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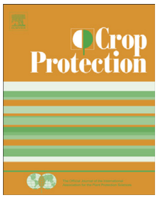

Influence of spray characteristics on potential spray drift of field crop sprayers: A literature review

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Spray drift is a practical consequence of agricultural spraying operations. Because of the agronomical and environmental impacts of this phenomenon, drift has been widely studied and extensive information is available. Here we present a literature review on the relationships between global physical descriptors of agricultural sprays, air conditions and resulting drift, generally studied in wind tunnels. Basic physical factors are droplet size, droplet velocity, and the physicochemical characteristics of the sprayed product. When possible, data available in the literature are collated to draw trends. Contradictory information sometimes appears especially regarding droplet velocity and drift control. The main physical factors consist generally of medians such as Volume Median Diameter (VMD or Dv50) that do not always represent the heterogeneity of a spray and especially the spatial distribution of particle size and velocity. Technological parameters such as nozzle height, spray angle, travel speed are then related to initial physical factors and their contribution to driftability of sprays.

1. Introduction

Pesticides were extensively used in farmland after the discovery of DDT (Dichloro Diphenyl Trichloroethane) in 1939. About 3 billion kg of pesticides are applied each year with a purchase price of nearly 40 billion US $/year (Pimentel, 2005). Pesticides are used to increase both productivity and quality of cultivated crops. On the other hand, they can cause serious environmental and public health problems. Consequences of pesticide application may cause persistent problems in rural and urban areas due to the transport of polluting agents from the crop-growing areas to air, water and other natural resources, via different pathways (Gil and Sinfort, 2005). Spray drift may involve exposure of bystanders, residents, livestock, terrestrial and aquatic ecosystems to pesticides (Hilz and Vermeer, 2013).

Spray drift has always been one of the major concerns in the spray application industry. A common definition of spray drift is given through several organizations including the US Environmental Protection Agency (EPA), British Crop Protection Council (BCPC) and International Organization for Standardization (ISO). Spray drift can then be defined as the physical movement of pesticide droplets or particles through the air at the time of pesticide application or soon thereafter from the target site to any non- or off-target site due to wind conditions (EPA, 2001; ISO 22856-1, 2008; BCPC, 1986). Spray drift may take several forms as droplet, dry particles or vapor. Particle drift increases when water and other pesticide carriers evaporate quickly from the droplet leaving tiny particles of concentrated pesticide. Vapour may arise directly from the spray or by evaporation of pesticide from sprayed surfaces (William and Smith, 2004). However many registered formulations are characterized by a low vapor pressure limiting the evaporation of active ingredients (Miller, 2003).

Spray drift is a complex phenomenon due to the combination effect of spraying equipment design, crop architecture, atmospheric conditions and the physicochemical properties of the spray mix. As such, the concomitant study of the influence of all parameters cited above appears unrealistic and literature mostly focuses on the influence of few parameters at a time. Main studies refer to (a) spray characteristics such as droplet size, spray shape and angle (Foqué et al., 2012), physicochemical properties of spray liquid (Butler Ellis and Tuck, 1999; Miller and Butler Ellis, 2000; Butler Ellis and Bradley, 2002; Herbst, 2003; Heinlein et al., 2007), (b) operating conditions : spray application technique (Van de Zande et al., 2003), boom height (De Jong et al., 2000; Baetens et al., 2009), operating

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pressure (Nuyttens et al., 2007b) and driving speed (Miller and Smith, 1997; Ghosh and Hunt, 1998; Womac et al., 2001) and (c) meteorological conditions (Threadgill and Smith, 1975; Miller, 1993; Miller et al., 2000; Gil and Sinfort, 2005).

Typical evaluation of spray drift is achieved through field tests with a complete sprayer (Ravier et al., 2005) whereas drift potential assessment generally requires a wind tunnel where generally only one nozzle is tested. Both methods are based on sampling process through a large variety of artificial collectors (Salyani, 2000; Salyani et al., 2006; Ferreira et al., 2010). Each method has its own advantages and disadvantages in terms of significance of drift data and repeatability due to atmospheric condition control (Hewitt and Wolf, 2004; Carlsen et al., 2006; Nuyttens, 2007; De Schampheleire et al., 2008; Donkersley and Nuyttens, 2011). Wind tunnel experiments provide an efficient method for supporting and complementing the data derived from field experiments. They allow the use of driftability indices, relative drift factors or drift potential factors to be developed for spray equipment (Walklate et al., 2000).

The objective of this paper is to draw a synthetical literature review on comprehensive works about spray drift to identify which physical factors were analyzed and when possible, compare the results. This paper focuses on experimental approaches developed in wind tunnels bringing some theoretical considerations, additionally. Modeling aspects are not covered in the scope of this paper.

A systemic representation of drift physical factors was adopted in this study as given in Fig. 1. In this figure three main systems are identified: (i) droplets, (ii) the spray pattern and (iii) external conditions. Drift potential can be attributed to a combination of these systems. It is obvious that the system “droplets” is a sub-system of the system “spray” but this representation was chosen to evidence that external conditions can interact both with individual droplets and their characteristics but also with the spray in its globality. The measurable characteristics of each system are indicated in boxes. This paper investigates how some measurable characteristics can be linked with spray drift as measured in a wind tunnel considering data present in the literature.

2. Droplet characteristics

At the droplet level, drift corresponds to a modification of droplet trajectory induced by the drag force due to external air velocity. The expression of the drag force F_d is given by Eq. (1):

$$F_d = \frac{1}{2}\rho_a C_d A (V_d - V_a)^2 [\mathrm{N}] \qquad (1)$$

where F_d is the drag force, C_d is the drag factor depending on the shape of the droplet (usually supposed spherical) and the Reynolds number, A is the frontal interaction area ($\pi D^2/4$) in m^2, V_a and V_d the velocities of air and droplet respectively, in m s^{-1} and ρ_a the air density in kg m^{-3}.

The drag force is then directly proportional to the square diameter and this factor is, by far, the most investigated parameter at the laboratory level. However, it also appears in this expression that the droplet relative velocity is an influential factor. In a first approach, one can consider that C_d is constant. The last influencing factor might then correspond to the density of the fluid.

