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Abstract

Spray drift is one of the main pollution sources identified when pesticides are sprayed on crops. In this work, in order to simplify the evaluation of hollow-cone nozzles according to their drift potential reduction, several models commonly used were tested by three indirect methods: phase Doppler particle analyser (PDPA) and two different wind tunnels. The main aim of this study is then to classify for the first time these hollow-cone nozzle models all of them used in tree crop spraying (3D crops). A comparison between these indirect methods to assess their suitability and to provide guidelines for a spray drift classification of hollow-cone nozzles was carried out. The results show that, in general terms, all methods allow hollow-cone nozzle classifications according to their drift potential reduction (*DPR*) with a similar trend. Among all the parameters determined with the PDPA, the V_{100} parameter performed best in differentiating the tested nozzles among drift reduction classes. In the wind tunnel, similar values were obtained for both sedimenting and airborne drift depositions. The V_{100} parameter displayed a high correlation (up to R^2=0.948) with the drift potential tested with the wind tunnel. It is concluded that in general, the evaluated indirect methods provide equivalent classification results. Additional studies with a greater variety of nozzle types are required to achieve a proposal of harmonized methodology for testing hollow-cone nozzles.

Keywords: Pesticide, spray, drift, drift potential, droplet size, nozzle classification.

Nomenclature

DP	drift potential (%)
DP_H	sedimenting drift potential (%)
DPR	drift potential reduction (%)
DPR_H	drift potential reduction based on sedimenting deposition in wind tunnel (%)
DPR_V	drift potential reduction based on airborne deposition in wind tunnel (%)
DPR_{DVx}	drift potential reduction based on D_{Vx} (%)
DPR_{Vx}	drift potential reduction based on V_x (%)
D_{Vx}	volume diameter, indicating that the *x* (% of spray volume) is in smaller droplets (µm)
DRN	drift reduction nozzle
FF	flat-fan
FC	full-cone
HC	hollow-cone
PDPA	phase Doppler particle analyser
STN	standard nozzle
V_x	volume fraction of droplets smaller than *x* µm in diameter (%)

WT1	ISO wind tunnel
WT2	volumetric wind tunnel

1. Introduction

Spray drift is one of the main pollution sources identified when pesticides (also known as plant protection products, PPP) are applied on crops. Harmful effects of pesticides on humans and the environment are known for years. The potential adverse consequences of PPP usage can be significantly dispersed along time and space. As a result, the effects of pesticides on living beings, including humans, may emerge far away from the place where the treatment was performed and often after a long time. Field spray treatments can cause exposure to humans by several ways such as inhalation and dermal contact with the PPP spray drift during the application or with the PPP volatilised fraction some time after the treatment (Butler Ellis et al., 2010 and 2018; Damalas, C. A. 2015). The spray drift of PPP can be evaluated with a variety of methodologies. These can be divided into two types: those applied in field with the aim of measuring actual drift under real-life conditions (direct methods); and those which attempt to estimate drift potential (*DP*) under controlled conditions (indirect methods).

In field trials, the use of passive collectors continues to be the most popular methodology for the evaluation of drift during an application (McArtney and Obermiller, 2008; Garcerá et al., 2017; Torrent et al., 2017; Kasner et al., 2018), even though the process required is time-consuming and labour-intensive. Other authors, with the aim of simplifying the process, have developed spray drift models, based on many spray drift trials carried out in field conditions, to predict this phenomenon (Holterman et al., 2017). In recent years, the application of light detection and ranging (LiDAR) systems (Hiscox et al., 2006; Gregorio et al., 2014, 2016) for the field measurement of spray drift has been proposed. These systems have important advantages over passive collectors, both in terms of sensor performance (range and time-resolved measurements) and lower labour requirements.

The aim of the so-called indirect methods is to determine *DP*, defined as the fraction of the spray, as a percentage of the output of a spray generator, that is displaced downwind as airborne spray (ISO 22856:2008). The main advantage of indirect methods is their capacity to delimit the complexity and large number of variables that intervene in the drift phenomenon, as the tests are performed under controlled and reproducible conditions. Dimensional analyses of droplet populations are key to interpreting spray drift, with V_{100} the droplet size parameter most related to drift prone situations, as reported by Bouse et al. (1990) and Arvidsson et al. (2011). For this reason, numerous studies have been performed with characterisations of nozzle-generated droplet populations. In the vast majority of these studies, fan-type nozzles have been tested (Nuyttens et al., 2007), which are normally used in the treatment of field crops (2D crops). However, it is also of interest to evaluate hollow-cone nozzles. These are used in tree crop treatments (3D crops), where larger amounts of PPP tend to be used and where *DP* may be augmented because of the use of air-assistance in the treatment. One of the few studies to undertake a classification of this type of nozzle was that of Van de Zande et al. (2008), using a phase Doppler particle analyser (PDPA), as was also the case in subsequent studies by Holterman (2008, 2009). In these latter studies, an analysis was made of the effects of different variables (minimum number of droplets, scanning typology, nozzle height with respect to the measuring point) on droplet sizing. Good correlations have been found in comparative studies of different techniques (PDPA, laser diffraction analysis and particle/droplet imaging analysis (PDIA) (Herbst (2001a; b).

However, with so many techniques (phase Doppler particle analysis (Tuck et al., 1997), laser diffraction analysis (Derksen et al., 1999), particle measuring system (PMS) (Teske et al., 2000), and particle droplet imaging analysis (Kashdan et al., 2007)) available to characterise nozzle-generated droplet populations, the results can vary. In this sense, to harmonize the results obtained through the different methodologies, the ISO 25358:2018 proposes a methodology based on a set of standard nozzles for the definition of droplet size class boundaries.

The wind tunnel is currently the most commonly used indirect method to study and classify nozzles according to their *DP*. Following this method, Taylor et al. (2004) determined the *DP* of

ASAE reference nozzles for different wind speeds and nozzle heights. Guler et al. (2006, 2007) and Ferguson et al. (2015, 2016) evaluated drift potential reduction (*DPR*), comparing standard and drift reduction flat-fan nozzles. In addition to the effect of nozzle type, evaluation has also been made of the effect of nozzle size (Nuyttens et al., 2009). Studies have also been made of the correlation between wind tunnel recorded data and field measured data in order to extrapolate the drift reduction values to field conditions (Butler Ellis et al., 2017; Torrent et al., 2017). Douzals et al. (2016, 2018) measured droplet size in a wind tunnel using different flat-fan nozzles, heights, orientations and wind speeds, defining new *DP* indicators such as drift ratio (DR) and time-of-flight (ToF). Another methodology to evaluate *DP* for different operating conditions is based on the use of a test bench (Balsari et al., 2007), which allows assessment of working parameters (Miranda-Fuentes et al., 2018) and classification of different application equipment according to their potential drift reduction (Gil et al., 2014; Grella et al., 2019).

Most of the previously cited studies reporting indirect drift assessments focused on flat-fan nozzles, being these the most used in field crops. The amount of spray drift generated by hollow-cone nozzles used in tree crops is significantly higher. Therefore, the main aim of the present study is to classify for the first time hollow-cone nozzles used in tree crops (3D crops). A second objective is to compare three indirect methodologies for *DPR* determination: PDPA, ISO wind tunnel (WT1) (discrete collection) and volumetric wind tunnel (WT2) (whole collection) to provide guidelines for drafting a harmonized methodology for testing hollow-cone nozzles.

2. Materials and methods

2.1. Droplet size characterization using a PDPA

The droplet size spectrum was characterized using a phase Doppler particle analyser device (PDPA, Dantec Dynamics A/S. Skovlunde, Denmark) at the Information and Technologies for Agricultural Processes Joint Research Unit (IRSTEA, Montpellier, France). A total of 16 nozzles were tested, including 12 hollow-cone types (HC), of which 7 were standard STN and 5 drift reduction (DRN models, 3 flat-fan (FF) and 1 full-cone (FC). The models of the hollow cone chose are the most used for spraying tree crops in Spain. The FF nozzles tested as threshold nozzles were the previously established by Van de Zande et al. (2008) in their HC classification, while the FC was an example of a cone nozzle used in citrus crops. The set of nozzles tested allowed a study to be made of nozzle type and size. The tested nozzle models and types are shown in Table 1, as well as the working pressure at which the measurements were taken, the flow rate and the measuring height of the PDPA. The nozzles correspond to different models of the Albuz ATR, TVI and AVI series (Solcera, Evreux, France), Lechler ID (Lechler GmbH, Metzingen, Germany), and TeeJet DG (Spraying Systems Co. Wheaton, IL, USA).

