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Assessing the influence of air speed and liquid flow rate on the droplet size and homogeneity in pneumatic spraying

(**Running title:** air speed and liquid flow rate influence on droplets in pneumatic spraying)

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Abstract

BACKGROUND: The efficacy of treatments in vineyards largely depends on the necessary balance between leaf coverage and spray drift and, therefore, knowledge about droplet size is of major importance, but scarce scientific information is available on pneumatic spraying, often adopted in this crop. The objective of this work was to obtain the relationships between the droplet size spectra characterization parameters and the main affecting factors in pneumatic nozzles.

RESULTS: Three liquid flow rates (LFR) and four air speeds (AS) were combined in laboratory conditions to assess their influence on the droplet size spectra (D10, D50 and D90), homogeneity (Relative Span Factor, RSF) and driftability (V_{100}) in two different air shear nozzles (cannon-type and hand-type nozzles). The droplet size parameters were significantly affected by LFR and AS, and a model was fitted to predict droplet size in every spout type. The droplet V_{100} was also affected by both factors. The RSF was similar in both cases but did not follow regular trends.

CONCLUSIONS: The findings obtained can help vineyard farmers and technicians to effectively increase the efficiency and, therefore, the efficacy of the pesticide treatments reducing at the same time the spray drift risk by appropriate selection of the pneumatic spraying operational parameters, namely LFR and AS.

Keywords: pesticide application, pneumatic spraying, droplet characterization, spray drift.

1 INTRODUCTION

Since the early 1990s, the increasing public concerns about environmental contamination by pesticides, spray drift reduction became a hot topic of research and development in the field of plant protection technology. The European Directive 128/2009/EC (SUD) represents the bedrock for the EU legislation concerning drift reduction and pesticide application efficiency.[1] Among the environmental contamination phenomena which may occur during Plant Protection Products (PPP) use, spray drift[2] still represents a major challenge when applying agrochemicals as non-target receptors can be acutely exposed to pesticide adverse effects.[3-9] Furthermore, the spray drift phenomenon is more important during spray applications carried out in bush/tree crops when compared with arable crops,[10] mainly due to the lack of administrative requirements and consensus in the pesticide industry regarding the dosing systems. For these reasons, higher efforts have been made in these called “special crops” over the last years.

One of the most important goals in pesticide application is to achieve a homogeneous spray deposition throughout the canopy according to the treatment specifications. Therefore, a highly efficacious and efficient spray application could simultaneously increase the benefits of PPP, reduce the risk of environmental contamination, and produce high-quality food in a sustainable agricultural frame.

According to Hofman and Solseng[11] the factors affecting pesticide emissions to the air during the application process can be divided into technical and environmental factors (weather conditions at the time of application, namely wind speed and direction, temperature, relative humidity and stability of the air at the application site). Among the technical factors, the size of the particles has a large impact on the off-target drift:[12,13] fine spray tends to increase the drift risk.[14] At the same time, the effect of droplet size and spray volume rate on spray deposit and coverage, which determine the technical performance and biological efficacy of spray applications in fruit crops, is recognized as crucial. The ideal droplet size spectrum can maximize spray efficiency for depositing and transferring a biologically effective dose to the target, while minimizing off-target losses. Hislop concluded that the efficacy of a particular pesticide was often dependent on the droplet size.[15] It was long believed that a high coverage of the target was usually better achieved with small droplets[16] because fine droplets gave a proportionally greater coverage for any given level of spray deposit.[17] In the past years, this belief led the farmers to the conclusion that only the use of conventional nozzles ensured the biological efficacy of treatments refusing the use of air induction nozzles (low-drift nozzles) as spray drift reducing technology. Although some literature data supported the thesis that air induction nozzles would result in reduced spray coverage and chemical efficacy when fungicide was applied,[18,19] lately it was demonstrated that, when impacting with targets, the air-filled droplets tended to explode and fracture into many smaller droplets, increasing the potential for spreading on the leaves, and producing similar,[20,21] or even greater[22,23] both coverage and deposition compared to conventional, finer sprays. Furthermore, several studies confirmed the equivalent biological efficacy of treatments performed in apple orchards using AI and conventional nozzles.[24-28] The AI nozzles showed the best performance in terms of coverage and biological efficacy when applying pesticides during unfavourable weather conditions (high wind, low humidity and high temperature), where conventional nozzles resulted in suboptimal performance.[29]

