Predicting spray drift reduction classification of flat-fan nozzles based on droplet size spectrum

Longlong Li[1,2], Ruirui Zhang[2,3*], Qing Tang[1,2], Wenlong Yan[4], Chenchen Ding[2,3], Gang Xu[2,3], Tongchuan Yi[1,3]

(1. *Intelligent Equipment Research Center, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China*;
2. *National Research Center of Intelligent Equipment for Agriculture, Beijing Academy of Agricultural and Forestry Sciences, Beijing 100097, China*;
3. *National Center for International Research on Agricultural Aerial Application Technology, Beijing 100097, China*;
4. *School of Agricultural Engineering, Jiangsu University, Zhenjiang 212013, Jiangsu, China*)

Abstract: Spray drift reduction classification evaluation provides theoretical support and technical basis for chemical precision applications. Traditional measurement of spray drift reduction relies on the wind tunnel experiment, which involves a complex testing process and a long measurement cycle. In this study, the feasibility of using a droplet size spectrum to implement drift reduction classification of flat-fan nozzles was studied. A phase doppler interferometry (PDI) was used to determine the droplet size spectra of seven types of flat-fan nozzles, including D_{V50}, V_{75}%, V_{100}%, V_{150}%, and V_{200}%, and the calculated drift reduction classifications were compared with the measurements obtained by the wind tunnel method. The results showed that droplet-spectrum-based spray drift potential reduction classification was highly correlated with the results obtained from the wind tunnel method, with the lowest correlation coefficient being 0.969. Spray drift potential reduction classification represented by V_{200}% shows the highest consistency with the wind tunnel measurements. This study confirms the positive potential of using droplet size spectra to estimate spray drift, and provides a method for the classification of agricultural nozzles.

Keywords: flat-fan nozzle, spray drift potential reduction, classification, droplet size, wind tunnel
DOI: 10.25165/j.ijabe.20251806.9727

Citation: Li L L, Zhang R R, Tang Q, Yan W L, Ding C C, Xu G, et al. Predicting spray drift reduction classification of flat-fan nozzles based on droplet size spectrum. Int J Agric & Biol Eng, 2025; 18(6): 24–32.

1 Introduction

The agricultural nozzle is a crucial component of plant protection machinery. Chemicals are atomized by the nozzle to form droplets, which can maximize the effectiveness of disease and pest control. During the chemical application process, approximately 20% to 30% of fine droplets are carried off to non-target zone under the influence of environmental wind and inappropriate applications, causing spray drift pollution and crop damage[1,2]. Given these severe consequences, spray drift has become a significant research topic in the field of chemical application technology. Droplet deposition measurements in non-target areas after spraying process are the most direct method to understand the spray drift characteristics of agricultural nozzles[3,4]. Spray drift and deposition characteristics of UAV sprayers equipped with different nozzles have also been widely studied[5-7]. The International Organization for Standardization (ISO) proposed test methods to evaluate the spray drift characteristics of plant protection machinery and chemical application techniques with specialized drift detection equipment. Based on this, many researches have been conducted on spray drift characteristics of boom sprayers[8-11] and air-assisted orchard sprayers [12-14]. In addition, some EU countries have classified sprayers, spray techniques, or nozzles as spray drift-reducing technologies. This classification is done by comparing the spray drift generated by a candidate spray with that of a reference spray according to ISO 22369-1[15,16].

Field experiments could accurately reflect the droplet drift patterns under actual conditions. However, due to the complexity and variability of meteorological factors, it is difficult to replicate the experimental results. The wind tunnel test achieves precise control of environmental meteorological factors and has proven to be a valuable method for evaluating the drift reduction performance of nozzles[17]. It has been widely used in the study of spray drift characteristics[18-20].

Based on wind tunnel experiments, scholars developed the DIX (drift potential index)[21] and DEIX (deposition evaluation index)[22]. By measuring the total droplet volume flux on the vertical and horizontal planes downwind, spray drift characteristics of nozzles can be scientifically compared. Taylor et al.[23] and Bai et al.[24] established evaluation indicators of DPR (drift potential reduction) and DIXRP (drift potential index reduction percentage) to assess the spray drift potential reduction performance of agricultural nozzles. With these evaluation methods, the effects of spray pressure, nozzle type, and adjuvants on spray drift have been investigated[25-27].

Received date: 2025-02-05 **Accepted date:** 2025-12-08

Biographies: Longlong Li, Associate Professor, research interest: agricultural aviation and precise spraying, Email: lill@nercita.org.cn; **Qing Tang**, Associate Professor, research interest: agricultural aviation, Email: tangq@nercita.org.cn; **Wenlong Yan**, MS candidate, research interest: agricultural engineering, Email: 2222216001@stmail.ujs.edu.cn; **Chenchen Ding**, PhD, research interest: intelligent agriculture, Email: dingcc@nercita.org.cn; **Gang Xu**, Senior Engineer, research interest: agricultural aviation and precise spraying, Email: xug@nercita.org.cn; **Tongchuan Yi**, Senior Engineer, research interest: electrics and electronics, Email: yitc@nercita.org.cn.

***Corresponding author: Ruirui Zhang**, Professor, research interest: agricultural aviation application and precise spraying. Beijing Nongke Mansion, No.11 Shuguang Huayuan Middle Road, Haidian District, Beijing 10097, China. Tel: +86-10-81128498, Email: zhangrr@nercita.org.cn.

However, both field and wind tunnel tests rely on passive collectors, and the processes of collector arrangement, collection, and sample analysis are complex, cumbersome, and costly.

Previous studies have demonstrated that droplet size is a major factor influencing the amount of spray drift as well as the spray deposition on canopy target[28,29]. Can droplet size be used directly to characterize the drift potential reduction performance of nozzles, thereby replacing field or wind tunnel tests to improve measurement efficiency? To this end, we tried to evaluate spray drift reduction performance of flat-fan nozzles based on droplet size spectrum, and the feasibility is verified using the traditional wind tunnel method. This study aims to provide a reference for researchers and practitioners in plant protection to quickly assess the spray drift characteristics of nozzles.