Table 1. Nozzles characterized with the PDPA.

Nozzle		Pressure	Nominal flow rate	PDPA measurement
Model	Type	(kPa)	(L min^{-1})	point height (m)
ATR 80 Lilac *		700	0.42	
ATR 80 Brown		700	0.56	
ATR 80 Yellow		700	0.86	
ATR 80 Orange	HC-STN	700	1.17	0.15
ATR 80 Red		700	1.62	
ATR 80 Grey		700/1000	1.76/2.08	
ATR 80 Green		700	2.00	
TVI 8001 Orange		700	0.61	
TVI 80015 Green		700	0.92	
TVI 8002 Yellow	HC-DRN	700	1.22	0.15
TVI 80025 Purple		700	1.53	
TVI 8003 Blue		700/1000	1.83/2.19	
AVI 80015 Green	FF-DRN	700	0.92	0.30
ID 9001C Orange		500	0.51	
DG 8002 Yellow	FF-STN	700	1.21	0.30
D3DC35 Brown	FC-STN	1000	2.00	0.15

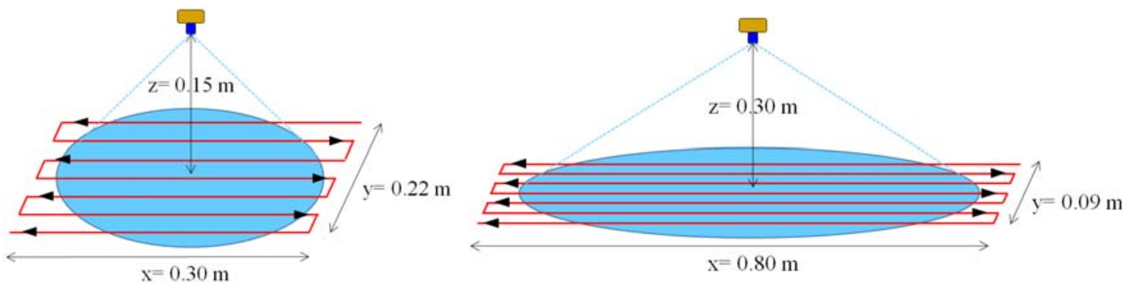
*HC-STN: Hollow-cone standard nozzle; HC-DRN: Hollow-cone drift reduction nozzle; FC-STN: Full-cone standard nozzle; FF-STN: Flat-fan standard nozzle; FF-DRN: Flat-fan drift reduction nozzle. * Reference nozzle.*

The flow rate of ten nozzles of each model was measured, and the nozzle which most closely approximated the nominal flow rate (with a deviation from the nominal flow rate in all cases below 5%) was the one chosen for testing. When coinciding, the same units of the nozzle models selected in this case were also used in the WT1 and WT2 tests (see sections 2.2 and 2.3).

Tap water was used as spray liquid for all nozzles. The temperature of the spray liquid was 20±1ºC and the liquid pressure was 500, 700 or 1000 kPa depending on the nozzle model tested (Table 1). All measurements were performed in an air conditioned room at 20±1ºC at 70-80% of relative humidity. Three repetitions for each nozzle model were carried out. Each repetition was performed with a different single nozzle unit, so three different units were tested for each model.

In all tests, the nozzle position was 0.15 m above the measuring point for all hollow-cone nozzles and 0.30 m for the flat-fan nozzles due to the fan length. To sample the whole cone section, the scan trajectory for the hollow-cone nozzles consisted of a continuous scan of the spray along 7 parallel lines 300 mm long with a separation of 36 mm (Fig. 1a). In the case of the FF-type nozzles, line length was 800 mm and line separation 15 mm (Fig. 1b). All measurements were carried out along the long axis of the spray cloud with a linear displacement of the nozzle at a constant speed of 3 mm s^{-1} during 780 s and 1860 s for the cone-type and FF-type nozzles, respectively.

Measurement acquisition was performed with the software BSA Flow v.4.50 (PDPA, Dantec Dynamics A/S. Skovlunde, Denmark) and only spherical droplets were considered (the percentage of non-spherical droplets was below 10% for all tested nozzles). For each nozzle several parameters were determined from the cumulative volumetric droplet size distribution and the following percentile characteristics calculated: i) D_{V10}, D_{V50}, and D_{V90}, representing the diameter below which smaller droplets constitute 10%, 50% and 90% of the total volume, respectively; and ii) the proportional characteristics V_{100} and V_{200}, representing the percentage of volume of drops having a diameter smaller than 100 µm and 200 µm, respectively.



(a) **(b)**

Fig. 1. Scanning path during PDPA droplet size characterization corresponding to the following nozzles: (a) HC-STN, FC-STN and HC-DRN; (b) FF-STN and FF-DRN.

2.2. ISO wind tunnel (WT1) tests

A detailed explanation is provided in this section of the methodology employed in the WT1 wind tunnel, situated in Maqcentre - Parc Científic i Tecnològic Agroalimentari de Lleida (PCiTAL, Lleida, Spain). The tunnel characteristics meet those of the International Standard ISO 22856:2008. The tunnel is 2.0 m wide, 1.0 m high and has an operating length of 7.0 m (Fig. 2). Test conditions in the tunnel interior were 2±0.1 m s^{-1} for air flow, with turbulences below 8%, and local speed variations below 5%.

A total of 38 nozzles were tested of different manufacturers: 19 HC-STN nozzles, 9 HC-DRN nozzles, 1 FC-STN nozzle, 6 FF-STN nozzles and 3 FF-DRN nozzles. Included in this list are the 28 most representative nozzle models and sizes used on tree crops in Spain. Ten additional nozzles used on field crops were also included to enable comparison with tests made in other laboratories. Test pressure for the HC nozzles was 500, 700 and 1000 kPa, for the FC nozzle was 1000 kPa and for the FF nozzles 200, 250, 300, 500 and 700 kPa depending on the nozzle tested (Table 2). In all tests, a mixture of a water-soluble fluorescent tracer, brilliant sulfoflavine (BSF) yellow (CI 56205) (Biovalley, Marne La Vallee, France), was sprayed at a concentration of 0.3 g L^{-1}, with a total of 3 repetitions per tested nozzle, following the methodology described by Torrent et al. (2017).

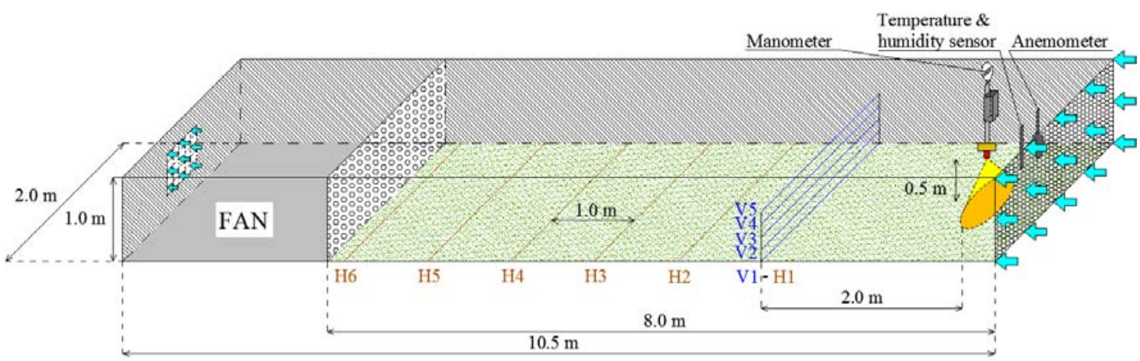


Fig. 2. Inside view setup of the WT1. Dimensions and position of the collectors (horizontals: H1-H6, verticals: V1-V5). Figure adapted from Torrent et al. (2017).

Table 2. Nozzles tested using WT1.