Likewise, in bush/tree crop spray applications, the air flow of the sprayer fan plays a crucial role in ensuring the biological efficacy of treatments and reducing the drift risk.[30,31] The parameters of air jet (air flow rate and velocity), related to the construction technique of fan type, together with sprayer forward speed are main factors influencing the quality of the treatments[32] and the spray off-target losses, significantly contributing to environmental pollution.[33]

Some authors relate the quality of the treatments to the type of fan outlet design, acting to address the fan air flow to the intended target.[34] For Dekeyser et al.,[35] the sprayer's discharge air system design caused major differences in spray distribution and off-target losses. The proper adjustment of air flow parameters affects the resultant trajectory of spray droplets and hence it plays an important role in spray deposition.[36] In orchards, sprayers producing air jets of great volume and low velocity penetrate the tree canopies more effectively than those of lower volumes and higher velocities.[37] In smaller trees and in vineyards, on the other hand, too high fan air volumes may reduce deposition owing to canopy compression.[38] Excessive fan air volumes have also been reported to increase drift losses in apple orchards,[39] in vineyards[40,41] and in young high tree plantations.[42] At the same time, the right adjustment of air jet (air flow rate and air direction), depending on the canopy size, leaf density, and row distance, resulted in spray drift reduction and deposition increase.[13,34-36,43,44]

Nowadays, the equation, high efficacious/efficient spray application and reduced spray drift risk, could be concurrently balanced, adopting the appropriate direct measures to prevent drift at sources by giving preference to the most efficient application techniques.[45] These decisions, made by farmers when selecting and operating the sprayers, currently could be supported using 'ad hoc' tools e.g. TOPPS Drift Evaluation Tool (www.topps-drift.org).[46,47]

When operating with hydraulic nozzles, the main available strategy to reduce spray drift is the use of air induction nozzles,[3,13,45] which proved to substantially reduce the spray drift,[45,48,49] compared to conventional nozzles, by maintaining similar deposition values[48,50] and, in this way, ensuring consistency in the biological efficacy of treatments.[28,51] On the other hand, to the date no innovative environmentally friendly commercial solutions are available for pneumatic sprayers on the market.

The pneumatic diffusers generally mounted on vineyard sprayers[52] and, in some cases, in orchard sprayers,[53] consist of spouts in which spray droplets are generated by the action of a high-speed, high-pressure air stream on a liquid conveyed at low pressure (0.15 MPa maximum) inside the spout.[54,55] The Venturi effect created at the internal part of the spouts generates very fine droplets. Although there have been very few studies of droplet size generated by pneumatic sprayers,[56] the average mean volumetric diameters of the droplets (VMD or D50) are known to be typically smaller than 100 μm, which is the threshold below which droplets become very driftable.[49,57,58]

In recent years, some authors documented a spray drift reduction using a pneumatic electrostatic sprayer, as a secondary effect of improvement of the overall deposition and distribution on the foliage canopy,[59-62] because electrostatic force fields guide and govern the trajectories of charged spray droplets, even when not necessarily in the way desired.[63] However, as it is well known that the main parameters affecting spray drift is droplets size spectra,[49] the first way to directly reduce the off-target losses involves necessarily the increase of the droplet size spectra produced by the air spouts in pneumatic spraying.