2 Materials and methods

Experiments were conducted at the National Experiment Station for Precision Agriculture in Xiaotangshan, Beijing. Spray drift tests were conducted at the IEA-II wind tunnel developed by Intelligent Equipment Research Center, Beijing Academy of Agriculture and Forestry Sciences (Figure 1). This wind tunnel features an open-ended design, with a working section of 6.0 m length, 2.0 m width, and 2.0 m height. A uniform and stable wind field was generated under the combined action of the rectifier and rectifying device. The adjustable range of the wind speed in the working section was 0.5-7.0 m/s, the turbulence was less than 0.3%, and the wind uniformity was less than 0.5%[16]. These wind tunnel specifications fulfilled the requirements of the ISO 22856:2008 standard[30].

a. Overall appearance of the wind tunnel b. Spray drift test section

Figure 1 Wind tunnel used in spray drift test

Phase doppler interferometer system (PDI, PDI-300, Artium Technologies Inc., USA) was used to determine the droplet size spectrum of the nozzles used. Considering the focus of this study is to assess the spray drift potential reduction performance using the droplet size spectrum and droplet size directly affects the evaluation results, the flat-fan nozzles with spray angle 110° were selected. Preliminary tests were conducted for nozzle selection based on the D_{V50} (VMD, volume median diameter) at a spray pressure of 0.3 MPa[27]. The determined flat-fan nozzles used included standard nozzles ISO F110-03, ISO F110-04 (Hardi International Inc., Denmark), and XR 110-03 (TeeJet Technologies Inc., USA), low-drift nozzle ISO LD 110-04, anti-drift nozzles ISO MD 110-02 and ISO MD 110-03 (Hardi International Inc., Denmark), as well as AIXR 110-03 nozzle (TeeJet Technologies Inc., USA), respectively. Among them, standard flat-fan nozzles have a uniform deposition distribution with a higher droplet density, and low-drift nozzle features a pre-spraying inlet at the front of the nozzle body, which reduces droplet velocity and pressure. The anti-drift nozzle utilizes the Venturi air-inclusion principle to discharge larger bubble-containing droplets which produce small droplets when impacting the target. Seven nozzles have D_{V50} values ranging from 153.20 to 379.77 μm, exhibiting a good gradient distribution in droplet size, which facilitates the applicability analysis of this new method. Currently, research on the spray drift reduction performance of agricultural nozzles predominantly uses the flat-fan nozzle 110-03 as the reference. This nozzle is commonly employed and has a relatively moderate spray drift characteristic, which facilitates comparisons of spray drift reduction performance between different nozzles[23,31-33]. In this study, standard flat-fan nozzle XR 110-03 was selected as the reference.

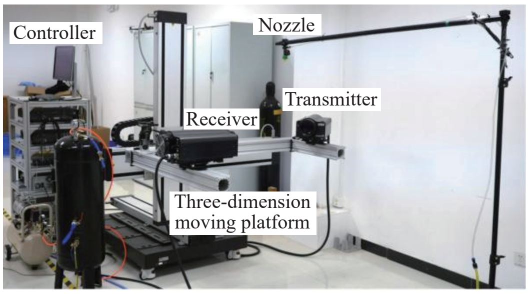
The addition of adjuvants to spray solutions to simulate actual application conditions is a standard practice in spray drift testing. In this study, silicone adjuvant with a concentration of 2.5‰ (chemical composition: ethoxy modified polytrisiloxane, Hebei Nongxun Biological Technology Co., Ltd., China) was used as the spray solution. The spray pressure was set at 0.3 MPa[27]. The orifice size of each nozzle was measured using a stereomicroscope (ZSM0745, Beijing Ruihongcheng Technology Development Co., Ltd.). The flow rate and orifice size are listed in Table 1.

Table 1 Orifice size and flow rate at 0.3 MPa spray pressure for the nozzles used

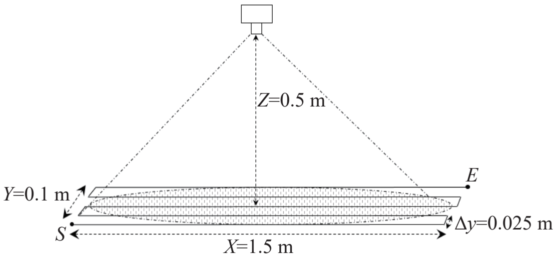
Category	Type	Flow rate/ $L \cdot min^{-1}$	Orifice length/ mm	Orifice width/ mm
Standard flat-fan	ISO F110-03	1.19	2.07	0.61
	XR 110-03	1.25	1.97	0.51
	ISO F110-04	1.54	3.06	0.73
Low-drift	ISO LD 110-04	1.61	3.04	0.87
Anti-drift	ISO MD 110-02	0.84	2.50	0.63
	ISO MD 110-03	1.18	3.06	0.85
	AIXR 110-03	1.24	3.03	0.83

2.1 Droplet size spectrum measurement

Phase doppler interferometer system consists of a three-dimensional moving platform, optical transmitter and receiver, advanced signal analyzer (ASA), data management computer, and AIMS 2.3.0.1 software. PDI measurement relies on emitting two interfering light beams that intersect and pass through the atomization zone. During this process, the interference light will change its propagation angle due to the scattering or refraction of droplets. The optical receiver captures this scattered information and transmits it to the ASA signal processor, which calculates the droplet size values through computer software. This instrument covers a size range of about 0.5-1500 μm. Typically, droplet size measurement is often performed using a laser particle size analyzer[34]. Previous research has confirmed differences in the droplet spectrum at various locations within the atomization zone below the nozzle[35]. Single-point measurement is not sufficient to characterize the actual spray atomization performance. To address this, our study employs a two-dimensional measurement to determine the droplet size spectrum in the atomization plane. As shown in Figure 2, the nozzle is fixed at 0.5 m above the horizontal measurement plane[22]. To characterize the atomization characteristics more comprehensively, all measurements were carried out through the long axis of the spray atomization, the length and width of the rectangular scan pattern were 1.5 m and 0.1 m, and the distance interval in the Y direction was 0.025 m. The optical module is driven by the three-dimensional moving platform at a speed of 0.04 m/s along the preset trajectory. The three-dimensional moving platform consists of aluminum alloy frames and a lead screw mechanism. The optical module mounted on the aluminum alloy frame is driven by the lead screw, ensuring stable and vibration-free operation.



a. Phase doppler interferometer system



b. Scanning path of phase doppler interferometer system

Note: Z is the vertical distance between the scanning surface and nozzle, m; S represents the start position; E represents the end position; X represents horizontal scanning distance, m; Y represents total of scanning lengths in longitudinal direction, m; Δy represents distance between the round-trip scanning lines, m.

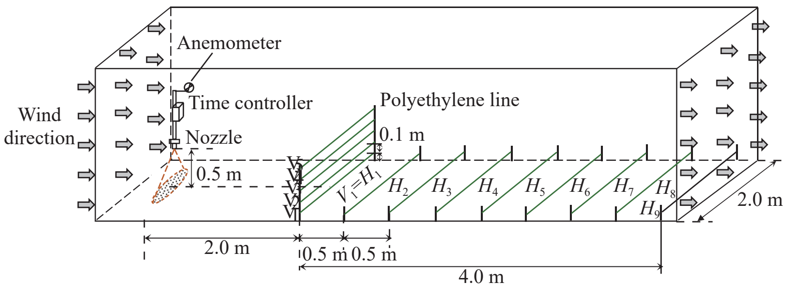
Figure 2 Droplet size spectrum measured by phase doppler interferometer system

Seven characteristic parameters, including D_{V10}, D_{V50}, D_{V90}, V_{75}%, V_{100}%, V_{150}%, and V_{200}% were calculated; among them, D_{V10}, D_{V50}, and D_{V90} represent the diameters for which smaller droplets constituted 10%, 50%, and 90% of the total volume, respectively. V_{75}%, V_{100}%, V_{150}%, and V_{200}% represent the volume percentages of droplets with diameters smaller than 75 μm, 100 μm, 150 μm, and 200 μm, respectively.