Nozzle			Pressure	Flow rate
Manufacturer	**Model**	**Type**	**(kPa)**	**(L min^{-1})**
Abba	AG 1030.015 Green	HC-STN	700	0.92
	AG 1030.02 Yellow		700	1.22
	AG 1030.025 Lilac		700	1.53
Agrotop	Air Mix HC 80.025 Lilac	FF-DRN	500	0.60
Albuz	ATI 60.015 Green	HC-STN	700	0.92
	ATI 60.025 Lilac		700	1.53
	ATR 60 Red		700	1.62
	ATR 60 Yellow		700	0.86
	ATR 80 Grey		1000	2.08
	ATR 80 Lilac*		700	0.42
	ATR 80 Orange		700	1.17
	ATR 80 Red		700	1.62
	ATR 80 Yellow		700	0.86
	AVI 80015 Green	FF-DRN	700	0.92
	TVI 80015 Green	HC-DRN	700	0.92
	TVI 8002 Yellow		700	1.22
	TVI 80025 Purple		700	1.53
	TVI 8003 Blue		1000	2.19
Hardi	1553-14	HC-STN	1000	0.60
	1553-18		1000	1.10
	F110.03 Blue	FF-STN	300	1.20
Lechler	ID 9001C Orange	FF-DRN	500/700	0.51/0.60
	ITR 8001 Orange	HC-DRN	700	0.60
	ITR 80015 Green		700	0.90
	ITR 8002 Yellow		700	1.22
	LU 120.06 Grey	FF-STN	700	0.60
	TR 80015 Green	HC-STN	700	0.90
	TR 8002 Yellow		700	1.22
	TR 8003 Blue		700	1.81
Lurmark	F11003 Blue	FF-STN	300	1.18
	HCX 10 Black	HC-STN	500	0.86
	HCX 12 Yellow		500	1.03
Teejet	D3DC35 Brown	FC-STN	1000	2.00

DG 8002 Yellow	FF-STN	700	1.21
TXA 8002 VK Yellow	HC-DRN	700	1.20
TXA 8003 VK Blue		700	1.80
XR 8008 VK White	FF-STN	250	2.88
XR 8015 (Steel)		200	4.90

*HC-STN: Hollow-cone standard nozzle; HC-DRN: Hollow-cone drift reduction nozzle; FC-STN: Full-cone standard nozzle; FF-STN: Flat-fan standard nozzle; FF-AIN: Flat-fan air induction nozzle. * Reference nozzle.*

2.3. Volumetric wind tunnel (WT2) tests

The WT2 tunnel is located at the facilities of the Information & Technologies for Agricultural Processes Joint Research Unit (IRSTEA, Montpellier, France). This tunnel was designed based on a criterion different to ISO 22856:2008. The tunnel is 3.0 m wide, 2.0 m high and has an operating length of 9.0 m, with a total of 180 grooves along the floor of the tunnel which are 50 mm wide and 100 mm deep (Fig. 3). The fluid is collected using 60 collecting tubes, making it necessary to position the set of tubes in three consecutive sections to cover the whole tunnel. The tunnel is comprised of a closed circuit in which air flow is generated by 6 air fans. Air temperature and humidity are automatically controlled. The most important distinguishing feature of the WT2 tunnel is that, unlike the WT1 tunnel that uses droplet collectors to determine sedimenting and airborne drift, a distribution test bench composed of slightly inclined grooved channels are situated on the tunnel floor to collect the sedimented droplets. The liquid deposited in each groove travels towards a measuring tube system where the flow of each groove is measured individually using load cells (Douzals and Al Heidary, 2014).

The sprayed fluid was tap water at a temperature of 20±1ºC. Ambient conditions in the tunnel interior were 20±1ºC and 70-80% relative humidity. Air flow speed was 2.0±0.1 $m{\cdot}s^{-1}$.

The selected nozzle units were those whose flow rate closest to the nominal, as explained in section 2.1. As can be seen in Table 3, a total of 4 Albuz hollow cone nozzles were tested, two of which were STN type (ATR 80 Lilac and ATR 80 Grey) and two DRN (TVI 80025 Purple and

TVI 8003 Blue), at a pressure of 700 kPa. The ATR 80 Grey and TVI 8003 nozzles were also tested at 1000 kPa to facilitate a comparison with the WT1 tests. Pressure was set with a 5 kPa precision and automatically corrected with a frequency of 3 Hz.

Each nozzle was tested in both vertical position, as in the WT1 (position for field crops), and in horizontal position (position for tree crops). The nozzles were situated 1.25 m from the start of the collection area. As shown in Fig. 2, the collection area considered for deposition evaluation was between grooves g_i and g_f, positioned at 2.00 m and 7.70 m downwind from the tested nozzle, respectively. In addition, tests were conducted with the ATR 80 Grey and TVI 8003 Blue nozzles spraying vertically and horizontally, using two units at the same time situated on a bar and separated from each other by a distance of 1.50 m.

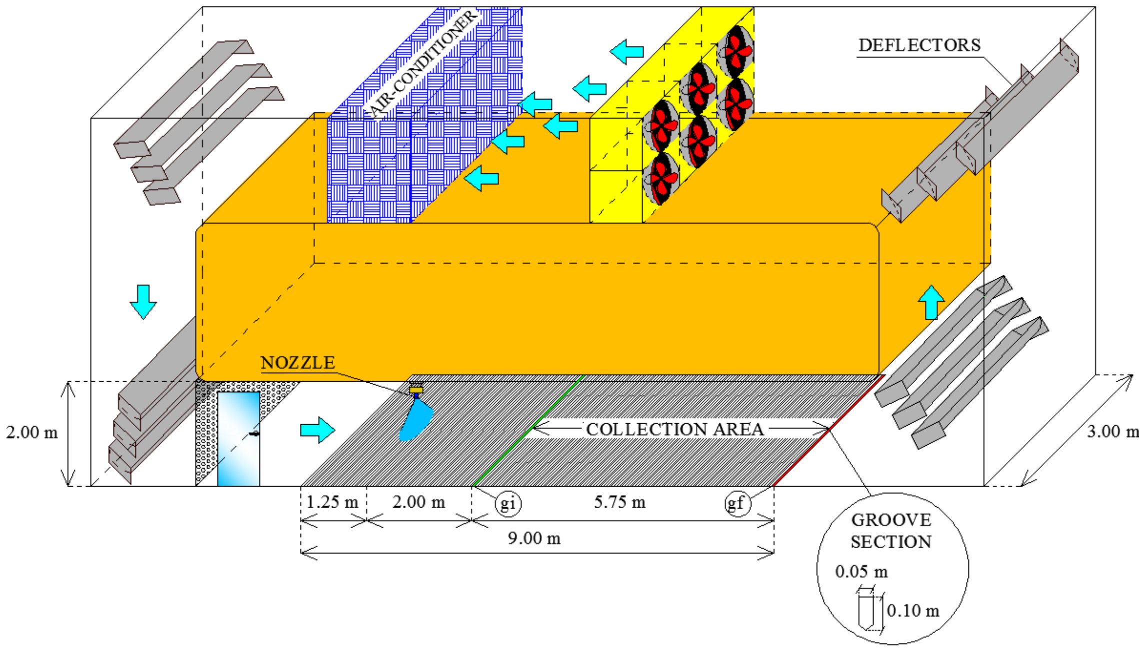


Fig. 3. Inside view setup of the WT2. Dimensions, nozzle and collection area positions.

Table 3. Nozzles tested using WT2.

Nozzle		Pressure	Flow rate	VS-1N	HS-1N	VS-2N	HS-2N
Model	Type	(kPa)	(L min^{-1})				
ATR 80 Lilac *	HC-STN	700	0.42	X	X	-	-
ATR 80 Grey		700/1000	1.76/2.08	X	X	X	X
TVI 80025 Purple	HC-DRN	700	1.53	X	X	-	-
TVI 8003 Blue		700/1000	1.83/2.19	X	X	X/-	X

HC-STN: Hollow-cone standard nozzle; HC-DRN: Hollow-cone drift reduction nozzle

*VS-1N: Vertical spraying with 1 nozzle; HS-1N: Horizontal spraying with 1 nozzle; VS-2N: Vertical spraying with 2 nozzles; HS-2N: Horizontal spraying with 2 nozzles. * Reference nozzle.*

2.4. Data analysis

Details are provided in this section of the post-processing of the results obtained for each of the test methodologies (PDPA, WT1 and WT2).

