $x = 0.40$ m.

corresponds to horizontal spraying ($x = 0.40$ m).

Three size classes were chosen here. The first class covers droplets below $100 \mu\text{m}$ in diameter, and these droplets are considered to be the most prone to drift [9]. The second class corresponds to droplets with a diameter bounded by $100 \mu\text{m}$ and $500 \mu\text{m}$. The third class corresponds to droplets with a diameter greater than $500 \mu\text{m}$, and these droplets are often supposed to runoff from the crops.

3.1 Droplet Size

3.1.1 Droplet Number Distribution

As far as IDK nozzle concerned, whatever the nozzle orientation, the droplet number distribution remains almost unchanged. Droplets with a diameter between $100 \mu\text{m}$ and $500 \mu\text{m}$ represent more than 70% of the total droplet number. Droplets with a diameter lower than $100 \mu\text{m}$ represent about 13% of the total droplet number.

For TVI nozzle, more than 30% of the droplets have a diameter lower than $100 \mu\text{m}$, when it sprays vertically; whereas, this rate drops to 11%, when TVI nozzle sprays horizontally.

As regard to TXA nozzle, more than 70% of the total droplet number is in droplets with a diameter lower than $100 \mu\text{m}$, in case of vertical spraying. This rate drops to 50%, when TXA nozzle sprays

horizontally. Furthermore, TXA nozzle does not deliver any droplet with a diameter larger than $500 \mu\text{m}$.

Fig. 2 shows that larger droplets are measured in the vertical plane $x = 0.40$ m, compared to the horizontal plane $z = 0.40$ m. Indeed, the finest droplets may fall to the ground before reaching the measurement plane, or the larger droplets may be provided with a high kinetic energy.

3.1.2 Droplet Volume Distribution

For IDK and TVI nozzles, whatever the orientation, droplets with a diameter lower than $100 \mu\text{m}$ are less than 0.5% of the total spray volume. The IDK nozzle delivers the largest droplets, with approximately 70% of the spray volume in droplets with a diameter larger than $500 \mu\text{m}$. For TVI nozzle, 70% of the total volume is in droplets bounded by $100 \mu\text{m}$ and $500 \mu\text{m}$.

For the TXA nozzle, the percentage of the spray volume in finest droplets (with a diameter lower than $100 \mu\text{m}$) is 18.6%, when the nozzle sprays vertically, while this percentage drops to 11.8% in the other nozzle orientation.

Results shown in Figs. 2 and 3 suggest that nozzle orientation has a greater impact in terms of number distribution than in terms of volume distribution. Indeed, the impact is all the more significant when the nozzle delivers fine droplets. In other words, nozzle orientation has a little impact on IDK nozzle, a greater

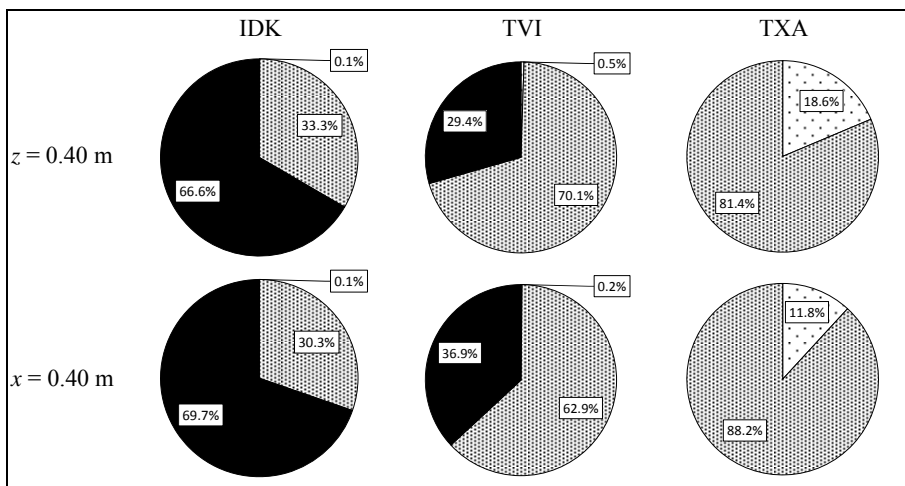


Fig. 3 Volume distribution by size classes for the three nozzles in both nozzle orientations.