Eq. (1) corresponds to a dynamic process: diameter (A) may change with evaporation, V_a is not constant (neither in time nor in

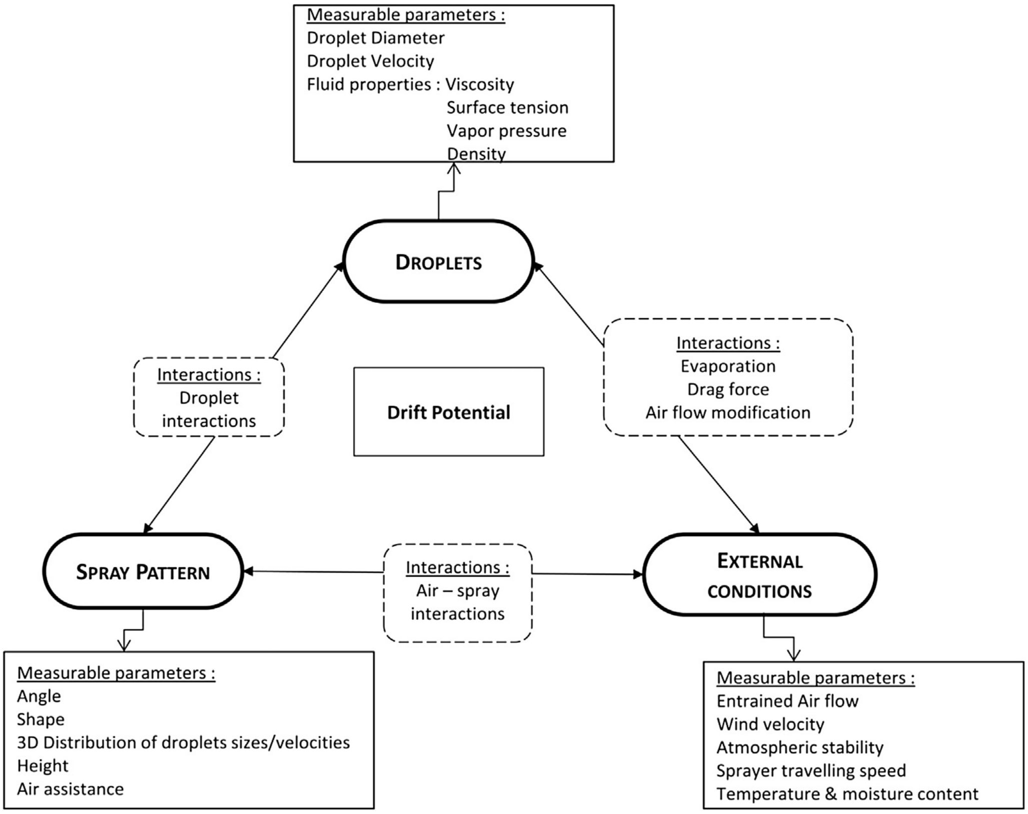

Fig. 1. Systemic representation of spray components contributing to drift potential. Interactions between components and components measurable parameters are indicated in dash and solid rectangles respectively.

Table 1
Methods used for droplet size and drift potential measurements.

Reference	Droplet size measurement device	Distance from nozzle	Wind velocity	Nozzle number and position	Collecting method	Drift potential value
(1)	Oxford Laser VisiSize	350 mm	2 m s^{-1}	1 nozzle-fixed	Ground deposition on polythene wires 2 mm ϕ from 2 to 7 m – each m	Average deposition
(2)	Malvern Mastersizer	150 mm	2 m s^{-1}	1 nozzle – 2 m s^{-1} lateral speed	Ground deposition onfilter papers (25 * 100 mm) from 2 to 6 m – each m	Integrated deposition
(3)	Oxford Laser VisiSize	350 mm	2 m s^{-1}	2 nozzles – 2.78 m s^{-1} lateral speed	Ground deposition on polythene wires 2 mm ϕ from 2 to 7 m – each m	Average deposition
(4)	Malvern Spraytec	Not specified	2 m s^{-1}	1 nozzle – fixed	Ground deposition on polythene wires 2 mm ϕ from 2 to 7 m – each m	Average deposition

(1) Butler Ellis et al., 2002; (2) Stainier et al., 2006; (3) Miller et al., 2011; (4) Taylor et al., 2004.

Table 2
Effect of nozzle type, nozzle size, injection pressure, nozzle angle (°), nozzle height (cm), and Dv50 (µm) on spray drift potential (% applied volume).

Reference	Nozzle type	Nozzle size	Pressure, Bar	Nozzle angle, °	Nozzle height, cm	Dv50, µm	Spray drift% wind tunnel
(1)	AI	03	3	110	50	539	1.7
	AI	03	3	110	50	545	1.57
	AI	03	3	110	50	747	0.67
	AI	03	3	110	50	790	0.67
(2)	FF	01	4.5	110	50	107	22
	FF	03	3	110	50	163	8
	FF	06	2	120	50	244	6
	FF	08	2.5	80	50	365	2.5
	FF	10	3	65	50	434	2
(3)	FF	03	3	110	50	259	8
	FF	03	3	80	50	272	5
(4)	FF	02	3	120	50	142	9.4
	FF	02	3	120	50	293	6.47
	FF	02	3	120	50	118	14.03
	FF	02	3	120	50	124	13.37
	FF	02	3	120	50	215	12.4
	FF	02	3	120	50	253	7.2
	FF	02	3	120	50	243	8.63
	FF	02	3	120	50	184	8.9
	FF	02	3	120	50	220	7.53
	FF	02	3	120	50	239	7.29
	FF	02	3	120	50	195	14.47
	FF	02	3	120	50	195	15.33
	FF	02	3	120	50	185	15.94
	FF	02	3	120	50	175	15.06
	FF	02	3	120	50	178	15.44
	HC	02	3	80	50	114	14.24
	HC	02	3	80	50	190	9.15
	HC	02	3	80	50	107	16.32
	HC	02	3	80	50	105	16.44
	HC	02	3	80	50	204	14.69
	HC	02	3	80	50	191	9.93
	HC	02	3	80	50	168	11.78
	HC	02	3	80	50	153	11.84
	HC	02	3	80	50	170	11.81
	HC	02	3	80	50	160	11.52
	HC	02	3	80	50	150	18.33
	HC	02	3	80	50	160	16.41
	HC	02	3	80	50	143	16.31
	HC	02	3	80	50	152	16.06
	HC	02	3	80	50	147	17.18
	AI	02	3	120	50	470	1.23
	AI	02	3	120	50	552	1.32
	AI	02	3	120	50	412	2.98
	AI	02	3	120	50	422	1.67
	AI	02	3	120	50	523	1.26
	AI	02	3	120	50	527	1.44
	AI	02	3	120	50	487	1.45
	AI	02	3	120	50	451	2.23
	AI	02	3	120	50	476	1.87
	AI	02	3	120	50	492	1.55
	AI	02	3	120	50	457	2.36
	AI	02	3	120	50	469	2.65
	AI	02	3	120	50	476	2.65
	AI	02	3	120	50	451	2.38
	AI	02	3	120	50	438	2.75

(1) Butler Ellis et al., 2002; (2) Miller et al., 2011; (3) Taylor et al., 2004; (4) Stainier et al., 2006. FF: Flat Fan, AI: Air Injection and HC: Hollow Cone nozzles.

space) and V_d changes during the droplet travel from the nozzle output to the target (Hinkle, 1991).