2.4.1. Statistical analysis

For the case in which a comparative analysis was made of the PDPA, WT1 and WT2 methodologies, the results shown in the tables and figures correspond to the mean value of the 3 replicate tests made in each case.

To study the effect of nozzle type, size and working pressure from the results obtained, a one-way analysis of variance (ANOVA) with Fisher's least significant difference (LSD) test was performed for each effect. Previously, the normality and homogeneity of variance of the studied variables were verified with the Shapiro-Wilk test and Levene’s test, respectively. A confidence level of 95% was considered in all tests. Statistical analyses were done using JMP® Pro 13 (SAS Institute Inc., Cary, NC, 1989-2007 for Windows).

2.4.2. Spray drift potential reduction

In the first methodology tested, droplet size characterisation using PDPA, the characteristic parameters D_{V50}, V_{100} and V_{200} were used as *DP* indicators.

For the case of WT1, the *DP* of each nozzle was calculated in accordance with ISO 22856:2008, based on the following expressions:

$$DP_V(WT1) = \sum_{i=1}^{5} V_{T(i)} \quad (1)$$

$$DP_H(WT1) = \sum_{j=1}^{6} H_{T(j)} \quad (2)$$

where $DP_V(WT1)$ and $DP_H(WT1)$ represent the total airborne and the total sedimenting *DP* for the WT1, respectively. $V_{T(i)}$ is the airborne *DP* at the vertical collector line *i* (%) (there were 5 vertical collector lines); while $H_{T(j)}$ is the sedimenting *DP* at the collector line *j* (%) (there were 6 horizontal collector lines), according to the following expressions:

$$V_{T(i)} \text{ or } H_{T(j)} = \left(\frac{v_{(i/j)} \cdot \frac{d_C}{D_C}}{q_N \cdot (t_S/60)} \right) \cdot 100 \quad (3)$$

where: $v_{(i/j)}$ is the volume deposited in the collector line *i* or *j* (L), given by Eq. (4); d_C, the distance between collectors (0.1 m for vertical collectors and 1.0 m for horizontal collectors); D_C, the collector diameter (0.002 m); q_N, the nozzle flow rate (L min^{-1}); and t_S, the spraying time (s).

$$v_{(i/j)} = \frac{v_D \cdot F}{C_D \cdot 10^6} \quad (4)$$

where: v_D is the sample dilution volume (L); *F*, the fluorimeter reading (µg BSF L^{-1}); and C_D, the BSF concentration (g BSF L^{-1}).

For the case of WT2, only the DP_H was determined. This was calculated as the global fraction of the sprayed liquid transported by the grooved channels along the tunnel, from a distance 2.00 m downwind from the nozzle position to 7.70 m. Finally, DP_H was calculated using the following expression:

$$DP_H(WT2) = \sum_{g=gi}^{gf} H_{T(g)} \quad (5)$$

where: gi and gf are the grooves at 2.00 and 7.70 m downwind from the tested nozzle, respectively; and $H_{T(g)}$ is the sedimenting spray mass at groove g (%), according to the following expression:

$$H_{T(g)} = \frac{W \cdot 60}{t_C \cdot q_N} \quad (6)$$

where: W is the collected liquid mass (kg); t_C is the collection time (s); and q_N is the nozzle flow rate (L min^{-1}).

From the corresponding *DP* values obtained for each methodology and nozzle, the *DPR* was then calculated. The *DPR* was determined by relating the value of the *DP* of the candidate nozzle (C) with the *DP* value of the reference nozzle (R), in all cases the Albuz ATR 80 Lilac at 700 kPa, using the following expression:

$$DPR = \left(1 - (DP_C/DP_R)\right) \cdot 100 \quad (7)$$

where: DP_C is the drift potential of the candidate nozzle (%); and DP_R is the drift potential of the reference nozzle (%).

3. Results

3.1. Droplet size characterization using a PDPA

Table 4 shows the characteristic parameters of the droplet population (D_{V10}, D_{V50}, D_{V90}, V_{100}, V_{200}) obtained with the PDPA. As expected, the DRN nozzles produced larger droplets than the STN nozzles.

Table 4. Droplet size spectrum characteristics of the tested nozzles arranged according to the V_{100} value.

Nozzle		Pressure	D_{V10}	D_{V50}	D_{V90}	V_{100}	V_{200}
Model	Type	(kPa)	(µm)	(µm)	(µm)	(%)	(%)
ATR 80 Lilac *	HC-STN	700	57.20	95.30	144.10	54.87	99.06
ATR 80 Brown	HC-STN	700	61.70	105.93	158.10	44.34	97.66
ATR 80 Yellow	HC-STN	700	62.30	113.93	181.40	38.10	93.56
D3DC35 Brown	FC-STN	1000	68.47	126.63	237.30	30.19	83.66
ATR 80 Orange	HC-STN	700	67.90	125.37	196.47	29.99	90.80
ATR 80 Grey	HC-STN	1000	70.93	132.87	219.40	26.16	85.80
ATR 80 Red	HC-STN	700	74.33	139.00	226.33	23.01	83.30
ATR 80 Grey	HC-STN	700	75.17	144.20	240.80	21.91	79.40
ATR 80 Green	HC-STN	700	79.27	151.50	253.97	18.97	75.71
DG 8002 Yellow	FF-STN	700	105.27	222.10	408.33	8.72	41.25
AVI 80015 Green	FF-DRN	700	190.23	414.37	853.90	1.44	11.54
ID 9001C Orange	FF-DRN	500	287.87	589.63	842.43	0.34	3.30
TVI 8003 Blue	HC-DRN	700	264.23	489.47	792.47	0.32	3.86
TVI 8003 Blue	HC-DRN	1000	281.50	514.47	809.97	0.27	3.11
TVI 8001 Orange	HC-DRN	700	279.33	552.57	841.47	0.25	3.43
TVI 80015 Green	HC-DRN	700	273.03	513.63	821.03	0.25	3.38
TVI 8002 Yellow	HC-DRN	700	287.60	534.47	813.20	0.24	2.94
TVI 80025 Purple	HC-DRN	700	300.83	549.17	811.80	0.18	2.42

*HC-STN: Hollow-cone standard nozzle; HC-DRN: Hollow-cone drift reduction nozzle; FC-STN: Full-cone standard nozzle; FF-STN: Flat-fan standard nozzle; FF-DRN: Flat-fan drift reduction nozzle. * Reference nozzle.*

When considering the V_{100} values (Table 4), significant differences were found between Albuz STN and DRN nozzles of similar flow rate (ATR 80 Yellow-TVI 80015 Green, ATR 80 Orange-TVI 8002 Yellow and ATR 80 Red-TVI 80025 Purple at 700 kPa; ATR 80 Grey-TVI 8003 Blue at 1000 kPa). Also, as nozzle size increased, the V_{100} value decreased for the STN nozzles and significant differences between different sizes were observed (ATR 80 Lilac-ATR 80 Yellow-ATR 80 Orange-ATR 80 Red at 700 kPa). However, no significant differences between nozzle size were observed for the DRN nozzles, with a V_{100} value even being obtained with the largest tested hollow-cone nozzle size (TVI 8003 Blue) which was higher than the other values. A similar trend was observed in the V_{200}, D_{V10}, D_{V50} and D_{V90} parameters.

The effect of pressure was analysed for an STN (ATR 80 Grey) and DRN (TVI 8003 Blue) nozzle, at 700 and 1000 kPa. In the case of the STN, significantly higher V_{100} and V_{200} values, and lower droplet size values, were obtained at 1000 kPa. In contrast, no significant differences were observed in any of the characteristic parameters for the DRN nozzle.

Table 5 shows the *DPR* results calculated on the basis of the V_{100}, V_{200} and D_{V50} parameters. Nozzle classification was established based on the DPR_{V100} according to ISO 22369-1:2006. Threshold nozzles corresponding to 25%, 50%, 75%, 95% and 99% drift reduction classes are ATR 80 Yellow, ATR 80 Grey at 1000 kPa, DG 8002 Yellow at 700 kPa, AVI 80015 Green at 700 kPa and ID 9001C Orange, respectively. For the V_{100} parameter, it can be seen how all the DRN models are classified in the same drift reduction class of 99%, except for AVI 80015 Green. The *DPR* values determined based on V_{200} and D_{V50} are lower than those calculated with the V_{100}, with lower spray drift reduction classes being obtained.