Under practical conditions, with most pneumatic sprayers, there are two options to increase the dimension of the generated droplets. The first one is to reduce the fan air speed:[45] higher air speeds produce finer droplets. Nevertheless, a reduction of the fan air speed could compromise the spray penetration into the canopy, as it can result in a reduced coverage in the inner parts.[53] On the other hand, the second option is to increase the liquid flow rate:[45] the higher liquid flow rates produce larger droplets.[64] However, the liquid flow rate is not easy to change, as it depends on the forward speed, set by the operator. Other options that may be considered are a) the change of the of the air spout size,[45] as the larger the air spout's outlet section, the slower the outcoming air, or b) as recently suggested by Miranda-Fuentes et al.,[65] to change the position of the elements that release the liquid into the air stream. In any case, it is easy to appreciate that, for a given pneumatic sprayer configuration, the modification of the droplet size is very difficult to achieve.

Another aspect that should be noticed is that the most common pneumatic sprayers used in vineyards are those which have the capability to spray more than one row at the same time, known as multi-row pneumatic sprayers (e.g. in France, where pneumatic sprayers are widespread, they represent 70 – 80% of sprayers used in large vineyards).[66] These sprayers are equipped with two different types of pneumatic nozzles:[55] a) hand-type nozzles, with individual air spouts disposed as "fingers" of the main spout and whose mission is to spray the row next to the sprayer, and b) the cannon-type nozzles, with a main wide spout with very high air velocity that aims at spraying the further row, i.e. the row placed next to the one sprayed with the hand. This results in different droplet size spectra produced by the two spout types, for the same level of fan air speed and liquid flow rate. Therefore, it could end up with a different spray coverage in both row sides, depending on the nozzle that sprayed each one.

As mentioned before, the droplet size is a key parameter in the whole spraying process for guaranteeing the spray efficacy whilst also determining its efficiency. Nevertheless, scarce droplet size information is available for farmers when planning a treatment. Therefore, it is necessary to determine the influence of the main operational parameters (liquid flow rate and air speed) on the generated droplet spectra characteristics. The objectives of the present work were to assess the influence of the main operational parameters in pneumatic spraying, i.e. air speed and liquid flow rate, on the droplet size (D50, D10 and D90) and droplet homogeneity (RSPAN) for both hand-type and cannon-type pneumatic nozzles. It was also an objective to develop models to estimate the droplet size parameters as a function of the aforementioned operational parameters.

2 MATERIALS AND METHODS

Abbreviations

AFR: Air flow rate.

AS: Air speed.

D10 (D[v,0.1]): Diameter for which a volume fraction of 10% is made up of drops with diameters smaller than this value (expressed in µm).

D50 (D[v,0.5]): Volume median diameter (VMD) or diameter for which a volume fraction of 50% is made up of drops with diameters smaller than this value (expressed in µm).

D90 (D[v,0.9]): Diameter for which a volume fraction of 90% is made up of drops with diameters smaller than this value (expressed in µm).

LFR: Liquid flow rate in the spraying circuit.

PPP: Plant Protection Product

RSF: Relative SPAN factor, a measure of the droplet homogeneity in the spray population.

SUD: Sustainable Use Directive 128/2009/EC

V_{100}: Percentage of sprayed volume composed of droplets finer than 100 µm.

VMD: Volumetric mean diameter, equivalent to D50.

2.1 Trial location and laboratory deployment

The trial was performed at laboratory facilities of the Department of Agricultural, Forest, and Food Sciences (DiSAFA) of the University of Turin (Grugliasco, Turin, Italy). The methodology used for the droplet size characterization and the trial deployment is carefully described and detailed in previous works.[65] Very briefly, the laboratory arrangement (Fig. 1) was divided into different spaces: the spray generation area (Fig. 1a) consisted of a test bench (CIMA S.p.A., Pavia, Italy) simulating a real pneumatic sprayer, including both pneumatic and hydraulic systems, funnelling the air to a unique application unit (pneumatic nozzle). The control of the system was carried out from the control/data acquisition area (Fig. 1b), which included a control box to regulate the bench's fan rotary speed, which included a digital tachometer and a display for real-time visualization of the data. Last, there was the droplet size measurement area (Fig. 1c) in which the instrument for the droplet size measurement was placed.