2.1. Droplet size

Spray nozzles are known to produce different droplet quality in sizes. Size distribution is usually described by statistical descriptors (ASABE, 2009; BCPC, 1986; Doble et al., 1985) whilst an ISO standard is in preparation. In general the description of droplet distribution refers to the median value of the distribution related to total number of droplets (Number Median Diameter: NMD) or to the total volume: Volume Median Diameter (VMD) or Dv50 (Lefebvre, 1989). Other descriptors such as Sauter Mean Diameter can be also found (Butler Ellis and Tuck, 1999; Vallet and Tinet, 2011). These descriptors are integrative as they consider cumulative data but they cannot directly represent the whole distribution span.

From a practical point of view, droplet diameter is strongly affected by nozzle type and operating pressure. All technologies generating larger droplets will benefit drift mitigation: low pressure, pre-orifice, deflector, induction chamber, air inclusion.

Several experimental studies in wind tunnels concerned the effect of Dv50 on drift. Being rigorous, these measurements do not only relate droplet diameter effect but also the global distribution of droplets within the spray as well as interactions between air flow and spray that will be discussed in part 3. Among the existing results in the literature, several papers were using comparable methodologies as presented in Table 1. Table 2 introduces data extracted from these previous papers. Note that other wind velocities were tested i.e. 4 m s^{-1} (2) and 4–6–8 m s^{-1} (3) but represented only a few cases and were not considered in the present paper.

Data from Table 2 plotted in Fig. 2 were mainly obtained by integration of collected deposits using horizontal collectors (filter papers or strings) placed at minimum 2 m downwind with a wind velocity from 2 m s^{-1}. In all cases, drift potential values are expressed in percentage of the applied volume. An exponential fits these data with acceptable correlation ($R^2 = 0.93$). The population of nozzles with Dv50 below 300 μm corresponds either to Flat fan nozzles – 110° top angle and Hollow Cone nozzles with corresponding pressures. The population of nozzles with Dv50 above 300 μm corresponds to Flat Fan – 65°) and 80° top angles and Air Injection nozzles.

In addition to Dv50 criteria, other droplet size distribution parameters are known to be strongly related to drift. Arnold (1990) focused on the volumetric fraction of particles less than 50 μm in diameter and an extensive number of authors promoted the volumetric fraction of particles less than 100 μm diameter (Wolf, 2000; Landers and Schupp, 2001; Osborne et al., 2002; Van de Zande et al., 2002; Hobson et al., 1993). For other authors there is a need to extend the limit to the volumetric fraction of particles less than 200 μm (Hewitt et al., 1998). If those parameters are usually considered as thresholds, they do not totally reflect the droplet distribution itself and its spatial heterogeneity in the spray.

2.2. Droplet velocity

In general, droplets have their maximum velocity close to the nozzle orifice and eventually slow down during transport to the target. Referring to Bernouilli's equation, the conversion of pressure into initial liquid velocity is given by the Eq. (2):

$$V = C\sqrt{2\cdot\frac{\Delta P}{\rho_L}}\left[\mathrm{ms}^{-1}\right] \tag{2}$$

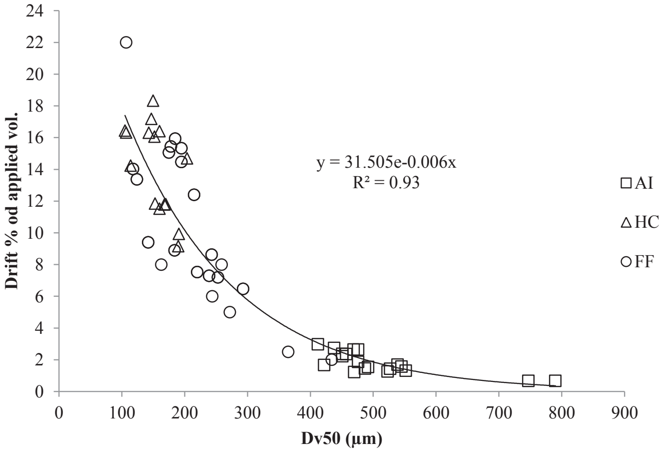

Fig. 2. Percentage of applied volume collected in wind tunnel vs. Dv50 of various nozzles. AI: air Injection nozzle; FF: Flat Fan and HC: Hollow Cone (Butler Ellis et al., 2002; Taylor et al., 2004; Stainier et al., 2006; Miller et al., 2011).

where V is the initial velocity, ΔP is the injection pressure in Pa and ρ_L is the liquid density in kg m^{-3}. C is a discharge coefficient that depends on the shape of the orifice.

Within static air, droplet velocity quickly decreases and reaches a constant value, the terminal velocity is obtained considering the balance of forces on Stockes regime's condition (i.e. the drag force is balanced by friction forces) giving Eq. (3):

$$V_t = \frac{\rho_L\cdot g\cdot D^2}{18\cdot\eta_a}\left[\mathrm{m\ s}^{-1}\right] \tag{3}$$

where V_t is the terminal velocity, ρ_L is the density of droplet (kg m^{-3}), g is the gravitational acceleration (m s^{-2}), D is the diameter of droplet (m), and η_a is the dynamic viscosity of air (kg m^{-1} s^{-1}).

Very few papers have been published on the effect of droplet velocity on spray drift. Depending on authors, methodologies and parameters of influence, the relationship between droplet size, droplet velocity and drift mitigation capability is variable. As for the studies related in section 2.1, the results depend on the global distribution of velocities that will be discussed in section 3. Nuyttens et al. (2007a,b) studied the effect of the droplet size and velocity characteristics with different nozzle – pressure

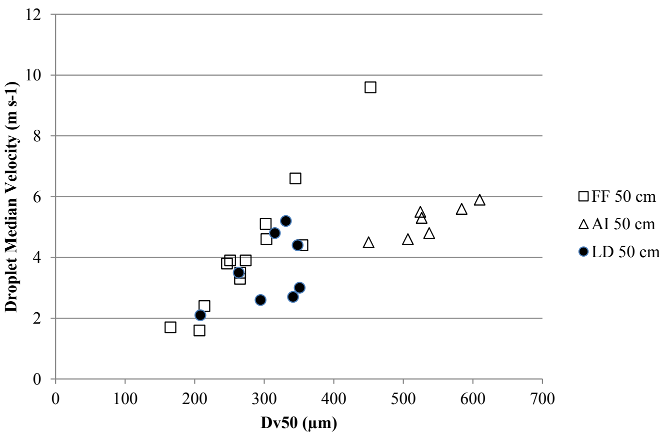

Fig. 3. Distribution of droplet median velocity depending on droplet size for various Flat Fan (FF) Air Injection (AI) and Low Drift (LD) nozzles – 3 bar–50 cm (Nuyttens et al., 2007a,b, 2009).

combinations; they measured and compared the results with the results obtained by other researchers using different measuring techniques and procedures. The relationship they obtained between Dv50 and droplet median velocity (V50) is given by Fig. 3 for different nozzle types. The results showed the effect of nozzle type, size and pressure on the droplet size and velocity spectra.