Table 5. *DPR* values of the tested nozzles based on three droplet size indicators (V_{100}, V_{200} and D_{V50}). Albuz ATR 80 Lilac is considered the reference nozzle. The threshold nozzles for drift reduction classes are in bold. The position number of each nozzle is given in brackets. Classification changes when considering DPR_{V200} or DPR_{DV50} instead of DPR_{V100} are highlighted in grey.

Nozzle		Pressure	DPR_{V100}	DPR_{V200}	DPR_{DV50}	Spray drift
Model	Type	(kPa)	(%)	(%)	(%)	reduction class
ATR 80 Lilac	HC-STN	700	0 (1)	0 (1)	0.00 (1)	Reference
ATR 80 Brown	HC-STN	700	19.18 (2)	1.41 (2)	10.04 (2)	<25%
ATR 80 Yellow	**HC-STN**	**700**	**30.55 (3)**	**5.55 (3)**	**16.35 (3)**	25%
D3DC35 Brown	FC-STN	1000	44.97 (4)	15.55 (6)	24.74 (5)	
ATR 80 Orange	HC-STN	700	45.34 (5)	8.34 (4)	23.98 (4)	
ATR 80 Grey[(a)]	HC-STN	**1000**	**52.32 (6)**	**13.39 (5)**	**28.27 (6)**	50%
ATR 80 Red	HC-STN	700	58.06 (7)	15.91 (7)	31.44 (7)	
ATR 80 Grey	HC-STN	700	60.07 (8)	19.85 (8)	33.91 (8)	
ATR 80 Green	HC-STN	700	65.43 (9)	23.57 (9)	37.10 (9)	
DG 8002 Yellow[(b)]	FF-STN	**700**	**84.11 (10)**	**58.36 (10)**	**57.09 (10)**	75%
AVI 80015 Green[(c)]	FF-DRN	**700**	**97.37 (11)**	**88.35 (11)**	**77.00 (11)**	95%
ID 9001C Orange[(d)]	**FF-DRN**	**500**	**99.39 (12)**	**96.66 (15)**	**83.84 (18)**	99%
TVI 8003 Blue	HC-DRN	700	99.41 (13)	96.10 (12)	80.53 (12)	
TVI 8003 Blue	HC-DRN	1000	99.51 (14)	96.86 (16)	81.48 (14)	
TVI 80015 Green	HC-DRN	700	99.54 (15)	96.59 (14)	81.45 (13)	
TVI 8001 Orange	HC-DRN	700	99.54 (16)	96.54 (13)	82.75 (17)	
TVI 8002 Yellow	HC-DRN	700	99.56 (17)	97.03 (17)	82.17 (15)	
TVI 80025 Purple	HC-DRN	700	99.68 (18)	97.55 (18)	82.65 (16)	

[a, b, c, d] Threshold nozzles corresponding to 25%, 50%, 75%, 95% and 99% drift reduction classes, respectively.

HC-STN: Hollow-cone standard nozzle; HC-DRN: Hollow-cone drift reduction nozzle; FC-STN: Full-cone standard nozzle; FF-STN: Flat-fan standard nozzle; FF-DRN: Flat-fan drift reduction nozzle.

3.2. ISO wind tunnel (WT1) tests

Table 6 shows the results obtained in sedimenting and airborne drift potential reduction (DPR_H and DPR_V, respectively) for the 38 tested nozzles. Using these results, a classification of the nozzles was made based on the DPR_H, determining their spray drift reduction class according to the thresholds of 25%, 50%, 75%, 90% and 95% (Table 6). In general, it can be seen that the

DPR$_H$ and *DPR*$_V$ values are similar for a specific nozzle, with similar classifications obtained for both parameters. It can also be seen that, for nozzles with a reduction greater than 90%, the *DPR*$_H$ takes slightly higher values than the *DPR*$_V$.

Table 6. *DPR* values of the tested nozzles determined from WT1 measurements. Albuz ATR 80 Lilac is considered the reference nozzle. The threshold nozzles for drift reduction classes are in bold. The position number of each nozzle is given in brackets. Classification changes when considering *DPR*$_V$ instead of *DPR*$_H$ are highlighted in grey.

Nozzle		Pressure	DPR_H	DPR_V	Spray drift
Model	**Type**	**(kPa)**	**(%)**	**(%)**	**reduction class**
ATR 80 Lilac	HC-STN	700	0 (1)	0 (1)	Reference
1553-14	**HC-STN**	**1000**	**9.5 (2)**	**39.49 (5)**	<25%
ATR 60 Yellow	**HC-STN**	**700**	**27.73 (3)**	**36.83 (3)**	25%
TR 80015 Green	HC-STN	700	31.34 (4)	35.14 (2)	
TXA 8002 VK Yellow	HC-DRN	700	32.18 (5)	39.43 (4)	
1553-18	HC-STN	1000	39.23 (6)	53.08 (9)	
AG 1030.015 Green	HC-STN	700	41.91 (7)	58.81 (11)	
HCX 10 Black	HC-STN	500	46.06 (8)	49.41 (7)	
HCX 12 Yellow	HC-STN	500	46.43 (9)	46.76 (6)	
TR 8002 Yellow[a]	**HC-STN**	**700**	**53.1 (10)**	**52.17 (8)**	50%
ATI 60015 Green	HC-STN	700	55.1 (11)	60.04 (13)	
LU 12006 Grey	FF-STN	200	57.92 (12)	59.19 (12)	
TXA 8003 Blue	HC-DRN	700	60.44 (13)	58.55 (10)	
ATR 80 Yellow	HC-STN	700	63.56 (14)	66.45 (14)	
AG 1030.02 Yellow	HC-STN	700	67.76 (15)	69.50 (16)	
DG 8002 Yellow	FF-STN	700	70.60 (16)	67.32 (15)	
F11003 Blue	FF-STN	300	71.47 (17)	77.72 (22)	
ATR 80 Orange	HC-STN	700	71.5 (18)	70.95 (17)	
TR 8003 Blue	HC-STN	700	74.34 (19)	73.18 (18)	
F11003 Blue	FF-STN	300	74.96 (20)	76.39 (21)	
ATR 60 Red[b]	**HC-STN**	**700**	**75.81 (21)**	**74.68 (19)**	75%
AG 1030.025 Lilac	HC-STN	700	78.67 (22)	75.57 (20)	
Air Mix HC 80025 Lilac	FF-DRN	500	85.68 (23)	86.62 (25)	
ATR 80 Red	HC-STN	700	87.77 (24)	81.96 (23)	

ID 9001C Orange	FF-DRN	700	88.60 (25)	88.74 (27)	
AVI 80015 Green	FF-DRN	700	88.80 (26)	89.98 (28)	
ATR 80 Grey[(c)]	**HC-STN**	**1000**	**90.25 (27)**	**82.24 (24)**	
ATI 60025 Lilac	HC-STN	700	90.86 (28)	86.81 (26)	
ID 9001C Orange	FF-DRN	500	93.58 (29)	93.23 (30)	90%
D3DC35 Brown	FC-STN	1000	94.46 (30)	91.16 (29)	
TVI 8002 Yellow	HC-DRN	700	94.63 (31)	93.96 (32)	
XR 8008 White[(d)]	**FF-STN**	**250**	**95.11 (32)**	**93.84 (31)**	
ITR 8001 Orange	HC-DRN	700	95.52 (33)	95.13 (33)	
TVI 80015 Green	HC-DRN	700	95.71 (34)	95.60 (34)	
ITR 80015 Green	HC-DRN	700	95.87 /(35)	95.76 (36)	95%
TVI 8003 Blue	HC-DRN	1000	95.95 (36)	95.93 (37)	
TVI 80025 Purple	HC-DRN	700	96.45 (37)	96.32 (38)	
XR 8015 (Steel)	FF-STN	200	97.17 (38)	95.72 (35)	
ITR 8002 Yellow	HC-DRN	700	97.19 (39)	97.07 (39)	

[a, b, c, d] Threshold nozzles corresponding to 25%, 50%, 75%, 90% and 95% drift reduction classes, respectively.