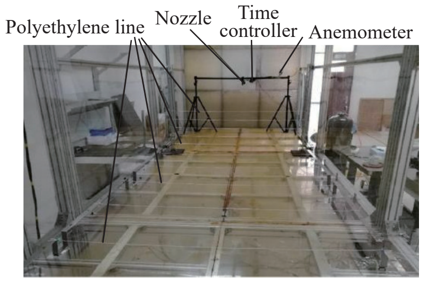
2.2 Spray drift measurement in wind tunnel

The test procedure adhered strictly to wind tunnel test regulations and the ISO 22856 methodology. To eliminate the influence of the tunnel floor on the wind flow turbulence and droplet bouncing and to prevent passive collectors from touching the floor, an artificial ground was set at a height of 0.1 m above the tunnel floor. The single nozzle was fixed 0.5 m above the artificial ground in an upwind direction, with the spray fan perpendicular to the wind direction. Polyethylene lines with diameters of 2.0 mm were used as passive collectors. Based on the wind tunnel method described in the literature[25], we collected airborne drift deposits in the vertical plane and sediment drift deposits in the horizontal profile, respectively. The comprehensive deposits data obtained further validated the effectiveness of using droplet size spectrum to evaluate potential spray drift reduction. For the vertical plane, five polyethylene lines (V_1-V_5) were arranged horizontally across the wind tunnel at a horizontal distance of 2.0 m from the nozzle in the downwind direction, at heights from 0.1 to 0.5 m with intervals of 0.1 m. Nine lines (H_1-H_9) were arranged in a horizontal array at distances of 2.0 to 6.0 m in 0.5 m intervals. An anemometer was arranged in the wind tunnel to monitor the wind speed in the working section. The layout of the experimental setup is shown in Figure 3.

Previous studies demonstrated that the agreement between measuring results from different wind tunnel configurations and sampling methodologies was closest for wind speeds ranging from 2.0 to 2.5 m/s[36]. And the spray drift results of static single nozzle are most similar to the field test results when the wind speed is 2.0 m/s[37]. In this study, the wind speed in the wind tunnel was set to 2.0 m/s. Yellow tartrazine with a mass fraction of 8 g/L was added to the Silicone additives solution as the tracer for drift deposits determination[13].



a. Layout schematic diagram of testing device in wind tunnel



b. Test device arranged within the drift test section

Figure 3 Spray drift test in wind tunnel

A timer combined with an electromagnetic valve was used for spraying time control. Once the spraying duration reaches the preset value, the timer automatically powers off, causing the electromagnetic valve to close and stop the spray. The spraying time was strictly controlled to be 10 s, and spray pressure was set at 0.3 MPa. When the droplets on the line surface had completely dried, the collection lines were collected in a plastic zipper bag and stored in a dark box. Each trial was repeated three times.

2.3 Drift potential reduction classification

2.3.1 Droplet size spectrum-based measurement

D_{V50}, droplet volume median diameter, is widely used to characterize droplet size. Many researchers have also pointed out that when droplet size is below a certain value, spray plumes are more prone to drift; 75 μm[38], 100 μm[39,40], 150 μm[41,42], and 200 μm[20,43] were considered as the critical values. For this purpose, this study uses D_{V50}, V_{75}%, V_{100}%, V_{150}%, and V_{200}% as the basic parameters to evaluate the anti-drift performance of the nozzles. The drift potential reduction percentage (DPR) of candidate nozzle relative to the reference is calculated as follows:

$$\mathrm{DPR}(D_{V50}) = \frac{D_{V50}^{\mathrm{OS}} - D_{V50}^{\mathrm{rS}}}{D_{V50}^{\mathrm{OS}}} \times 100\% \tag{1}$$

$$\mathrm{DPR}(V_{d\%}) = \frac{V_{d\%}^{\mathrm{rS}} - V_{d\%}^{\mathrm{OS}}}{V_{d\%}^{\mathrm{rS}}} \times 100\% \tag{2}$$

where, DPR (D_{V50}) represents the drift potential reduction percentage characterized by D_{V50}, %; D_{V50}^{rS} is the volume median diameter of the reference spray, μm; D_{V50}^{OS} is the volume median diameter of the candidate spray, μm; DPR($V_{d\%}$) is the drift reduction percentage characterized by the proportion of the total volume of droplets smaller than diameter d, which are 75, 100, 150, and 200 μm, respectively; $V_{d\%}^{\mathrm{rS}}$ and $V_{d\%}^{\mathrm{OS}}$ are the proportions of the total volume of droplets smaller than the diameter d of the reference and candidate sprays, %.

2.3.2 Wind tunnel-based measurement

According to the procedures of ISO 22856:2008, the first step is to determine the drift deposition on the surface of the collector line and calculate the drift potential (DP) in both the vertical and horizontal profiles. Drift potential is defined as the ratio of droplets carried by cross-wind to non-target areas to the total spout from the spray system. The reference spray is then compared, and each candidate nozzle's DPR is calculated separately.

10 mL of deionized water was added into plastic zipper bags for dissolving the tracer on collector lines, and the absorbance of the eluent was measured using a visible light spectrophotometer (752 N, INESA, Shanghai, China) at a wavelength of 426 nm. The amount of the sprayed mixture on each line was calculated using the following equation:

$$V'_{i/j}=\frac{V_W\times F_S}{N\times F_a}\times 10^3 \tag{3}$$

where, $V'_{i/j}$ is the deposit volume on each collector line, μL; i represents the polyethylene lines arranged in the vertical plane, ranging from 1 to 5 from bottom to top; j represents the lines arranged in the horizontal direction and takes values from 1 to 9 in the downwind direction; V_W denotes the volume of deionized water for tracer elution, mL; N indicates the dilution factor of the spray solution; F_s represents the absorbance value of the eluent; and F_a is the absorbance value of spray solution in the tank.

Drift deposit is directly correlated with the nozzle output. Due to the differences in nozzle flow rates, to compare spray drift characteristics of different nozzles used, drift deposits were normalized[44]:

$$V_{i/j}=\frac{6\times V'_{i/j}}{V_N}\times 10^{-3} \tag{4}$$

where, $V_{i/j}$ is the normalized droplets amount of collector line in the vertical or horizontal direction; V_N is the flow rate of nozzle, mL/min.

Drift potential (DP) indicates that during the chemical application process, there is a possibility of a relative (rather than absolute) amount of spray liquid being carried out of the targeted area by air movement[44]. Referring to the study by Nuyttens[25], the three approaches of DP_{V1}, DP_{V2}, and DP_{H} were used as characterization parameters for DP.

(1) DP_{V1}

This approach, proposed by Miller et al.[45], indicates that under the assumption of a similar total flux of airborne drift produced by two spraying methods in the vertical plane, the method with the higher deposit height would be more prone to drift.

$$DP_{V1}=\sum_{i=1}^{i=5}V_i\times\frac{d_{\mathrm{C}}}{D_{\mathrm{C}}} \tag{5}$$

where, DP_{V1} is the drift potential based on airborne drift deposits in vertical plane; d_{C} is the corresponding line height from the ground, and when i ranges from 1 to 5; d_{C} corresponds to 0.1, 0.2, 0.3, 0.4, and 0.5 m, respectively; D_{C} is the diameter of the collector line, with $D_{\mathrm{C}}=2$ mm.