Liu et al. (2006) studied four nozzle types at different operating pressures. In any cases, droplets generated by a flat fan nozzle with narrow spray angle (i.e. 80°) were found to have the highest velocity as estimated through travel time between the ejection point of the nozzle to the target.

Data found in the literature are introduced in Table 3 where V50 indicates median droplet velocities for various hydraulic driven nozzles and measurement conditions.

When focusing on droplet size expressed in terms of Dv50 with median velocities measured at 50 cm from the nozzle outlet (Table 3), different behaviors are observed depending on the nozzle technology (Fig. 3). Flat Fan and Air Injection nozzles show a linear dependence of the median velocity with droplet size but with different slopes. In contrast, no real trends are visible for Pre-orifice (LD) nozzles.

Both droplet size and velocity contribute to droplet kinetic energy (E_k) and its value was also introduced in Table 3 by using the following Eq. (4):

$$Ek = \frac{1}{2} m V50^2 [\mathrm{J}] \tag{4}$$

With m, the median droplet mass as given by Eq. (5), from the Dv50 value:

$$m = \rho_L \frac{\pi}{6} Dv50^3 [\mathrm{kg}] \tag{5}$$

$V50$ the median velocity (m s^{-1}), E_k is the estimated kinetic energy of droplets in J assuming the same liquid density for all droplets including those generated by air injection nozzles.

Median velocity is found to vary from 1 to 12 m s^{-1} but with a high dependence on the measurement distance from the nozzle outlet.

Table 3
Droplet size, droplet velocity and median kinetic energy for various nozzles and operating pressures.

Reference	Distance (mm)	Nozzle	Pressure (bar)	Dv50	V50	Est. Drift %	E_k (μJ)
(1)	350	FF 110 01	4.5	172.9	3.35	13.29	1.52E−02
		FF110 03	3	257.3	6.72	5.65	2.01E−01
		FF 120 06	2	349.8	6.51	2.91	4.75E−01
		LU 120 03	3	256	6.91	5.71	2.10E−01
		XR 110 03	3	262	5.22	5.43	1.28E−01
		BubbleJet 03	3	431	6.08	1.86	7.75E−01
		IDK 120 03	3	489	5.85	1.42	1.05E+00
		AI 110 03 VS	3	628	6.03	0.83	2.36E+00
		LU 120 03	5	231	8.2	7.12	2.17E−01
		XR 110 03	5	240	6.36	6.56	1.46E−01
		BubbleJet 03	5	359	6.71	2.76	5.45E−01
		IDK 120 03	5	406	6.51	2.11	7.43E−01
		AI 110 03 VS	5	546	7.14	1.12	2.17E+00
		FF80 08	2.5	391.8	12.01	2.28	2.27E+00
(2), (3)	500	FF 110 01	4.5	165.4	1.7	14.62	3.42E−03
		FF110 03	3	251	3.9	5.95	6.30E−02
		FF 120 06	2	355	4.4	2.82	2.27E−01
		80 08	2.5	453	9.6	1.67	2.24E+00
		80 15	2	561	6.6	1.05	2.01E+00
		AXI 110 02	3	207	1.6	9.02	5.94E−03
		AXI 110 04	3	265.5	3.5	5.28	6.00E−02
		AXI 110 06	3	302.2	5.1	3.99	1.88E−01
		API 110 02	3	208.3	2.1	8.90	1.04E−02
		API 110 04	3	263.6	3.5	5.36	5.87E−02
		API 110 06	3	315.4	4.8	3.64	1.89E−01
		Hardi ISO F110 02	3	214.2	2.4	8.38	1.48E−02
		Hardi ISO F110 03	4	246.5	3.8	6.19	5.66E−02
		Hardi ISO F110 03	3	273.6	3.9	4.95	8.16E−02
		Hardi ISO F110 03	2	265.4	3.3	5.28	5.33E−02
		Hardi ISO F110 04	3	303.4	4.6	3.96	1.55E−01
		Hardi ISO F110 06	3	345.1	6.6	3.00	4.69E−01
(2), (3)	500	ATR 80 blue	3	298.6	3.5	4.10	8.54E−02
		ATR 80 green	3	256	2.6	5.71	2.97E−02
		ATR 80 orange	3	191.1	1.2	10.71	2.63E−03
		Hardi LD F110 02	3	294.9	2.6	4.21	4.54E−02
		Hardi LD F110 03	3	348.2	4.4	2.94	2.14E−01
		Hardi LD F110 04	3	331.2	5.2	3.28	2.57E−01
		ADI 110 02	3	341.7	2.7	3.06	7.61E−02
		ADI 110 04	3	351.1	3	2.89	1.02E−01
		Hardi Injet 110 02	3	506.8	4.6	1.31	7.21E−01
		Hardi Injet 110 03	3	537.4	4.8	1.16	9.36E−01
		Hardi Injet 110 04	3	584	5.6	0.97	1.64E+00
		Hardi Injet 110 06	3	610	5.9	0.88	2.07E+00
		AVI 110 02	3	450.4	4.5	1.69	4.84E−01
		AVI 110 04	3	526.5	5.3	1.21	1.07E+00
		AVI 110 06	3	524.8	5.5	1.22	1.14E+00

(1) Miller et al., 2008; (2) Nuyttens et al., 2007a,b; (3) Nuyttens et al., 2009. Drift % is estimated from Fig. 2 correlation curve.