HC-STN: Hollow-cone standard nozzle; HC-DRN: Hollow-cone drift reduction nozzle; FC-STN: Full-cone standard nozzle; FF-STN: Flat-fan standard nozzle; FF-DRN: Flat-fan drift reduction nozzle.

Classification of the Albuz nozzles, shown in Fig. 4, is based on the DPR_H and DPR_V. The STN (ATR) nozzles, with the exception of the ATR 80 Grey for the DPR_H which is at the upper limit, are below the 90% reduction threshold. In contrast, all the DRN (TVI) nozzles are above this threshold.

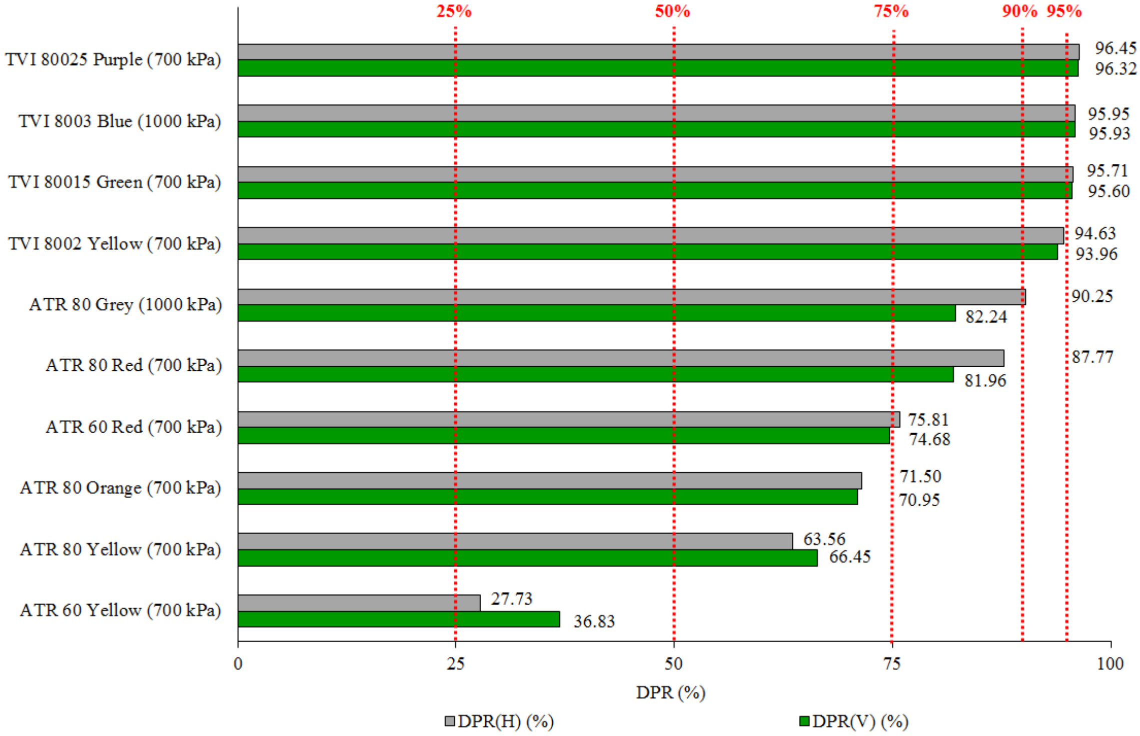


Fig. 4. Nozzle classification based on DPR_H and DPR_V measured with WT1. Reference nozzle: Albuz ATR Lilac at 700 kPa.

3.3. Volumetric wind tunnel (WT2) tests

In the WT2 tests, four different spray configurations were studied, with the nozzles oriented vertically and horizontally and using in each case one or two nozzles simultaneously. In most of the deposition curves (Fig. 5), two peaks can be observed, each corresponding to the two extremes of the hollow cone generated by the nozzle. Also apparent is the similarity between the DRN-generated curves, with no nozzle size effect observable as also seen in the WT1 tests (Fig. 5). In the single-nozzle tests, there are clear differences in the deposition curves generated from the vertical (Fig. 5a) and horizontal (Fig. 5b) nozzle positions. In the vertical spray, the deposition peaks are higher, though shorter distances are attained of up to 1.5-2 m for the DRN and 4 m for the STN nozzles. In contrast, with horizontal spraying, the distances increase to 3-4 m for the DRN and 6 m for the STN nozzles, due to the respective droplet sizes. In the double-nozzle tests, similar results were obtained, after normalising for the spray flow rate, to those of the single-nozzle tests (Fig. 5c, 5d).

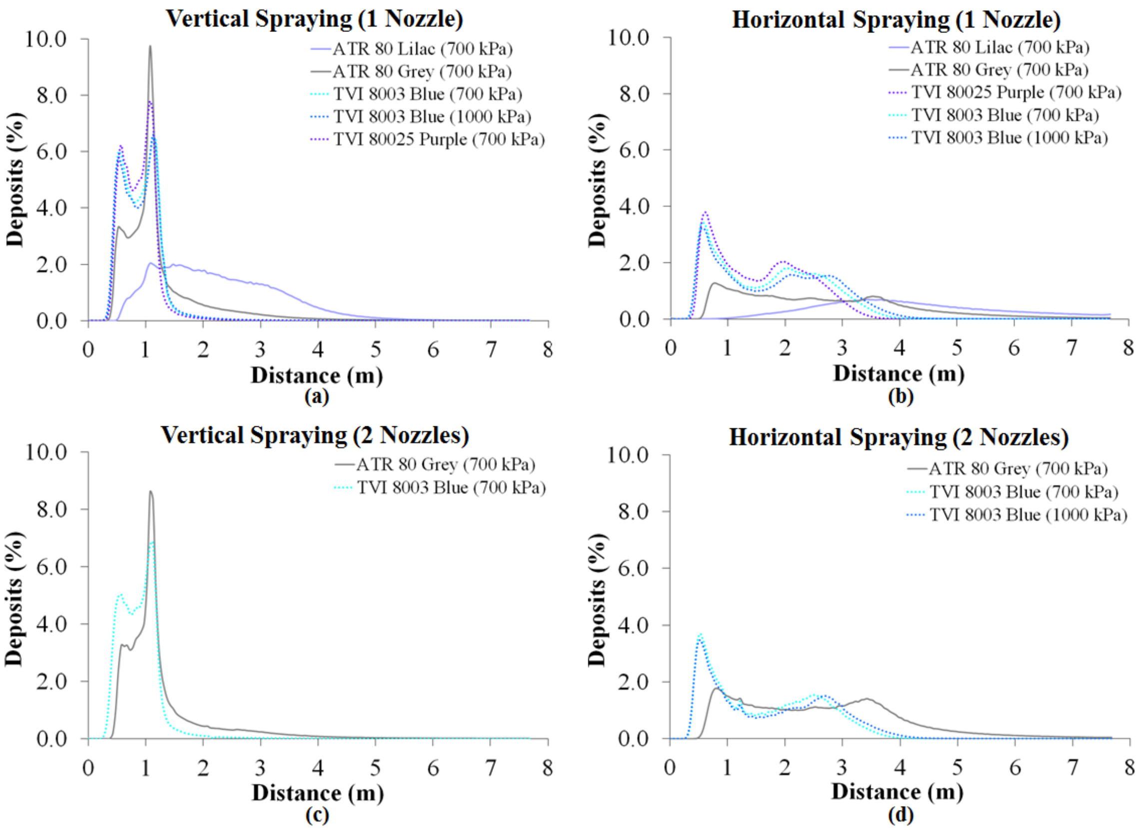


Fig. 5. Deposition curves corresponding to four different spraying arrangements using WT2. (a) Vertical spraying with 1 nozzle; (b) Horizontal spraying with 1 nozzle; (c) Vertical spraying with 2 nozzles; (d) Horizontal spraying with 2 nozzles.