(2) DP_{V2}

DP_{V2} was proposed by Nuyttens[25] based on the numerical integration method for the measurement of the airborne drift deposits in the vertical plane, defined as:

$$DP_{V2}=\sum_{i=1}^{i=5}V_i\times\frac{\Delta d_{\mathrm{C}}}{D_{\mathrm{C}}} \tag{6}$$

where, DP_{V2} is the drift potential based on the numerical integration method; Δd_{C} is the interval distance between adjacent lines, and when i ranges from 1 to 5; Δd_{C} corresponds to 0.1, 0.2, 0.3, 0.4, and 0.5 m, respectively.

(3) DP_{H}

DP_{H} was calculated using the drift deposits in horizontal direction.

$$DP_{\mathrm{H}}=\sum_{j=1}^{j=9}V_j\times\frac{\Delta d_{\mathrm{C}}}{D_{\mathrm{C}}} \tag{7}$$

where, DP_{H} represents the drift potential on the horizontal curve; j ranges from 1 to 9; and Δd_{C} corresponds to 0.25, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, and 0.25 m, respectively.

(4) DPR

The DP of the candidate nozzle was compared with the reference nozzle, and the drift potential reduction percentage (DPR) was calculated:

$$\mathrm{DPR}=\frac{DP^{\mathrm{rS}}-DP^{\mathrm{OS}}}{DP^{\mathrm{rS}}}\times 100\% \tag{8}$$

where, DPR is the drift potential reduction percentage,%; DP^{rS} is the drift potential of the reference nozzle; DP^{OS} is the drift potential of the candidate nozzle.

2.3.3 Drift potential reduction classification (DPRC)

According to ISO22369-1:2006[15], the defined drift potential reduction classifications (DRRC) are presented as follows: A (≥ 99%), B (95% to ≤99%), C (90% to ≤95%), D (75% to ≤90%), E (50% to ≤75%), and F (25% to ≤50%). Class G was defined as a reduction of <25%.

3 Results and discussion

3.1 Droplet size spectrum measurement

3.1.1 Droplet size characterization

As listed in Table 2, D_{V50} of the standard flat-fan nozzle XR 110-03 is the smallest at 153.20 μm, while the anti-drift nozzle ISO MD 110-03 produces the largest droplet size, with a D_{V50} of 379.77 μm. Overall, the droplet sizes produced by the anti-drift nozzles were larger than those of the low-drift nozzles and standard nozzles, and the V_{75}%, V_{100}%, V_{150}%, and V_{200}% exhibit a decreasing trend.

Table 2 Results of droplet size spectrum of the nozzles

Category	Type	D_{V10}/ μm	D_{V50}/ μm	D_{V90}/ μm	V_{75}/ %	V_{100}/ %	V_{150}/ %	V_{200}/ %
Standard flat-fan	XR110-03	70.98	153.20	284.23	10.92	22.03	48.44	74.56
	ISO F110-03	82.00	188.02	365.29	7.86	15.57	35.12	57.92
	ISO F110-04	94.53	237.27	430.08	6.26	11.09	24.06	42.11
Low-drift	ISO LD110-04	122.68	286.27	516.36	2.94	6.10	15.83	31.05
Anti-drift	ISO MD 110-02	138.78	312.61	559.83	1.90	4.23	11.94	26.05
	AIXR 110-03	154.57	364.17	780.88	1.63	3.36	9.20	20.29
	ISO MD 110-03	162.94	379.77	688.01	1.19	2.68	7.88	18.47

The nozzles in the same category share identical structures. Under the same spray conditions, droplet size is positively correlated with the nozzle's orifice size. A larger orifice size leads to larger droplet size. For example, the orifice length and width of the ISO F110-04 nozzle are 0.99 mm and 0.12 mm higher than those of the ISO F110-03 nozzle (Table 1), and the D_{V50} of the former is 49.25 μm higher than that of the latter.

It is generally believed that anti-drift nozzles, due to their air-inclusion design, produce bubble-containing droplets, resulting in larger droplet sizes compared to conventional nozzles with the same flow rate. Nevertheless, this comparison is rather partial since it overlooks the impact of the orifice size. Similarly, some researchers express doubt about this assumption, wondering whether the increase in droplet size for air-inclusion anti-drift nozzles is due to the presence of bubbles within the droplets or if it is influenced by a combination of bubble-containing and nozzle orifice size[46]. More thorough exploration of the atomization characteristics of anti-drift nozzles is required to fully understand these effects.

The length and width of the orifice of the low-drift nozzle ISO LD 110-04 are comparable to those of the anti-drift nozzle ISO MD 110-03, while D_{V50} value of the latter is 93.50 μm greater than that of the ISO LD 110-04. It is demonstrated that for different categories of nozzles, it is rather challenging to compare the droplet sizes among them solely based on the orifice size. Instead, a comprehensive assessment should be conducted by taking into account both the nozzle structure and the orifice size.

3.1.2 Droplet size spectrum-based classification

With Equations (1) and (2), the drift reduction rates (DPR) of the spray nozzles were computed respectively using parameters D_{V50}, V_{75}%, V_{100}%, V_{150}%, and V_{200}%. Referring to ISO 22369-1(2006), drift reduction capabilities of the nozzles used were categorized, and the results are presented in Table 3. The DPR values calculated based on various parameters, ranked in descending order, are as follows: anti-drift ISO MD 110-03, anti-drift AIXR 110-03, anti-drift ISO MD110-02, low-drift ISO LD110-04, standard flat-fan ISO F110-04, and the standard flat-fan ISO F110-03. Among them, the anti-drift nozzle ISO MD 110-03 demonstrates the most superior drift reduction performance, with a DPR (V_{100}%) reaching 87.83%, which represents an increment of 58.51 percentage points compared to that of the standard flat-fan nozzle ISO F110-03. Meanwhile, the DPR (V_{100}%) of the low-drift nozzle ISO LD 110-04 exceeds that of the standard flat-fan nozzle ISO F110-03 by 42.99%. For diverse categories of nozzles, the anti-drift nozzles possess the prime drift reduction performance, trailed by the low-drift nozzles, while the standard flat-fan nozzles exhibit the weakest drift reduction performance.