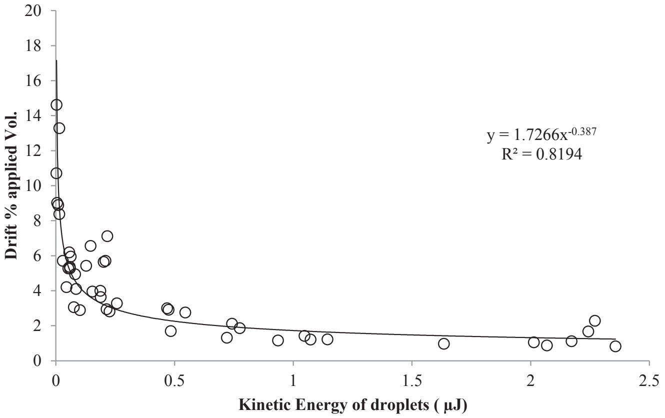

Fig. 4. Percentage of applied volume collected in wind tunnel vs. kinetic energy of various nozzles from several literature references (Nuyttens et al., 2007a,b, 2009; Miller et al., 2008).

A simulation of drift values (Drift est.) was introduced in Table 2 from *Dv*50 values obtained with the correlation shown in Fig. 2, for various nozzles and operating conditions. Estimated drift values are plotted vs. Kinetic energy (E_k) on Fig. 4 and an acceptable correlation is observed. Lower kinetic energy may be due to both low diameter and velocity. As a general statement, E_k is proportional to $V50^2$ and $Dv50^3$ and the last parameter is the most influential. When AI nozzles are used, the variation of droplet density (due to air inclusion) might also be taken into account. However the determination of droplet density inside a spray is still very difficult.

Finally Giles and Ben-Salem (1992) investigated the effects of intermittent flow on the droplet velocity and kinetic energy within spray clouds from flat-fan nozzles. Droplet velocity and energy were slightly reduced and median diameter increased as the frequency of intermittency increased under identical operating conditions. However, Pulse Modulation Width (PWM) control systems are still poorly represented in the literature.

2.3. Physicochemical properties of spray liquid

The effect of the physicochemical properties of spray liquid on drift potential in the wind tunnel was studied over a long period (Maas and Krasel, 1988; Western et al., 1999; Hewitt et al., 2001). Parameters such as the surface tension coefficient and viscosity are considered as the most important factors affecting spray drift (Hilz and Vermeer, 2013). Modifying the physical properties of spray liquids to lower surface tension or higher viscosity with additives may sometimes affect spray droplet size with a direct consequence on drift control. However combined effects of nozzle technology with *ad hoc* operating conditions and chemical properties of a spray mix were questioned in the past (Rizk and Lefebvre, 1989) and still appears unpredictable.

Table 4
Effect of additives on Dv50 with an FF 110 03 nozzle at 3 bars as measured with PDPA Butler Ellis et al. (1997).

Spray liquid	Composition	Concentration	Dv50 µm	% Vol < 100 µm
Water	–		256	2.9
Ethokem	Cationic surfactant	0.50%	234	4.8
Li 700	Soybean phospholipids	0.50%	275	1.6
Agral	Non ionic wetting agent	0.10%	247	3.6
Axiom	Mineral oil	1%	260	2.6
Codacid oil	Vegetable oil	1%	268	2.0
Silwett L-77	Organo-silicone	0.15%	276	1.5

In many cases, surfactants may improve pesticide application in terms of wetting effect, sticking properties, drift retardant, etc. (Hoffmann et al., 2003; Carlsen et al., 2006; Celen, 2010) but effects on drift mitigation cannot hardly be proven without either droplet size or drift measurements.

Most research work which has been done on drift-reducing effects of surfactants has considered water solutions but De Schampheleire et al. (2009) stated that the physicochemical characteristics of the complete spray mixture including active ingredient(s), co-formulants and surfactant shall be considered. It is also known that physical and chemical properties can be affected by the sprayer circuit due to shear in the pump, in the agitation circuit and in the pressure control valve (Hilz and Vermeer, 2013).

Effects of additives on water and their impact on droplet size and drift potential were measured in a wind tunnel with a FF 110 03 nozzle by (Butler Ellis et al., 1997). As shown in Table 4, mineral or vegetable oils did not modify the Dv50 significantly. When compared to water, cationic surfactant (Ethokem) and non-ionic wetting agent (Agral) are found to produce smaller droplets. In the meantime, soybean phospholipids (Li 700) and organo-silicone (Silwet L-77) involved the production of larger droplets.

Sanderson et al. (1997) measured the combined effect of chemical formulation (EC, WDG and LF) and surfactant composition on droplet size (Malvern 3000 and in-field potential drift values (from artificial collectors placed along a 10 m mast) for aerial spraying. Great differences appeared between chemical formulations but also due to surfactant composition. In general and as already seen on Table 4, the use of a non-ionic surfactant leads to a decrease in the size of droplets and an increase in drift values. Similar results are shown on Table 5. In contrast to non-ionic surfactants, crop oils induce no significant modification in droplet size (compared to EC solo) as well as in drift values.

An extract from (Stainier et al., 2006) exhaustive study is proposed in Fig. 5 where the effect of nozzle type, chemical formulation and adjuvant on droplet size is introduced. Two formulations of phenmediphan (SC and EC) were compared with pure water and several adjuvants: Actirob B is an esterified crop oil – 0.4% w/v, Tensiofix D03: a non-ionic surfactant 0.2% w/v, Break-Thru S-240 : organo-silicones surfactant (trisiloxane), 0.15% w/v and Silwet L-77: organo – silicones (heptamethyltrisiloxane) – 0.1% w/v. Three main situations can be considered. (a) With pure water, Actirob B and Silwet L-77 induce greater droplets as Tensiofix D03 and Break-Thru S-240 generate smaller droplet sizes. This phenomenon occurs for the three nozzles. (b) When a suspension concentrate formulation (SC) is used, water always generates greater droplet size compared to any of the tested adjuvants. Tensiofix D03 and Break-Thru S-240 modalities generate smaller droplets compared to Actirob B and Silwett L-77 but the distribution in droplet size is

Table 5
Effect of chemical formulation and additives on Dv50 and drift potential as measured in field conditions (aerial application with D8-46 nozzle at 1.52 bar).

Spray liquid	Dv50 (µm)	Drift % in-field
Propanil (EC)	177	19.8
EC + non ionic surf.	174	21.5
EC + Crop Oil	177	20.6
Propanil (WDG)	219	14.4
WDG + non ionic surf.	208	14.7
WDG + crop oil	220	13.9
Propanil (LF)	236	11.5
LF + non ionic surf.	212	13.4
LF + crop oil	238	11.4

EC: Emulsifiable Concentrate, WDG: Water Dispersible Granular, LF: Liquid Flowable (from Sanderson et al., 1997).