Fig. 6 shows nozzle classification relative to the reference nozzle (ATR Lilac at 700 kPa) based on sedimenting drift WT2 measurements. In the vertical configuration, depositions at distances from the nozzle beyond 2 m were considered, as proposed in ISO 22856:2008. The DPR_H values enabled differentiation of nozzle type, with the DRN (TVI 80025 Purple and TVI 8003 Blue) nozzles situated in the 95% spray drift reduction class, and the STN (ATR 80 Grey) in the 75% class. Contrastingly, nozzle type classification was not possible in the horizontal spraying tests, with DPR_H values below 50% obtained in all cases. It was consequently decided to consider only depositions beyond 3 m, allowing in this way nozzle type differentiation (STN, DRN). Other interesting result to be underlined is the non-correspondence between the classification of HS-1N (>3 m) related to VS-1N (>2 m) and the great capacity of the first one to discriminate classes.

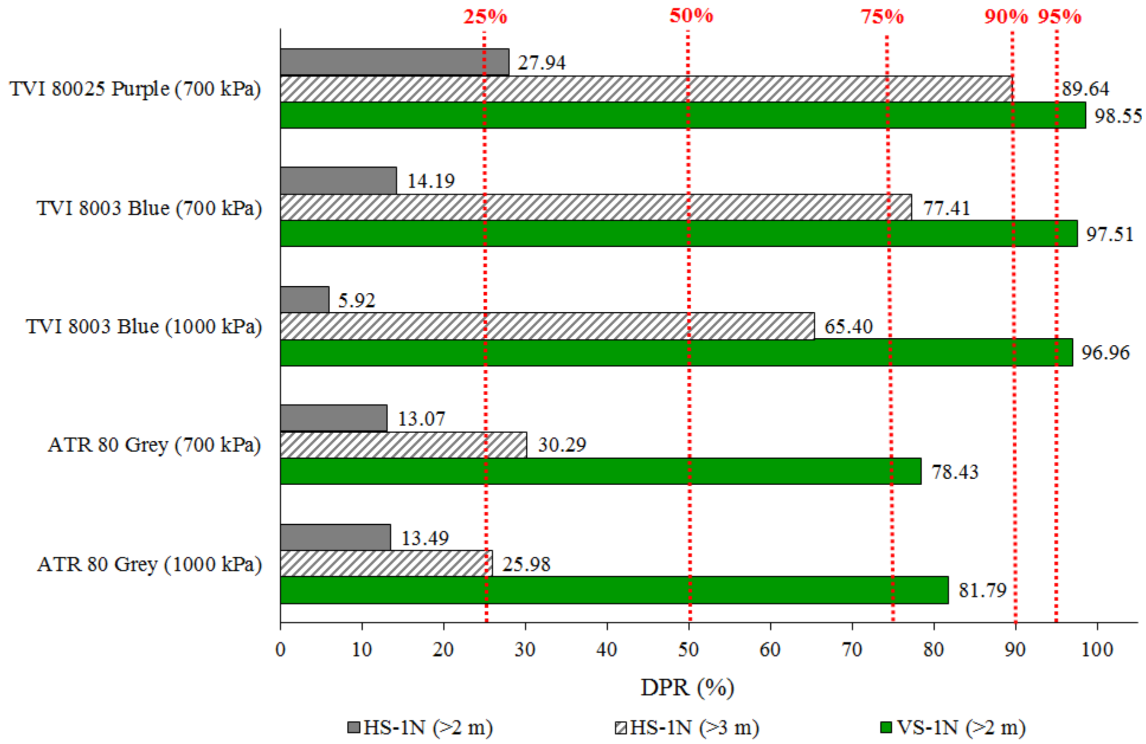


Fig. 6. Nozzle classification based on DPR_H measured with WT2. HS-1N (>2m) and HS-1N (>3m): a single nozzle spraying in horizontal position, considering depositions at distances further than 2 m and 3 m, respectively. VS-1N (>2m): a single nozzle spraying in vertical position, considering depositions at distances further than 2 m. Reference nozzle: ATR Lilac at 700 kPa.

3.4. Methods comparison

Shown in Table 7 is a comparison of the drift reduction classes established on the basis of the parameters evaluated with the PDPA (V_{100}, V_{200}, D_{V50}) and the WT1 (sedimenting and airborne depositions), for the 8 hollow-cone nozzle models tested with both methodologies and 2 more tested only with the PDPA at a different pressure. Based on the *DPR* values determined in sections 3.1 and 3.2 and in accordance with ISO 22369-1:2006, the following drift reduction classes are presented: A (≥99%), B (95≤99%), C (90≤95%), D (75≤90%), E (50≤75%) and F (25≤50%). Class G is also defined for reductions below 25%.

The different models are ordered from highest to lowest DPR_{V100} value.

The other parameters evaluated also followed a decreasing reduction class order. However, two exceptions were observed: TVI 8002 Yellow at 700 kPa tested in WT1 (DPR_H and DPR_V) and ATR 80 Grey at 1000 kPa also tested in WT1 (DPR_H). In the first case, the TVI 8002 Yellow nozzle should be in the same drift reduction class as the other DRN models. It can be seen in Table 6 that the *DPR* values for this nozzle obtained in WT1 are very close to the limit of classes B and C, and so, in effect, it could be considered equivalent to the other DRN models. With respect to the second exception, ATR 80 Grey, this appears in Table 7 in the position following ATR80 Red due to its higher, though very close, V_{100} value (Table 4). If this nozzle had been tested at the same pressure as the other STN models (700 kPa), the respective positions of these two nozzles would very probably have been inverted, with which the class C would be justified. In fact, the DPR_H values of both nozzles were very similar and very close to the limit between classes C and D (Table 6).

Table 7. Drift reduction classes determined from PDPA and WT1 evaluated parameters. Classes are defined according to the following *DPR* values: A (≥99%), B (95≤99%), C (90≤95%), D (75≤90%), E (50≤75%), F (25≤50%) and G (≤25%). Nozzles are sorted by DPR_{V100}.

Nozzle		Pressure	PDPA			WT1	
Model	Type	(kPa)	DPR_{V100} (%)	DPR_{V200} (%)	DPR_{DV50} (µm)	DPR_H (%)	DPR_V (%)
TVI 80025 Purple	HC-DRN	700	A	B	D	B	B
TVI 8002 Yellow	HC-DRN	700	A	B	D	C	C
TVI 80015 Green	HC-DRN	700	A	B	D	B	B
TVI 8003 Blue	HC-DRN	1000	A	B	D	B	B
TVI 8003 Blue	HC-DRN	700	A	B	D	-	-
ATR 80 Grey	HC-STN	700	E	G	F	-	-
ATR 80 Red	HC-STN	700	E	G	F	D	D
ATR 80 Grey	HC-STN	1000	E	G	F	C	D
ATR 80 Orange	HC-STN	700	F	G	G	E	E
ATR 80 Yellow	HC-STN	700	F	G	G	E	E

HC-STN: Hollow-cone standard nozzle; HC-DRN: Hollow-cone drift reduction nozzle.

A comparison is shown in Fig. 7 of the *DPR* of the three nozzle models (ATR 80 Grey at 1000 kPa, TVI 8003 Blue at 1000 kPa, and TVI 80025 Purple at 700 kPa) which were evaluated with all three methodologies used in this study. For each methodology, the *DPR* is expressed considering the following parameters: PDPA (D_{V50}, V_{100} and V_{200}), WT1 (sedimenting and airborne deposition), and WT2 (sedimenting deposition with vertically positioned nozzle).

The *DPR* values of WT2 (V-1N) are comparable to those obtained in WT1, both for the STN model and the two DRN models. For the set of 3 nozzles, the same considerations can also be maintained as established for Table 7, with values of different order of magnitude observed between WT and PDPA for the STN model and of the same order for the DRN models.