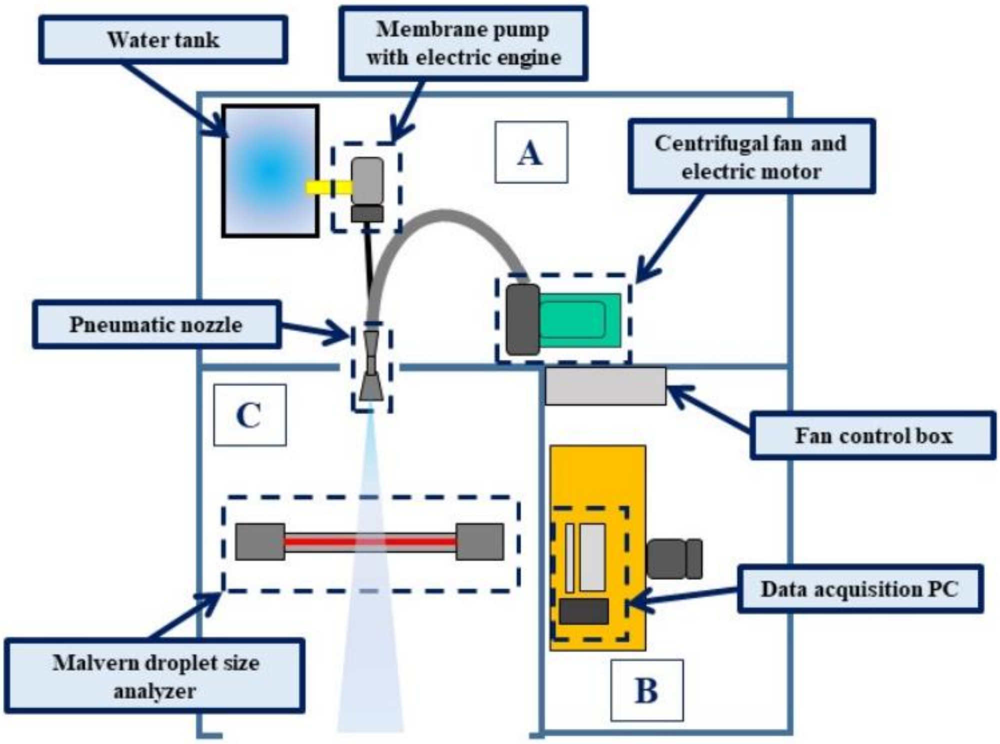


Figure 1. Trial deployment with a) spray generation area, b) control/data acquisition area and c) droplet size measurement area.

The droplet size measurement was performed by using a Malvern SprayTec ® instrument (STP5342, Malvern Instruments Ltd., Worcestershire, UK) (Fig. 2a). The measurement range of the instrument ranged from 0 to 2,000 μm. The selected data acquisition frequency was 1 Hz, and each basic measurement dataset consisted of 60 measurements, i.e., one-minute acquisition time. Between the two possible lenses that can be mounted on the system — 300 and 750 mm — the 300 mm one (measurement range: 0.1 ÷ 900 μm) was selected because of the small size of droplets generated by pneumatic spraying. The data were acquired through a specific software (SprayTec Software v3.30, Malvern, Fig. 2b), which enabled the data pre-visualization on the computer screen, with the main parameters for every data collected real-time visualized in the screen.