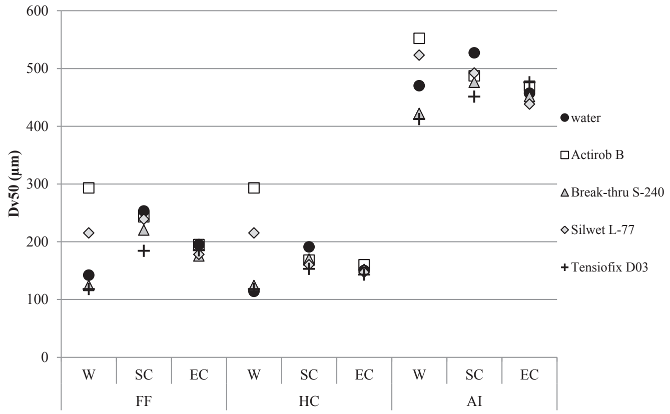

Fig. 5. Effect of nozzle type, adjuvant and phenmediphan formulation – 4.45%w/v (W, SC or EC) on droplet size (Dv50). FF: Flat Fan, HC: Hollow Cone and AI: Air Injection. From Stainier et al. (2006).

much reduced compared to pure water conditions (a). (c) With an EC formulation, the amplitude of droplet size is drastically reduced whatever the adjuvant. In this case the standard deviation in droplet size is less than 5%.

In general, the effect of the combination of nozzle type, adjuvant and chemical is not easily predictable: indeed the effect of an adjuvant as seen with pure water is totally modified when spraying EC or SC formulation of phenmediphan. Whatever the combination of chemical and adjuvant, the effect of nozzle type is rather predominant.

Moreover, the effects of additives are often rate sensitive. The main practical consequence of surfactant overdosage may be revealed by strong modifications of the spray pattern, angle, flow distribution homogeneity as shown by Douzals et al. (2012).

2.4. *Droplet evaporation*

Evaporation of a spray droplet is a common physical phenomenon that occurs during or after the application of the pesticide. Evaporation of solvent (usually water) and solute (dissolved or suspended chemicals) is an important issue but barely studied in the literature. When the solvent is water, the capability of air to absorb water vapor is given by the psychometric diagram, linking vapor content, temperature and air enthalpy value (kJ g^{-1} of dry air). Increasing the temperature as well as decreasing the relative humidity both involve a higher capacity for evaporation of eventual surrounding droplets. The air volume under the boom of a working sprayer can be considered as an infinite reservoir for evaporation. Indeed, considering a 18 m boom width, at 50 cm height and at 8 km h^{-1}, the air flow interacting with sprays is about 20 m^3 s^{-1}. Depending on the wind direction, these previous numbers may probably increase. Comparatively, liquid flowrate generated by FF 02 nozzles on the 18 m boom generates a liquid flow of about 4.8×10^{-4} m^3 s^{-1}.

The quantification of the effect of evaporation on spray drift is not an obvious issue as evaporation is time dependent. Evaporation has been integrated in many models such as AgDisp or random walk model studied by Miller and Hadfield (1989). In the spray drift model IDEFICS, (Holterman et al., 1997; Holterman, 2003) assumed that only water would evaporate during the application and all solutes would be chemically inert. This seems reasonable for short distance downwind drift (until 10–20 m from the edge of the crop). The droplet that moves through the air, or floats in the air, is subjected to evaporation and will decrease in size. Due to the difference in vapor pressure between droplet and air, the droplet cools down due to evaporation, until it reaches its wet-bulb temperature. At the same time, a thin layer of saturated vapor has formed around the droplet. The temperature of the droplet is lower than that of the ambient air, heat flows toward the droplet and feeds the evaporation process.

The rate of decrease of the diameter D of a spherical droplet in the air due to evaporation described by (Williamson and Threadgill, 1974), which is somehow analogous to the so called D^2 law described by (Mokeba et al., 1997) in the following Eq. (6) :

$$\frac{dD}{dt} = \frac{-4\cdot M_l\cdot D_f\cdot \Delta P}{D\cdot \rho_L\cdot R\cdot T_f}\left(1+0.27\cdot Re^{1/2}\cdot Sc^{1/3}\right)[\mathrm{m}] \tag{6}$$

where D is the droplet diameter, t the time of variation (s), M_l is the molecular weight of the evaporating liquid (water 0.018 kg mol^{-1}), ρ_L is the liquid density (kg m^{-3}), D_f is the average diffusion coefficient for vapor molecules in the saturated film around the droplet (m^2 s^{-1}), T_f is the average absolute temperature (K), Re is Reynolds number, Sc is Schmidt's number, ΔP is the difference between the vapour pressure near the droplet and that in the ambient atmosphere (atm), and R is the gas constant. Schmidt number is a dimensionless quantity relating viscous transport of material to diffusive transport.

Reynolds (Re) and Schmidt's (Sc) numbers should both be evaluated for the saturated film, at temperature T_f.

Reynolds number and Schmidt's numbers are calculated from Eq. (7) and Eq. (8) :

$$Re = \frac{\rho_a\cdot V\cdot D}{\mu_a} \tag{7}$$

$$S_c = \frac{\nu_a}{K_v} \tag{8}$$

where V is the relative velocity of droplet in the surrounding air (m s^{-1}), D is the diameter (m), ρ_a is the air density (kg m^{-3}), μ_a is the air dynamic viscosity (kg m^{-1} s^{-1}), ν_a is the kinematic viscosity of air (m^2 s^{-1}), K_v is the coefficient diffusion of the liquid sprayed into air. Evaporation is then closely related to atmospheric conditions but also to droplet initial size as well as to physicochemical characteristics as described by Eq. (6). Practical consequences are shown in Fig. 6 where the kinetic of partial evaporation is represented by a 66% reduction in diameter as a function of initial diameter of spray droplets. Considering a nozzle with a range of droplet initial velocities between 1 and 12 m s^{-1} (Table 3) and a

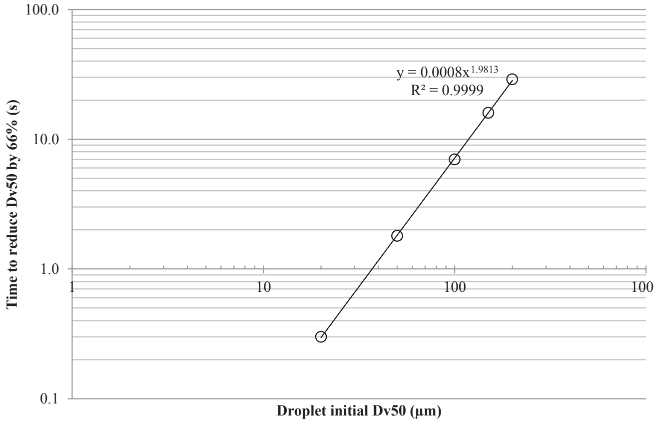

Fig. 6. Evaporation kinetic of evaporation form spray droplet according to initial diameter from Hofman and Solseng (2001). Conditions assumed: Temperature 32 °C (90 °F), Relative humidity 36%, spray pressure 1.72 bar, pesticide solution 3.75%.