Table 3 DPR and DPRC calculated based on droplet size spectrum

Category	Type	D_{V50}		V_{75}%		V_{100}%		V_{150}%		V_{200}%	
		DPR/%	DPRC	DPR/%	DPRC	DPR/%	DPRC	DPR/%	DPRC	DPR/%	DPRC
Standard flat-fan	ISO F110-03	18.52	<25%	28.02	25%	29.32	25%	27.50	25%	22.31	<25%
	ISO F110-04	35.43	25%	42.67	25%	49.66	25%	50.33	50%	43.52	25%
Low-drift	ISO LD 110-04	46.48	25%	73.08	50%	72.31	50%	67.32	50%	58.35	50%
Anti-drift	ISOMD 110-02	50.99	50%	82.60	75%	80.79	75%	75.35	75%	65.06	50%
	AIXR 110-03	57.93	50%	85.07	75%	84.75	75%	81.01	75%	72.79	50%
	ISOMD 110-03	59.65	50%	89.10	75%	87.83	75%	83.73	75%	75.22	75%

Taking the drift reduction rate typified by V_{100}% as an illustration, the drift reduction performance grades of the two flat-fan nozzles stand at class 25%, that of the low-drift nozzle ISO LD 110-04 amounts to class 50%, and those of the three anti-drift nozzles reach class 75%. As discerned in 3.1.1, droplet size generated by anti-drift nozzles is larger than that produced by low-drift and standard flat-fan nozzles, and the volume fraction of fine droplets is lower, resulting in superior drift reduction performance. Low-drift nozzles feature a pre-spraying inlet design, where the liquid is retained after entering the nozzle chamber, thereby reducing spray pressure and velocity. Consequently, the droplet size generated by low-drift nozzles is larger than that of standard flat-fan nozzles.

For nozzles within the same category, the DPR (V_{100}%) of the anti-drift nozzle ISO MD 110-03 surpasses that of the ISO MD 110-02 nozzle by 7.04%. The length and width of the orifice are 0.56 mm and 0.22 mm greater than those of the latter, respectively. Generally, for nozzles of the same kind, a larger orifice size correlates with enhanced drift reduction performance, which can be attributed to the variation in droplet size induced by the orifice size.

Differences exist in both the drift reduction rates and the grading outcomes of their drift reduction performance, which are obtained through the utilization of diverse parameters. With the exception of the standard flat-fan nozzles ISO F110-03 and ISO F110-04, the drift reduction rates of the remaining nozzles, in descending order, are DPR (V_{75}%), DPR (V_{100}%), DPR (V_{150}%), DPR (V_{200}%), and DPR (D_{V50}). The classification results of drift reduction performance for each nozzle, characterized by V_{75}% and V_{100}%, are consistent. The drift reduction levels of the anti-drift nozzles ISO MD 110-03, AIXR 110-03, and ISO MD 110-02 is class 75%, that of the low-drift nozzle ISO LD 110-04 is 50%, and that of the standard flat-fan nozzles ISO F110-04 and ISO F110-03 is 25%.

3.2 Wind tunnel tests

3.2.1 Airborne drift

The normalized airborne drift deposits and drift potential in the vertical direction are presented in Table 4. Among the three nozzle categories, anti-drift nozzles exhibit the least airborne drift, trailed by the low-drift nozzles, while the standard flat-fan nozzles possess the highest airborne drift. Through comparative analysis with the droplet size spectrum (Table 2), a larger D_{V50} and lower proportion of fine droplets are observed, suggesting a diminished drift potential of the nozzle. For nozzles of the same category, a larger orifice size leads to lower droplet drift deposits, which can be ascribed to the augmented droplet size resulting from the orifice size increment. The ranking of drift potential via the DP_{V1} and DP_{V2} remains consistent. Standard flat-fan nozzle XR110-03 exhibits the highest drift potential, with DP_{V1} and DP_{V2} values of 0.384 and 0.137, respectively. In contrast, the anti-drift nozzle AIXR110-03 demonstrates the lowest drift potential, with corresponding values of 0.072 and 0.027.

Figure 4 illustrates the normalized airborne drift deposits at varying heights from the wind tunnel floor. It was observed that the drift deposits reach a maximum at a distance of 0.1 m from the wind tunnel floor. The drift deposit curves in the vertical plane of each nozzle exhibit variations. For the low-drift nozzle ISO LD 110-04, and anti-drift nozzles ISO MD 110-02, AIXR 110-03, and ISO MD 110-03, the drift deposition declined gradually with the increase of sampling height. For the standard flat-fan nozzle XR 110-03 and ISO F110-03, drift deposits on the collector line at a height of 0.3 m exceeded those at 0.2 m. The possible reason for this situation may be that the two nozzles produce droplets with smaller droplet size, with a relatively higher proportion of fine droplets, where $V_{100\%}$ exceeds 15%. These fine droplets remain suspended in the air for a longer period, resulting in higher drift deposits at 0.3 m height compared to the 0.2 m. Miller et al.[45] have demonstrated that deposit height is positively correlated with drift potential and that a greater deposit height means worse drift performance. Based on the aforementioned principle, it can be inferred that under identical spraying conditions, the standard flat-fan nozzles are more prone to causing droplet drift than anti-drift or low-drift nozzles.

Table 4 Normalized airborne drift deposits and drift potential in vertical direction

Category	Type	Average normalized drift deposits ×10⁻⁴	DP_{V1}	DP_{V2}
Standard flat-fan	XR 110-03	6.645	0.384	0.137
	ISO F110-03	5.871	0.308	0.122
	ISO F110-04	3.932	0.194	0.081
Low-drift	ISO LD 110-04	2.090	0.108	0.043
Anti-drift	ISO MD 110-02	1.993	0.107	0.040
	AIXR 110-03	1.358	0.072	0.027
	ISO MD 110-03	1.409	0.076	0.029

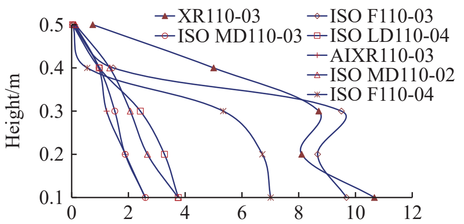


Figure 4 Normalized ariborne drift distribution at different height in vertical direction

3.2.2 Sediment drift

The normalized sediment drift deposit and drift potential in the horizontal plane are presented in Table 5. Similar to the findings in the vertical plane, the normalized drift deposits, in descending order, pertain to the standard flat-fan nozzles, low-drift nozzles, and anti-drift nozzles successively. Specifically, the drift amount of the standard flat-fan nozzle XR 110-03 attains the highest value, which is 4.673×10^{-4}, whereas that of the anti-drift AIXR 110-03 nozzle registers the lowest value, amounting to 0.756×10^{-4}.

Table 5 Normalized deposition and drift potential in horizontal direction

Category	Type	Average normalized drift deposits ×10⁻⁴	DP_{H}
Standard flat-fan	XR 110-03	4.673	1.051
	ISO F110-03	3.924	0.897
	ISO F110-04	2.826	0.650
Low-drift	ISO LD 110-04	1.434	0.329
Anti-drift	ISO MD 110-02	1.160	0.275
	AIXR 110-03	0.756	0.178
	ISO MD 110-03	0.783	0.186

Figure 5 shows the normalized drift deposit distribution within the range of 2.0-6.0 m downwind from the nozzles. The results reveal that the normalized drift amounts decline gradually with the increase in the distance. The sediment drift of the three standard flat-fan nozzles is conspicuously higher than those of the low-drift and anti-drift nozzles. For the XR 110-03 and ISO 110-03 nozzles, the sediment drift amounts at a distance of 4.0 m are equivalent to those of the low-drift and anti-drift nozzles at a distance of 2.0 m. Among these nozzles used, XR 110-03 nozzle exhibits the largest droplet deposition, while anti-drift nozzle AIXR 110-03 and MD 110-03 are relatively proximate at each sampling point and possess the lowest sediment drift.