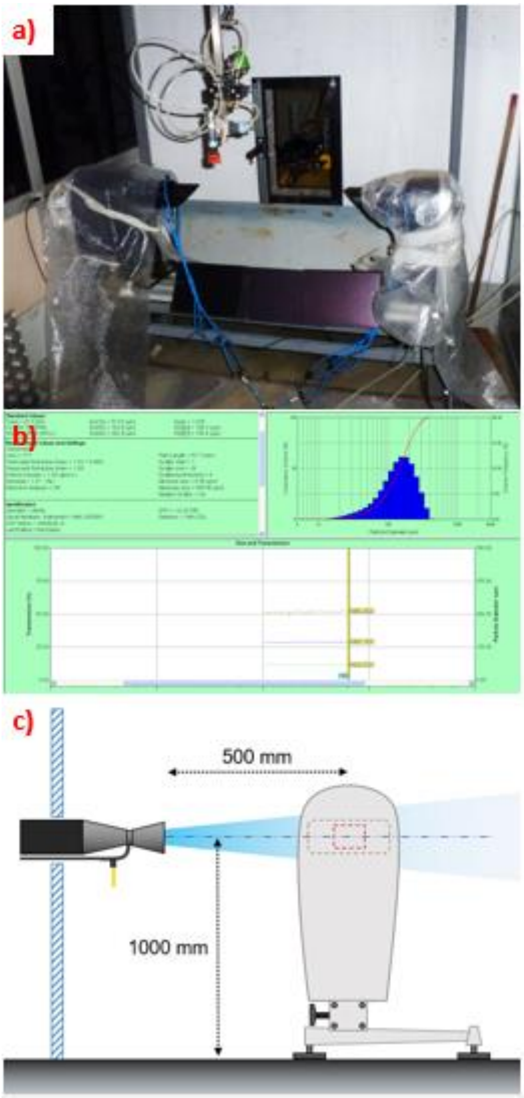


Figure 2. a) Malvern SprayTec ® droplet size measuring instrument. b) SprayTec software for data acquisition and analysis. c) Spray droplet measurement deployment.

The spraying nozzle was set fixed in a platform (Fig. 2a), with a height of 1 m above the floor (Fig. 2c). The laser beam to measure the droplet size was placed in a chamber were the spray was released (Fig. 1c) and it was aligned with the longitudinal axle of the nozzle, and set at 500 mm distance from the spout (Fig. 2c); based on preliminary tests,[65] 500 mm is the minimum distance at which the droplets size values stay constant and stable.

2.2 Spraying system and operational parameters adopted

The most common and widespread vineyard pneumatic sprayers are normally intended to perform the treatment in two consecutive rows rather than one, so they are equipped with two different types of pneumatic spouts: at the bottom of spray-head are mounted two hand-type nozzles characterized by individual air spouts disposed as fingers of the main spout, whose mission is to spray the row next to the sprayer pass, and on the top of spraying unit are mounted two cannon-type nozzles, with a main wide spout that aims at spraying the further row (Fig. 3a). Therefore, for the purpose of this work, the two types of pneumatic nozzles mounted on spray-head “2 hands-2 cannons TC.2M2C” (CIMA S.p.A., Pavia, Italy) were tested.

Therefore, a cannon-type (Fig. 3b) and a hand-type (Fig. 3c) spouts were set at the end of the spray test bench (Fig. 1a). An electrically-driven membrane pump (AR 202, Annovi Reverberi S.P.A., Modena, Italy) was used to water-feed the system and a manometer with a measurement resolution of ±0.01 MPa was used to control the circuit liquid pressure. The test bench’s centrifugal fan was the same usually mounted on the commercial sprayer model Cima 50 Plus 400L.