$d < 100 \mu\text{m}$; $100 \mu\text{m} \leq d \leq 500 \mu\text{m}$; $d > 500 \mu\text{m}$.
 Vertical spraying: $z = 0.40$ m; horizontal spraying: $x = 0.40$ m.

impact on the TVI and the highest impact on the TXA nozzle. Changing nozzles from vertical to horizontal position decreases the part of finest droplets.

3.2 Droplet Characteristics

The spray droplet characteristics when the spray is vertical and horizontal are summarized in Table 4 and Table 5, respectively. $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ correspond to diameter below which smaller droplets represent 10%, 50% and 90% of the total spray volume, respectively.

Comparison between Table 4 and Table 5 shows that global spray characteristics are only slightly affected by nozzle orientation. Droplet velocity distribution profile is much more affected than droplet size distribution. However, it was also confirmed that shifting nozzles from a vertical to a horizontal

position involves a decrease in the fraction of the finest droplets in sprays.

3.3 Axial Velocity Distribution

In pesticide spraying, slow droplets may fall down before reaching the targeted crop, when they are sprayed horizontally, like in vineyards. This could happen especially when spraying is performed without any air co-flow. The minimum axial velocity required to reach the crop depends of course on the distance between the sprayer and the crop and on the droplet diameter.

In Fig. 4, volume distribution by axial velocity classes of the three spray nozzles are compared when sprayed vertically ($z = 0.4$ m) and horizontally ($x = 0.4$ m) (Fig. 4). Three axial velocity classes were chosen, namely, < 1 m/s, $1\sim 5$ m/s and > 5 m/s. The class lower

Table 4 Spray droplet characteristics of $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ when nozzle sprayed vertically.

Nozzle brand	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)
Lechler IDK 90-01 C	335	586	967
CoorsTek TVI 80-0050	222	402	623
Teejet TXA 80-0067	82	143	206

Table 5 Droplet characteristics of $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ when nozzle was sprayed horizontally.

Nozzle brand	$D_{v0.1}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.9}$ (μm)
Lechler IDK 90-01 C	347	616	1,045
CoorsTek TVI 80-0050	242	436	744
Teejet TXA 80-0067	96	154	202

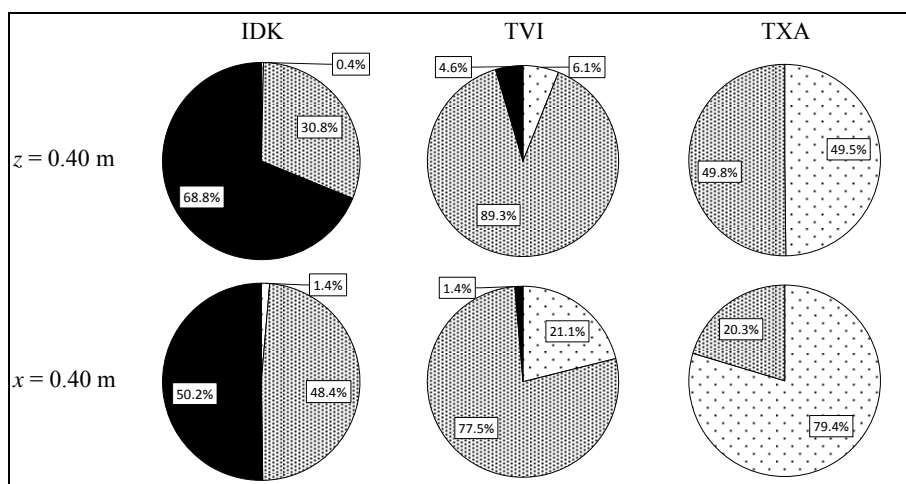


Fig. 4 Volume distribution by axial velocity classes for the three nozzles in both nozzle orientations.

Legend: $u < 1$ m/s; $1 \text{ m/s} \leq u \leq 5 \text{ m/s}$; $u > 5 \text{ m/s}$.

Vertical spraying: $z = 0.4$ m; horizontal spraying: $x = 0.4$ m.

than 1 m/s was chosen, as it is supposed that droplets with a low axial velocity do not reach the target and follow airstream.

Changing nozzle orientation from vertical to horizontal direction introduces a change in droplet velocity. Indeed, when the nozzle sprays downwards, gravity effect is added to axial velocity. Therefore, as shown in Fig. 4, the proportion of the slowest droplets increases when nozzle sprays horizontally, regardless of the nozzle. This modification is very low for IDK nozzle, for which 0.4% to 1.4% of the volume is in droplets with a velocity lower than 1 m/s. For TVI nozzle, the part of the slowest droplets represents 6% of the total volume in case of vertical spraying, while this part is 21% in case of horizontal spraying. For TXA nozzle, 50% of the total volume is in droplets with an axial velocity lower than 1 m/s when the spray is vertical, and 80% in case of horizontal spraying.