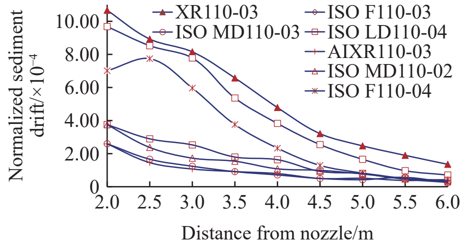


Figure 5 Normalized sediment drift distribution in horizontal direction

3.2.3 Wind tunnel-based classification

The drift potential reduction percentage (DPR) of each nozzle are presented in Table 6. The results measured by the three approaches (DPR_{V1}, DPR_{V2}, DPR_{H}) in 2.3.2 are consistent, indicating that the drift reduction performance of anti-drift nozzles is superior to that of low-drift nozzles and standard flat-fan nozzles. Anti-drift nozzle AIXR 110-03 exhibits the best anti-drift performance, with DPR_{V1}, DPR_{V2}, and DPR_{H} values of 81.11%, 80.25%, and 83.03%, respectively. In contrast, all the three values for the standard flat fan nozzle ISO F110-03 are below 20%, resulting in the weakest anti-drift performance among the six tested nozzles.

Table 6 DPR and DPRC calculated based on wind tunnel test

Nozzle category	Type	Vertical direction				Horizontal direction	
		DPR_{V1}/%	DPRC	DPR_{V2}/%	DPRC	DPR_{H}/%	DPRC
Standard flat-fan	ISO F110-03	19.73	<25%	10.99	<25%	14.65	<25%
	ISO F110-04	49.36	25%	41.37	25%	38.14	25%
Low-drift	ISO LD 110-04	71.84	50%	68.91	50%	68.70	50%
Anti-drift	ISO MD 110-02	72.19	50%	70.86	50%	73.84	50%
	ISO MD 110-03	80.26	75%	79.23	75%	82.31	75%
	AIXR 110-03	81.11	75%	80.25	75%	83.03	75%

With regard to the classification of the drift reduction performance, despite the variations in the values of DPR_{V1}, DPR_{V2}, and DPR_{H}, the classifications for each nozzle obtained using the three approaches are consistent. Specifically, the drift reduction performance of the standard flat-fan nozzle ISO F110-03 is in the 25% spray reduction class, whereas the anti-drift nozzle ISO MD 110-03 and AIXR 110-03 exhibit the optimal drift reduction performance, in the 75% class.

3.3 Methods comparison

According to ISO 22369-1:2006, drift potential reduction performance of the nozzles was categorized in accordance with the magnitude of DPR, with the classification standard being divided into four grades: *G* (<25%), F (25% to ≤50%), *E* (50% to ≤75%), D (75% to ≤90%) and *C* (90% to ≤95%)[15]. A comparison of the classification results based on droplet size spectrum and those based on wind tunnel tests is shown in Table 7. In the wind tunnel method, drift reduction performance of the anti-drift nozzles ISO MD 110-03 and AIXR 110-03 were in the 75%-90% class, and the anti-drift nozzle ISO MD 110-02 and the low-drift nozzle ISO LD 110-04 were in the 50%-75% class. Meanwhile, the standard flat-fan nozzles ISO F110-04 and ISO F110-03 were in the 25%-50% and ≤ 25% classes, respectively. In the droplet size spectrum-based method, differences existed in the drift potential reduction classifications based on DPR (D_{V50}), DPR (V_{75}%), DPR (V_{100}%), DPR(V_{150}%), and DPR (V_{200}%). With the exception of DPR (D_{V50}), the classifications of the ISO MD 110-03 and ISO LD 110-04 nozzles derived from the other four parameters were in line with the results of the wind tunnel method. Except for V_{150}%, the drift potential reduction classifications of the ISO F110-04 nozzle using the seven parameters of the droplet size spectrum method and the wind tunnel method were identical, all falling within the range of 25%-50%.

Table 7 Drift reduction classification performance of the nozzles based on DPR

Nozzles	Type	DPRC based on droplet size spectrum method					DPRC based on wind tunnel method		
		DPR(D_{V50})	DPR(V_{75}%)	DPR(V_{100}%)	DPR(V_{150}%)	DPR(V_{200}%)	DPR_{V1}	DPR_{V2}	DPR_H
Anti-drift	ISO MD 110-03	E 50≤75%	D 75≤90%	D 75≤90%	D 75≤90%	D 75≤90%		D 75≤90%	
	AIXR 110-03	E 50≤75%	D 75≤90%	D 75≤90%	D 75≤90%	E 50≤75%		D 75≤90%	
	ISO MD 110-02	E 50≤75%	D 75≤90%	D 75≤90%	D 75≤90%	E 50≤75%		E 50≤75%	
Low-drift	ISO LD 110-04	F 25≤50%	E 50≤75%	E 50≤75%	E 50≤75%	E 50≤75%		E 50≤75%	
Standard flat-fan	ISO F110-04	F 25≤50%	F 25≤50%	F 25≤50%	E 50≤75%	F 25≤50%		F 25≤50%	
	ISO F 110-03	G <25%	F 25≤50%	F 25≤50%	F 25≤50%	G <25%		G <25%	

Correlation analysis was carried out on the DPR values acquired from the droplet size spectrum and the wind tunnel tests (Table 8). The results demonstrate a good correlation with the lowest correlation coefficient being 0.969, which validates the feasibility of classifying the drift potential reduction performance of spray nozzles by means of the droplet size spectrum. Among these, the classification of drift potential reduction characterized by V_{200}% exhibits the highest consistency with the wind tunnel test; with the exception of the anti-drift nozzle AIXR 110-03, the classification results of the remaining nozzles are consistent. From Table 3, it can be noted that the DPR (V_{200}%) of nozzle AIXR 110-03 is 72.79%, which is relatively proximate to the critical value of 75% for class D (75≤90%). Torrent et al.[47] conducted a comparison of the drift potential reduction capabilities of hollow-cone nozzles through the utilization of the droplet size spectrum and wind tunnel method. The findings revealed that the classification performance denoted by V_{100}% exhibited the highest correlation with the outcomes of the wind tunnel test, possessing a correlation coefficient of 0.948. The primary factor taken into account was the difference in the atomization patterns of the flat-fan nozzle and hollow-cone nozzle. The spray plume generated by the flat-fan nozzles was distributed within a single flat-fan shaped surface, whereas the hollow-cone sprays form a hollow conical atomization configuration. The differences in the spatial distribution of droplet clusters caused by the atomization pattern may affect the deposit height, sediment distance, and distribution characteristics of drifting droplets in the wind tunnel test, thereby leading to variations in the spray drift amount. Despite differences in the droplet size parameters used to characterize drift potential reduction, the current results are encouraging. This study identified a simpler and potentially promising method for evaluating the spray drift characteristic of widely used flat-fan nozzles. This facilitates the selection of nozzles by government, farmers, and researchers.