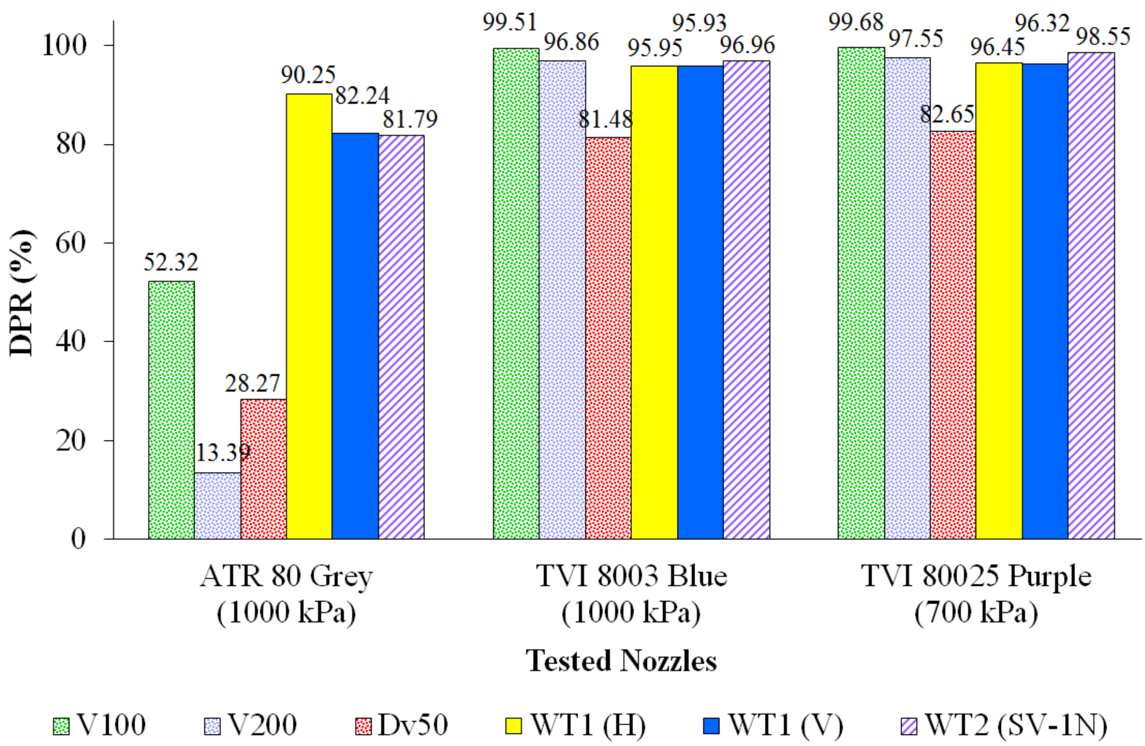


Fig. 7. Comparison between *DPR* values based on the following parameters: PDPA (D_{V50}, V_{100} and V_{200}), WT1 (V and H) and WT2 (SV-1N). Reference nozzle: ATR 80 Lilac at 700 kPa.

In order to identify the characteristic parameter of the droplet size spectrum which best fits the results obtained with WT1, 6 simple linear regressions were performed. In these regressions, the *DPR* values calculated using PDPA (DPR_{V100}, DPR_{V200} and DPR_{DV50}) and those obtained with WT1 (DPR_H and DPR_V) were correlated for the hollow-cone nozzles common to both methodologies (STN: ATR 80 Yellow, Orange and Red at 700 kPa, ATR 80 Grey at 1000 kPa; and DRN: TVI 8002 Yellow, 80015 Green, 80025 Purple at 700 kPa and TVI 8003 Blue at 1000 kPa).

The results of this study revealed that the characteristic parameter which best fits the *DPR* obtained with WT1 was the V_{100}, with coefficients of determination R^2=0.771 and R^2=0.948 corresponding to the DPR_H-DPR_{V100} and DPR_V-DPR_{V100} correlations, respectively. This was followed by the D_{V50} (R^2=0.674 and R^2=0.895, respectively) and V_{200} (R^2=0.612 and R^2=0.854, respectively).

4. Discussion

The droplet size measured for the hollow-cone nozzles using a PDPA showed that DRN nozzles produced larger droplets than the STN nozzles. This effect has been observed in previous research on flat-fan nozzles (Nuyttens et al., 2007; Guler et al., 2007). These results were compared with those reported by van de Zande et al. (2008), and it was seen that the D_{V10}, D_{V50} and D_{V90} values obtained in our study were lower for the STN and higher for the DRN nozzles. With respect to the V_{100} and V_{200} parameters, in our study higher values were obtained for the STN and lower values for the DRN nozzles. The differences between the results obtained in these two laboratories can be attributed to the characteristics and calibration of the equipment used and the actual nozzle units employed, as was previously indicated by Nuyttens (2007). Regarding the nozzle classification based on DPR values (Table 5), the $\mathrm{DPR}_{\mathrm{V100}}$ and $\mathrm{DPR}_{\mathrm{V200}}$ allow a similar classification only for DRN nozzles, while the $\mathrm{DPR}_{\mathrm{DV50}}$ classifies in a different way all types of nozzles.

Regarding the nozzle size, for the STN nozzles, the V_{100} value decreased when nozzle size increased and significant differences between different sizes were observed. For DRN nozzles, no significant differences were obtained. In flat-fan nozzles, Nuyttens et al. (2009) also observed the importance of the effect of nozzle type (STN and DRN) and that the effect of nozzle size was more important in the case of STN than DRN nozzles.

For both type of nozzles (STN and DRN) evaluated in WT1, equivalent DPR_H and DPR_V values were observed, obtaining similar classification for each nozzle. This similarity between sedimenting and airborne deposition results was also observed in FF-type nozzles tested by Taylor et al. (2004). However, for the risk assessment both measurements must be taken into account. In general, the DPR of the STN models (ATR 80 Yellow, Orange, Red and Grey) increases with nozzle size, as expected. In contrast, this behaviour has not been observed for DRN nozzles.

In WT2 vertical and horizontal nozzle positions were studied. In the case of vertical spraying, the deposition did not reach the final section of the tunnel (Fig. 5a). For nozzle classification in the horizontal configuration (Fig. 6) is preferable to consider depositions at distances further than 3 m instead of 2 m to avoid misinterpretations (e.g., parabolic droplet path). Moreover, in order to reduce the testing time, two nozzles could be used (Fig. 5c,d), as the deposition collected in both cases was almost proportional to the sprayed volume.

Methods comparison shows that the wind tunnel WT1 presents less capacity to discriminate between nozzle types (DRN, STN) than the PDPA (Table 7). This may be explained by the interaction of other factors in the tunnel other than droplet size (e.g. air-droplet fluid dynamics, which can be variable). Regarding the correlation between *DPR* values based on PDPA and WT1 measurements, the V_{100} was the best indicator of sedimenting (R^2=0.771) and airborne (R^2=0.948) deposition. The results showed that both wind tunnels (WT1 and WT2) classify in a similar way (Fig. 7) despite the different nozzle position (vertical and horizontal in WT1 and WT2, respectively).

To establish consistent comparisons between assessment methods it would be necessary to dispose of wider results with additional nozzle types. The results presented have been obtained by applying indirect methods under controlled conditions. However, in order to determine which of these methods best approaches the reality, the results obtained in this work should be contrasted with field drift measurements.

5. Conclusions

Different hollow-cone nozzle models were classified according to their drift potential reduction (*DPR*) using three indirect methods: PDPA, ISO wind tunnel (WT1), and volumetric wind tunnel (WT2). To the authors' knowledge, this is the first undertaken classification of hollow-cone nozzles with a wind tunnel, following ISO 22856:2008. The three indirect methods have shown that the DRN nozzles have *DPR* values greater than 90% in comparison with the STN. The use of this type of nozzles should be promoted with the aim of reducing the bystanders and residents' exposure, and the environment contamination.

The findings of this work show that an equally valid initial hollow-cone nozzle classification can be obtained with either the V_{100} or the DPR_V. Comparted to the wind tunnel, the PDPA allows a simplified and faster classification methodology. However, the wind tunnel cannot be overlooked when trying to evaluate sedimenting drift (DPR_H) for risk prevention of surface waters, soils and non-target areas in general.

The WT2 results point to the horizontal position of the tested nozzle as an interesting methodology for testing hollow-cone nozzles. Further studies are required to establish a new indirect methodology to classify cone nozzles, where the test conditions can be approximated to real working conditions in the field (droplet orientation and air-assistance).

Progress should be made in the development of new simplified methods for nozzle assessment under real operation conditions, an issue that is addressed in Part 2 of this work. Further studies are needed for a global evaluation of hollow-cone DRN. Neither the beneficial effect for environment and human risk mitigation nor the efficacy of the DRN have not yet been assessed. Finally, it should be verified that the balance of DRN in terms of environmental and efficacy against pests is favorable.

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