Fig. 4 shows that nozzle orientation may increase the part of the slowest droplets, suggesting a bad influence on drift. The strongest influence appears for the TXA nozzle, followed by TVI nozzle and IDK nozzle.

If one considers that the part of the spray volume that reach the crop consists of droplets with a sufficient diameter, for example greater than 100 μm and with a sufficient velocity, which means for example, droplets with an axial velocity greater than 1 m/s, then one may be interested in the part of the spray volume with these characteristics. Table 6 presents the volume distribution of spray droplets in two groups for the three nozzles and both spraying direction. The first group represents the volume of droplets with a diameter lower than 100 μm (whatever the velocity)

or with an axial velocity lower than 1 m/s (whatever the diameter). The second group covers other droplets, i.e., the droplets that are large enough and fast enough to reach the crop.

For the IDK nozzle, whatever the nozzle orientation, less than 1.4% of the spray volume is in droplets with a diameter lower than 100 μm or an axial velocity lower than 1 m/s.

For the TVI nozzle, when the spray is vertical downwards, 6.3% of the total spray volume is in droplets which have a diameter lower than 100 μm or a velocity lower than 1 m/s. When the spray is horizontal, this rate grows up to 21.2%.

For the TXA, this rate is equal to 63.8% of the spray volume when the spray is vertical, and grows up to 84% when the spray is horizontal.

In other words, if one considers that droplets that reach the crop need to be large and fast enough, in case of horizontal spraying, only 16% of the pesticide reaches the crop when the TXA nozzle is used, 78.8% when the TVI nozzle is used and 98.6% when the IDK nozzle is used.

However, these rates were calculated with arbitrary values for the minimum values of diameter and velocity. These rates depending on these values need of course to be more precise.

Moreover, the rate of droplets that reach the crop is not necessarily equal to the rate of droplets efficient for pesticide treatment. Indeed, it may be possible that droplets supplied with a high kinetic energy may rebound off the leaves. The classification in Table 6 is a first attempt to take into account axial velocity in nozzle classification.

Table 6 Volume distribution of spray droplets in two classes in both orientations for the three nozzles.

Nozzle brand	Orientation	Volume rate of droplet with $d < 100 \mu\text{m}$ or $u < 1 \text{ m/s}$	Volume rate of droplet with $d \geq 100 \mu\text{m}$ and $u \geq 1 \text{ m/s}$
Lechler IDK 90-01 C	Vertical ($z = 0.4 \text{ m}$)	0.4%	99.6%
	Horizontal ($x = 0.4 \text{ m}$)	1.4%	98.6%
CoorsTek TVI 80-0050	Vertical ($z = 0.4 \text{ m}$)	6.3%	93.7%
	Horizontal ($x = 0.4 \text{ m}$)	21.2%	78.8%
Teejet TXA 80-0067	Vertical ($z = 0.4 \text{ m}$)	63.8%	36.2%
	Horizontal ($x = 0.4 \text{ m}$)	84.0%	16.0%

4. Conclusions

The results of the study suggest that nozzle orientation slightly affects droplet size distribution. When the nozzle sprays horizontally, some droplets may fall down before reaching the measurement plane, or may coalesce with larger droplets. Therefore, size distribution is slightly shifted towards larger droplets, whatever the nozzle, when the nozzle is reoriented from vertical to horizontal position. For instance, values of the volume median diameter (or $D_{v0.5}$) vary from 586 μm to 616 μm for the IDK nozzle, from 402 μm to 436 μm for the TVI nozzle, and from 143 μm to 154 μm for the TXA nozzle. These values show that evaluating nozzles in terms of droplet size when nozzles are spraying vertically is correct, even if nozzles spray horizontally afterwards.

Nozzle orientation affects more significantly droplet axial velocity distribution. When nozzles spray horizontally, gravity and axial velocity are not collinear any more. Therefore, droplet velocity distribution is moved towards lower axial velocity. This point may increase drift. When the TXA nozzle sprays vertically, 50% of the spray volume is in droplets with an axial velocity lower than 1 m/s, whereas this rate grows up to 80% in case of horizontal spraying.

In order to assess drift related to nozzles, it is proposed to take into account droplet axial velocity in addition to standard droplet diameter.

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