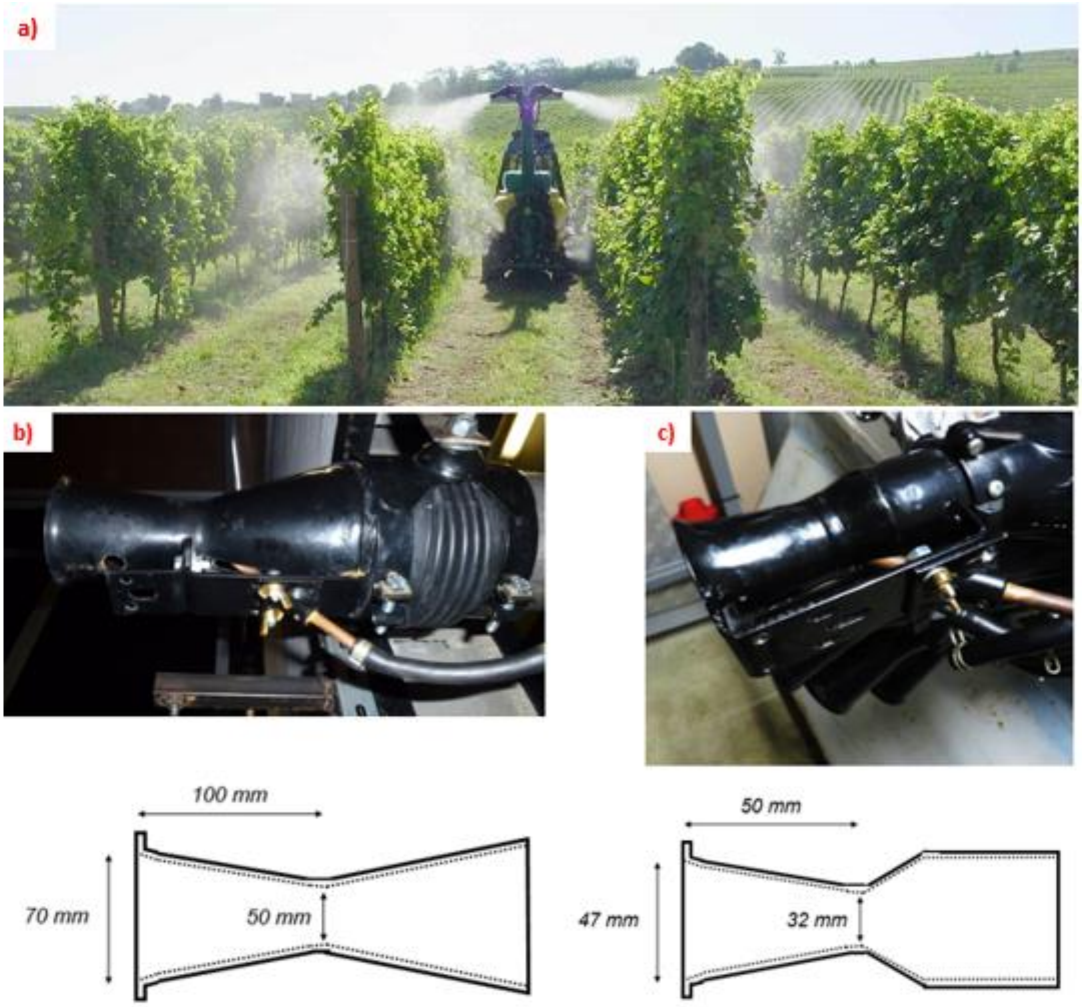


Figure 3. Multiple-row pneumatic sprayer Cima 50 Plus 400L equipped with spray head “2 hands-2 cannons” during field pesticide application; a) at the bottom of spray-head, two hand-type nozzles are mounted, and on the top, two cannon-type nozzles. Details of pneumatic nozzles tested in laboratory using test bench: b) main spout of cannon-type and c) single spout of hand-type.

Based on information previously acquired,[65] the rotary speed of both test bench and real sprayer Cima 50 Plus 400L need to be different to match the same air pressure conditions. Thus, the relationship between test bench’s fan rotary speed and sprayer’s fan rotary speed was used to translate usual field-working conditions to the bench rotation. Therefore, the same correlation between both rotation speeds, obtained in a previously deep investigation of cannon nozzle type, was used to set the test bench close to the operative field conditions (Fig. 4).[65]