Table 8 Correlation coefficients for DPR based on droplet size spectrum and wind tunnel test

	DPR(D_{V50})	DPR(V_{75}%)	DPR(V_{100}%)	DPR(V_{150}%)	DPR(V_{200}%)
DPR_{V1}	0.985	0.969	0.983	0.989	0.985
DPR_{V2}	0.988	0.979	0.992	0.993	0.989
DPR_H	0.989	0.993	0.997	0.994	0.991

4 Conclusions

In agricultural plant protection operations, rapid evaluation of nozzles can assist operators in selecting appropriate spray nozzles efficiently and rationally, particularly crucial in the context of pesticide application, where environmental protection concerns are receiving increasing emphasis. In this study, experiments were conducted using seven flat-fan nozzles from standard, low-drift, and anti-drift categories to explore the evaluation and classification of spray drift potential reduction based on droplet size spectrum, with comparison and validation against wind tunnel tests. The conclusions are presented as follows:

1) Regarding the classification of drift potential reduction performance based on the droplet size spectrum, for the six nozzles chosen in the experiment, taking into account the results characterized by the D_{V50}, V_{75}%, V_{100}%, V_{150}%, and V_{200}%, the drift potential reduction performance in descending order is anti-drift nozzles, low-drift nozzles, and standard flat-fan nozzles. For nozzles of the same category, the larger the orifice size, the better the drift potential reduction performance. The classifications of the drift reduction performance characterized by V_{75}% and V_{100}% are consistent.

2) In terms of the classification of drift reduction performance based on the wind tunnel tests, the standard flat-fan nozzle XR 110-03 exhibits the highest drift amount in both the vertical and horizontal planes, while anti-drift nozzle AIXR 110-03 shows the least spray drift and the best spray drift potential reduction performance.

3) Spray drift potential reduction classification based on the D_{V50}, V_{75}%, V_{100}%, V_{150}%, and V_{200}% are highly correlated with the wind tunnel tests, with the lowest correlation coefficient being 0.969. Among them, the classification results using V_{200}% show the highest consistency with the wind tunnel method, demonstrating the potential of this parameter in nozzle classification.

Existing studies have demonstrated that spray drift is directly associated with droplet size, which lays a theoretical foundation for nozzle classification using the droplet size spectrum. This study validates the feasibility of classifying the spray drift potential reduction performance of flat-fan nozzles using the droplet size spectrum. The results of the current study are encouraging and present opportunities for future studies. It is difficult for most farmers or agricultural technicians to conduct spray drift tests using wind tunnels, as the construction costs of such facilities are prohibitively high. This new method can serve as a powerful supplement, providing methodological guidance for farmers or agricultural technicians who face difficulty in conducting wind tunnel tests, helping them to make reasonable selections of nozzles. In this work, the nozzles we selected are limited. Subsequently, more experiments will be carried out using a variety of different types of nozzles to further verify the applicability of evaluating the drift potential reduction performance of nozzles based on the droplet size spectrum.

Acknowledgements

The authors acknowledge that this research was financially supported by the Innovation Capacity Building Foundation of Beijing Academy of Agriculture and Forestry Sciences (Grant No. KJCX20250921), National Natural Science Foundation of China (Grant No. 32301706, 32472008), and Cultivation Program for Outstanding Scientist Teams of Beijing Academy of Agriculture and Forestry Sciences (Grant No. JKTD2025004).

[References]

[1] Eun H-R, Kim S-H, Lee Y-H, Kim S-M, Lee Y-J, Jung H-Y, et al. Comparison of off-target pesticide drift in paddy fields from unmanned aerial vehicle spraying using cellulose deposition sampler. Ecotoxicology and Environmental Safety, 2024; 285: 117075.

[2] Zhang R R, Andrew J H, Chen L P, Li L L, Tang Q. Challenges and opportunities of unmanned aerial vehicles as a new tool for crop pest control. Pest Manag Sci, 2023; 79: 4123–4131.

[3] Wu L L, Li B L, He X K, Kienzle J. The nature of drift loss and the anti-drifting ability of different nozzles. Transactions of the CSAM, 1996; 27(S1): 124–128. (in Chinese)

[4] Qi L J, Fu Z T, Gao Z J. Spray pattern and drift potential of a spinning sisk. Journal of China Agricultural University, 2002; 7(2): 47–52. (in Chinese)

[5] Chen Y Y, Hou C J, Tang Y, Zhuang J J, Lin J T, Luo S M. An effective spray drift-reducing method for a plant-protection unmanned aerial vehicle. Int J Agric & Biol Eng, 2019; 12(5): 14–20.

[6] Wang S L, Lu D P, Beek J V, Zwertvaegher I, Wang W, Xu T, et al. Analysis of hydraulic nozzles for pesticide applications on atomization and droplets distribution characteristics. Chinese Journal of Pesticide Science, 2024; 26(1): 168–178. (in Chinese)

[7] Wang X N, He X K, Song J L, Wang Z C, Wang C L, Wang S L, et al. Drift potential of UAV with adjuvants in aerial applications. Int J Agric & Biol Eng, 2018; 11(5): 54–58.

[8] Balsari P, Gil E, Marucco P, Jan C V D. Field-crop-sprayer potential drift measured using test bench: Effects of boom height and nozzle type. Biosystems Engineering, 2017; 154: 3–13.

[9] Nuyttens D, Zwertvaegher I, Dekeyser D. Spray drift assessment of different application techniques using a drift test bench and comparison with other assessment methods. Biosystems Engineering, 2017; 154: 14–24.

[10] Gil E, Gallart M, Balsari P, Marucco P, Llop J. Influence of wind velocity and wind direction on measurements of spray drift potential of boom sprayers using drift test bench. Agricultural and Forest Meteorology, 2015; 202: 94–101.

[11] Pan X Y, Yang S, Gao Y Y, Wang Z C, Zhai C Y, Qiu W. Evaluation of spray drift from an electric boom sprayer: Impact of boom height and nozzle type. Agronomy, 2025; 15: 160.

[12] Grella M, Marucco P, Balsari P. Toward a new method to classify the airblast sprayers according to their potential drift reduction: comparison of direct and new indirect measurement methods. Pest Management Science, 2019; 75(8): 2219–2235.

[13] Gil E, Llorens J, Llop J, Fàbregas X, Gallart M. Use of a terrestrial LIDAR sensor for drift detection in vineyard spraying. Sensors, 2013; 13(1): 516–534.

[14] Miranda-Fuentes A, Marucco P, González-Sánchez E, Gil E, Grella M, Balsari P. Developing strategies to reduce spray drift in pneumatic spraying in vineyards: assessment of the parameters affecting droplet size in pneumatic spraying. Science of the Total Environment, 2018; 616–617: 805–815.

[15] ISO 22369-1. Classes in crop protection equipment–drift classification of spraying equipment. International Organisation for Standardisation ISO, Geneva, 2006.

[16] Li L L, Zhang R R, Chen L P, Hewitt A J, He X K, Ding C C, et al. Toward a remote sensing method based on commercial LiDAR sensors for the measurement of spray drift and potential drift reduction. Science of the Total Environment, 2024; 918: 170819.