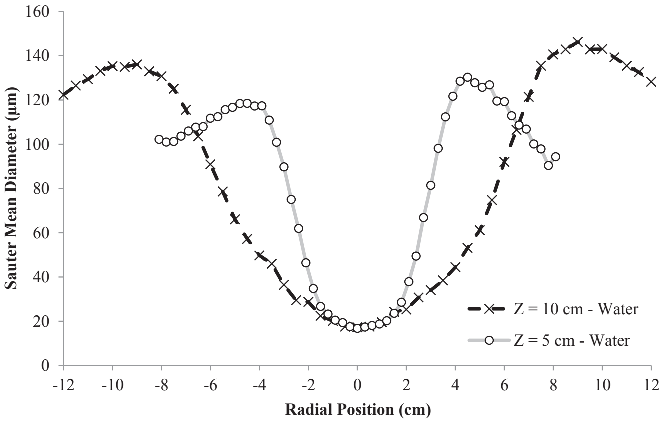

Fig. 7. Radial distribution of Sauter Mean Diameter of spray droplets – Hollow cone nozzle ATR Lilac – 7 bar–5 cm and 10 cm from the nozzle outlet. From Vallet and Tinet (2011).

typical travel distance of 50 cm, estimated travel times of spray droplets are 0.5 s and 0.04 s, respectively. According to Fig. 6 such short travel times will preferably affect droplets with a Dv50 lower than 40 µm. However, very few data are published on the effect of evaporation on the modification of pesticide concentration into residual droplets with regards to vapor tension or physicochemical characteristics of the spray mix.

2.5. *Conclusions on droplet characteristics*

As seen in the previous section, many studies have focused on the relationship between spray drift and droplet characteristics in terms of droplet size, droplet velocity and physicochemical properties. However these studies do not explicitly consider the distribution of droplets in a spray organization as a significant factor influencing spray drift. The following section introduces the main macroscopic factors related to spray organization and their relationship with spray drift.

3. Spray characteristics

3.1. *Droplet diameter distribution*

NMD as well as Dv50 are not homogenous in a spray as the spatial distribution of droplet size may certainly interfere with spray behavior in working conditions (Belhadef et al., 2012; Vallet and Tinet, 2013). Fig. 7 introduces the radial distribution of droplet size of an HC ATR Lilac nozzle at 7 bar from Vallet and Tinet (2011). Smaller droplets (20 µm) are mostly located in the center of the spray and surrounded by larger droplets (140 µm) (Fig. 7). As seen previously, the velocity drop and the extension of the spray sheet with the travel distance induce a greater sensitivity to spray drift for smaller droplets. Furthermore, similar Dv50 can be obtained with various nozzle technologies. This may involve peculiar behavior regarding drift (i.e. FF vs. HC vs. deflector nozzles) but updated data seems rather poor in the literature (Murphy et al., 2000).

Finally, most of low drift accreditation methods used in Europe are based on the performance of a single nozzle either in terms of droplet size (IDEFICS in The Nederlands, Van de Zande et al., 2002) or potential drift profile in a wind tunnel (DIX in Germany, Herbst and Ganzelmeier, 2000; LERAP in the UK, Guilbert, 2000). In those cases, interactions between several nozzles/sprays are then not considered and relationship with in-field drift data is not always possible. Drift accreditation used in France is also based on the evaluation of potential drift in a wind tunnel but for a small boom of 4 nozzles. Frontal and lateral drift mitigation performances are then evaluated in comparison with a small boom fitted with reference nozzles (Douzals and Al Heidary, 2014). Lateral and frontal drift conditions give different results that can not directly be explained by the cumulated spray surface in interaction with the wind (Douzals, 2012).

3.2. *Spray height*

Nozzle height is known to have a great influence on drift considering the cumulative effects of higher transport time and evaporation (Fig. 8). The effect of nozzle type and nozzle size (FF nozzles only) on velocity is introduced with similar injection pressure conditions. In order to compare homogeneous data, a velocity rate was defined as the ratio between the median velocity at a given distance and the initial velocity of droplets. Initial velocity was estimated from its theoretical value (Eq. (1)).

The velocity rate for different 03 nozzles measured at 35 and 50 cm is depending on nozzle type and measuring distance (Fig. 8). Compared to an FF, an AIFF nozzle at 35 cm generates droplets with a lower velocity rate. This phenomenon is generally attributed to a difference in droplet inertia between pure liquid droplets (Standard FF) and liquid/air bubble inclusions contained in droplets ejected by an FF AI. As a consequence, AI nozzles generate larger sized droplets but with relatively lower velocity when measured close to the ejection point (Fig. 8). However, an opposite behavior is observed at 50 cm where droplet velocity from an AI nozzle is still relatively high.

As a general trend, increasing the nozzle/boom height will increase susceptibility to drift for both nozzles. Miller et al. (2011) showed that the total airborne spray collected in a wind tunnel issued from an FF 110 nozzle is increasing from about 2 to 27 µL for respective nozzle heights of 350–850 mm. The practical consequence is that boom height is a parameter that is not always considered by authorities or that some spray drift reduction recommendations appear unrealistic (ex. boom height lower than 40 cm but with forward speed up to 12 km h^{-1}).

3.3. *Nozzle size*

The effect of nozzle size on droplet size and velocities was highlighted in several studies. Most visible effects were shown on

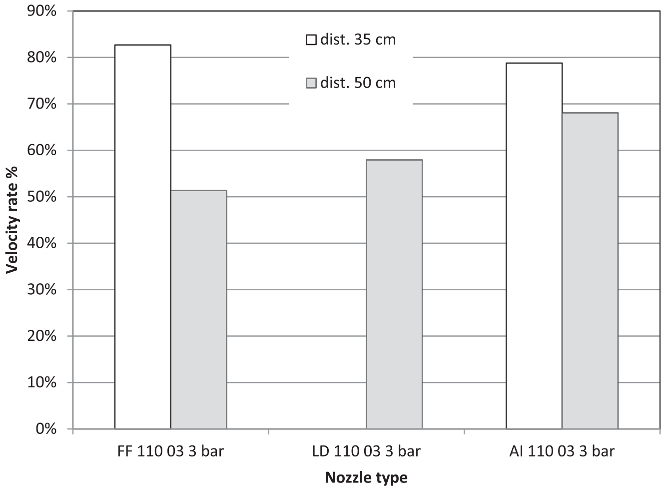

Fig. 8. Velocity rate of various nozzles – effect of nozzle type and measurement distance. FF: Flat Fan; LD: Pre orifice; AI: Air Injection nozzle. 100% corresponds to theoretical initial velocity with data from Nuyttens et al. (2007a,b, 2009) and Miller et al. (2008).