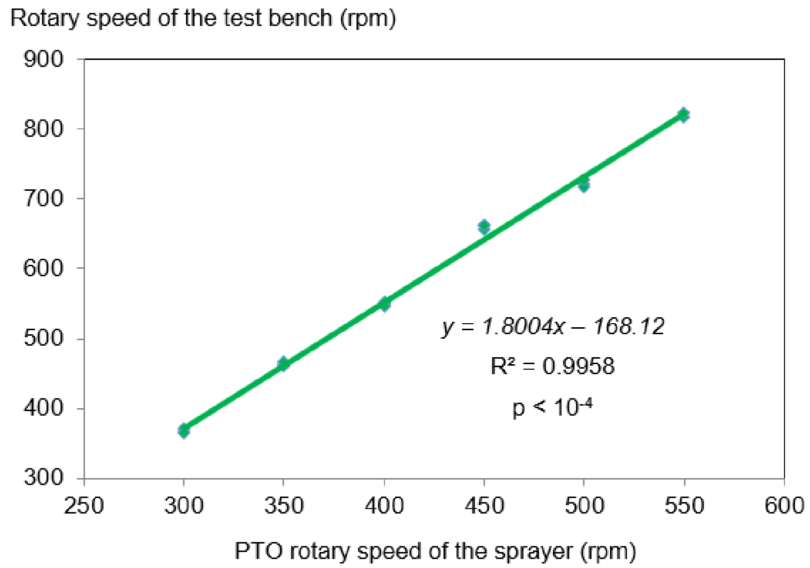


Figure 4. Correlation between sprayer and test bench fans' rotation speed values to meet the same air pressure.[65]

As shown in the Figure 4, the relationship between both rotary speeds is very accurate. Nevertheless, it is used as a reference, but prior to every test, a pressure measurement was carried out to conveniently adjust the rotary speed of the bench, so that it matched the exact pressure of the real sprayer's outlet. The rotary speed values in the real sprayer were checked with an optical tachometer (Photo tachometer, Lutron Electronic Enterprise Co, Ltd., Taipei, Taiwan), whilst those in the bench were set with the aforementioned integrated digital tachometer.

In the case of hand-type nozzle, no tests had been performed previously, so the pressure values needed to be checked in order to set the test bench's fan rotary speed as already operated in testing cannon nozzle. The correlation between test bench's air pressure and the sprayer's was performed by acquiring the air pressure in the hand-type nozzle of pneumatic sprayer at 350, 400, 450 and 500 rpm PTO speed, and matching these values with the test bench measurements; the same methodology proposed for the cannon-type nozzle by Miranda-Fuentes et al.,[65] was applied.

Based on the preliminary investigations above mentioned, aimed to properly setup the test bench, the operational parameters used to perform the laboratory measurements were those listed in Table 1. The liquid flow rate (LFR) and the air speed (AS) were measured for every rotation speed, once the pressure had been matched in both systems.

Table 1. Operational parameters used in the trials.

	Studied parameter	Studied levels	Regulation based on	Positions tested
CANNON	**Liquid flow rate** (LFR)	1.00 / 1.64 / 2.67 L min^{-1}	Position of the regulatory disc	Positions 3 / 5 / 7
	Air speed (AS)	72.8 / 81.0 / 89.6 / 97.6 m s^{-1}	Rotary speed of the fan	541 / 598 / 663 / 720 rpm
HAND	**Liquid flow rate** (LFR)	0.84 / 1.33 / 2.07 L min^{-1}	Position of the regulatory disc	Positions 3 / 5 / 7
	Air speed (AS)	57.9 / 64.6 / 74.3 / 84.2 m s^{-1}	Rotary speed of the fan	488 / 536 / 609 / 677 rpm

The tested LFR values were chosen according to the most frequent sprayer regulation in Northern Italy, following the sprayer manufacturer recommendations and the local farmers' practices (Tab. 1).