[17] Li L L, Chen L P, Zhang R R, Tang Q, Yi T C, Liu B Q, et al. Spray drift characteristics of pulse-width modulation sprays in wind tunnel. Int J Agric & Biol Eng, 2022; 15(4): 7–15.

[18] Ferguson C, Chechetto G, O'Donnell C, Dorr G, Moore J, Baker G, et al. Determining the drift potential of Venturi nozzles compared with standard nozzles across three insecticide spray solutions in a wind tunnel. Pest Management Science, 2016; 72: 1460–1466.

[19] Gao S, Zhou X X, Qin W C, Han P, Yan X J, Xue X Y, et al. Using a wind tunnel test to evaluate the effect of spray adjuvant on droplet drift during aerial low volume insecticide spraying. Chinese Journal of Applied Entomology, 2018; 55(4): 654–658.

[20] Ru Y, Zhu C Y, Bao R. Spray drift model of droplets and analysis of influencing factors based on wind tunnel. Transactions of the CSAM, 2014; 45(10): 66–72. (in Chinese)

[21] Herbst A. A Method to determine spray drift potential from nozzles and its link to buffer zone restrictions. 2001 ASAE Annual International Meeting, Paper No. 01-1047. DOI: 10.13031/2013.7333.

[22] Zhang R R, Li L L, Fu W, Chen L P, Yi T C, Tang Q, et al. Spraying atomization performance by pulse width modulated variable and droplet deposition characteristics in wind tunnel. Transactions of the CSAE, 2019; 35(3): 42–51. (in Chinese)

[23] Taylor W A, Womac A R, Miller P C H, Taylor B P. An attempt to relate drop size to drift risk. International Conference on Pesticide Application for Drift Management, Waikoloa, Hawaii, 2004.

[24] Bai G, Nakano K, Mizukami T, Miyahara S, Ohashi S, Kubota Y, et al. Characteristics and classification of Japanese nozzles based on relative spray drift potential. Crop Protection, 2013; 46: 88–93.

[25] Nuyttens D, Taylor W A, Schampheleirec M D, Verbovend P, Dekeyser D. Influence of nozzle type and size on drift potential by means of different wind tunnel evaluation methods. Biosystems Engineering, 2009; 103: 271–280.

[26] Wang C L, Zeng A J, He X K, Song J L, Herbst A. Spray drift characteristics test of unmanned aerial vehicle spray unit under wind tunnel conditions. Int J Agric & Biol Eng, 2020; 13(3): 13–21.

[27] Schampheleire M D, Nuyttens D, Baetens K, Cornelis W, Gabriels D, Spanoghe P. Effects on pesticide spray drift of the physicochemical properties of the spray liquid. Precision Agriculture, 2009; 10(5): 409–420.

[28] Zhou Q Q, Xue X Y, Zhou L F, Sun T, Tian Z. Feasibility and method of classification of spraying nozzle. Transactions of the CSAE, 2019; 35(9): 66–72. (in Chinese)

[29] Dorr G J, Hewitt A J, Adkins S W, Jim H N, Zhang H C, Noller B. A comparison of initial spray characteristics produced by agricultural nozzles. Crop Protection, 2013; 53: 109–117.

[30] ISO 22856: 2008, Equipment for crop protection-methods for the laboratory measurement of spray drift-wind tunnels.

[31] Ellis M C B, Alanis R, Lane A G, Tuck C R, Nuyttens D, Zande J C. Wind tunnel measurements and model predictions for estimating spray drift reduction under field conditions. Biosystems Engineering, 2017; 154: 25–35.

[32] Ferguson C J, Donnell C C, Chauhan S B, Steve W A, Kruger G R, Wang R B, et al. Determining the uniformity and consistency of droplet size across spray drift reducing nozzles in a wind tunnel. Crop Protection, 2015; 76: 1–6.

[33] Zande J C V D, Porskamp H A J, Holterman H J. Influence of reference nozzle choice on spray drift classification. Aspects of Applied Biology, 2002; 66: 49–55.

[34] Chen C C, Li S G, W X Y, Wang Y X, Kang F. Analysis of droplet size uniformity and selection of spray parameters based on the biological optimum particle size theory. Environmental Research, 2022; 204: 112076.

[35] Butler E M C, Tuck C R, Miller P C H. The effect of some adjuvants on sprays produced by agricultural flat-fan nozzles. Crop Protection, 1997; 16(1): 41–50.

[36] Parkin C S, Wheeler P. Influence of spray induced vortices on the movement of drops in wind tunnels. Journal of Agricultural Engineering Research, 1996; 63: 35–44.

[37] Phillips J C, Miller P C H. Field and wind tunnel measurements of the airborne spray volume downwind of the single flat-fan nozzles. Journal of Agricultural Engineering Research, 1999; 72(2): 161–170.

[38] Nuyttens D, Zdekeyser I, Dekeyser D. Comparison between drift test bench

results and other drift assessment techniques. Aspects of Applied Biology: International Advances in Pesticide Application, 2014; 122(2): 293–301.

[39] Arvidsson T, Bergstrom L, Kreuger J. Spray drift as influenced by meteorological and technical factors. Pest Management Science, 2011; 67: 586–598.

[40] Paolo B, Marco G, Paolo M, Mtta F. Assessing the influence of air speed and liquid flow rate on the droplet size and homogeneity in pneumatic spraying. Pest Management Science, 2019; 75: 366–379.

[41] Ferguson J C, Hewitt A J, O'Donnell C C. Pressure, droplet size classification, and nozzle arrangement effects on coverage and droplet number density using air-inclusion dual fan nozzles for pesticide applications. Crop Protection, 2016; 89: 231–238.

[42] Combellack J H, Westen N M, Richardson R G. A comparison of the drift potential of a novel twin fluid nozzle with conventional low volume flat-fan nozzles when using a range of adjuvants. Crop Protection, 1996; 15(2): 147–152.

[43] Zhu H, Reichard D L, Fox R D, Brazee R D, Ozkan H E. Simulation of drift of discrete sizes of water droplets from field sprayers. Transactions of the ASAE, 1994; 37(5): 1401–1407.

[44] Pergher G, Gubiani R, Cividino S R S, Dell'Antonia D, Lagazio C. Assessment of spray deposition and recycling rate in the vineyard from a new type of air-assisted tunnel sprayer. Crop Protection, 2013; 45: 6–14.

[45] Miller P, Mawer C, Merritt C. Wind tunnel studies of the spray drift from two types of agricultural spray nozzle. Aspects of Applied Biology, 1989; 21: 237–238.

[46] Guler H, Zhu H, Ozkan H E, Derksen R, Yu Y, Krause C. Spray Characteristics and Drift Reduction Potential with Air Induction and Conventional Flat-Fan Nozzles. Transactions of the ASABE, 2007; 50(3): 745–754.

[47] Torrent X, Gregorio E, Douzals J, Tinet C, Rosell-Polo J R, Planas S. Assessment of spray drift potential reduction for hollow-cone nozzles: Part 1. Classification using indirect methods. Science of the Total Environment, 2019; 692: 1322–1333.