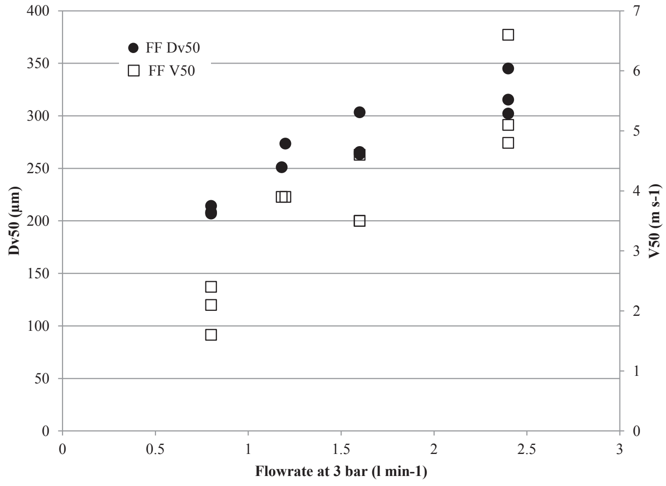

Fig. 9. Effect of flowrate on Dv50 and V50 for different sized FF nozzles at 3 bar. Dv50 and V50 were measured at 50 cm from nozzle outlet. Data from Nuyttens et al. (2007a,b, 2009).

Flat Fan nozzles (Fig. 9) extracted from Table 3.When plotting droplet sizes and velocities of different FF nozzles at the same pressure (Fig. 9), both parameters are directly dependant on flowrate. However there is only a slight influence of nozzle size to drift values (Table 2).

3.4. *Spray top angle*

Several studies have shown an interesting effect of spray angle with identical nozzle sizes. When comparing FF nozzles spray angle, drift was reduced by a factor 2 between a 110° and a 80° and by a factor 5 between a 110° and a 65° at 1100 mm nozzle height although droplet sizes where respectively increased by 5% and 30% (Miller et al., 2011). These macroscopic results might be explained by the spatial distribution of droplets size and velocity in the spray as well as droplet velocity modifications during travel period. To a greater extent than droplet size, spray angle might also be strongly affected by physicochemical composition of the spray mix (Douzals, 2012). In some cases the spray angle can be reduced from 110 to 65° involving drastic changes in cross distribution CV for a given height.

3.5. *Air-spray interactions*

Air velocity interacts with sprays because of the wind and the driving speed of the sprayer. Generally two cases are considered: when wind and driving speed are collinear and when they are perpendicular.

Wind is a complex phenomenon, varying with different magnitudes and frequencies in time and space as has been widely studied by bio-meteorologists. The role of wind and its description was the focus point on most drift modeling approaches (Gil et al., 2007). From an experimental point of view, the main interest of wind tunnels is to produce stable air flow compared to field conditions. Nevertheless the mode of production of this air flow and the shape features of the tunnels influence the air flow field and describing this flow by its mean velocity is a poor approach that could lead to different results in different equipments.

The effect of traveling speed involves a modification of the air velocity (relative wind) and one should consider this relative wind to analyze air speed influence. It can be pointed out that forward speed is generally not restricted by national regulations as it is for wind conditions during spraying operations.

The influence of the air velocity is directly visible on drift values for several reasons. When frontal, it counteracts the greatest surface area of the spray. In this case all the spray plume along the boom is affected. Quantitatively, frontal drift is generally about two times more important than lateral drift for a wide range of Flat Fan nozzles considering a small boom of 4 nozzles placed in a wind tunnel at 7.5 m s^{-1} (Douzals, 2012). In the case of lateral wind conditions, front sprays are greatly affected but sprays situated behind appear protected. The blooming development of “high speed” nozzles, mostly twin jets, among nozzle manufacturers shows the practical interest to higher productivity for farmers.

A comprehensive work on the interaction of spray with a frontal air flow is given by Ghosh and Hunt (1998). Depending on the position of the droplet in the spray plume, three vertical domains are defined in the spray plume whereas the air flow interferes more or less severely with regards to droplet velocity. Each domain is described in terms of entrainment velocity and air currents around droplets generated by weak and strong cross winds of respectively 1.0 and 10 m s^{-1}. The capability of droplet extraction from the spray is found to be dependent on the air/droplet velocity ratio vs. cross wind velocity. Until now this point has never been exploited within experimental approaches in wind tunnels.

Many studies realized in wind tunnel exploit the effect of front wind to generate drift. Most protocols in wind tunnels in Europe use polythene wires to collect a tracer and use short spray emissions (generally less than 10 s). Wind speed is about 2 m s^{-1}. Less data are available on the effect of wind velocity in conditions of lateral drift. Cumulative effects of forward speed and side wind can be easily obtained and simulated in a wind tunnel by placing the nozzle with an angle representing the vectorial sum of both wind direction and forward speed.

4. Conclusion

Spray physical factors described in the literature are related to droplet size, droplet velocity and physicochemical composition.

Droplet size is one of the major characteristics that have been widely studied and it appears closely related to droplet velocity. Although less studied than droplet size, droplet velocity might play an important role in the final spray characteristics and its susceptibility to drift. Unless there are other indications, it can be considered that droplet driftability is a consequence of droplet kinetic energy that involves both droplet size and velocity.

Regarding the evaporation process, knowledge of air conditions is essential. From a practical point of view, optimum air conditions for spraying operations are generally prescribed by authorities or advisors, but on-board meteorological equipments on tractors or sprayers are still not a generality on the market.

Chemical composition of the spray mix becomes more and more studied as drift retardant or drift control properties may involve a profitable market for the chemical industry. Although all previous parameters are generally studied independently, they do not represent the whole complexity of a spray with its spatial variation. Further work is then envisaged on (i) the definition of the macroscopic behavior of agricultural sprays based on physical parameters (droplet size and velocities) but also considering their spatial distribution. As a result, the potential gain in drift reduction might be generated by optimizing spray pattern for example. (ii) From a practical use, this research may also lead to the development of on-board controllers including local atmospheric conditions and spray pattern adjustment.

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