To obtain different LFR the CIMA disc with perimeter calibrated holes differing in diameter was used. Depending on the holes diameter, an higher or lower liquid flow rate could pass through and be released inside the air spout. This disc had a total of 15 different positions and, therefore, each position could generate different flow rates that in combination with different liquid pressures result in many different liquid flow rates. As the spray pressure was kept constant at 0.1 MPa (1 bar), as usual in this kind of spraying, the liquid flow regulatory element positions chosen for the laboratory trials were 3, 5 and 7 of the disc, corresponding to 1.00, 1.64 and 2.67 L min^{-1} for the cannon type nozzle (Tab. 1). In the case of the hand nozzle, the LFR for the entire hand (four fingers) was slightly lower than that of the cannon for the same disc positions 3, 5 and 7, namely 0.84, 1.33, and 2.07 L min^{-1} (Tab. 1). Nevertheless, the same disc positions were adopted during the laboratory measurements to keep constant the field-conditions normally available for the farmer. Testing both nozzles type, the liquid flow rates were carefully checked before to start the droplets size measurements; for this purpose the liquid supplied in a 30s time frame was measured using a Henhart Delta E200 digital chronometer (Hanhart 1882 gmbh, Gütenbach, Germany) and MBL Volumetrics™ glass graduated cylinders of 1 L capacity (Fisher Scientific, Göteborg, Sweden).

In total 12 different configurations were tested for both nozzles, namely cannon-type and hand-type, deriving from the combination of four AS and three LFR (Tab. 1).

2.3 Evaluation of air speed behaviour inside the spouts

The air speed in the longitudinal axle of every nozzle's spout was measured for every airflow rate of those included in the trial (Tab. 1). This is particularly important to understand the results of the droplet size measured. The instrument used to measure the air speed was a pitot-tube-based anemometer (Testo 400, Testo Inc., Lenzkirch, Germany) with ±0.01 hPa in differential pressure resolution, which results in 1.28 m s^{-1}, converted to air speed, and a measurement range up to +2000 hPa (571.43 m s^{-1}). Speeds were measured at a frequency of 1 Hz over a time period of 20 s, and the average value was automatically calculated by the device and noted down. In order to keep the Pitot tube precisely in the centre of the spout, a previously developed implement was used.[65] Three positions along the longitudinal axle of every spout were tested, in the part where the liquid hose is inserted (*MP1*, Fig. 5), the outer position of the spout (*MP3*, Fig. 5) and an intermediate one (*MP2*, Fig. 5). These positions corresponded to the measurements included in Table 2.

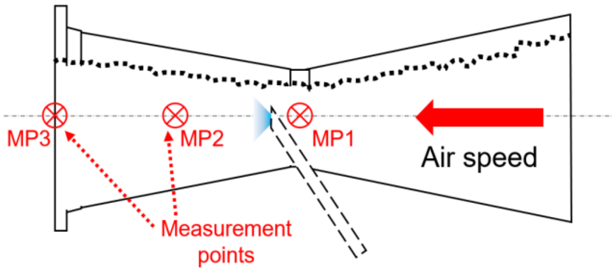
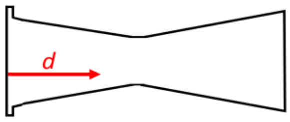


Figure 5. Air speed measurement points along the air spout in both nozzles, namely cannon-type and hand-type.

Table 2. Air speed measurement positions inside the spout.

	Distance to the edge of the spout (cm)	
Measurement position*	**Cannon spout**	**Hand spout**
MP1	10.0	5.0
MP2	5.0	2.5
MP3	0.0	0.0

* According to Figure 4

2.4 Characterization of droplets size spectra: experimental design, trial development and data acquisition.

The trials were designed as a completely randomized factorial, as the independent variables, i.e., the air speed (AS) and the liquid flow rate (LFR), were independently set for every combination in every nozzle type (Tab. 1).

The dependent variables measured were the D50 (*D[v,0.5]*), D10 (*D[v,0.1]*), D90 (*D[v,0.9]*) and V_{100}; this last droplet size parameter identify the volume fraction made up of drops with diameters smaller than 100 µm (expressed in %) and it is commonly used to express the “driftability” that is the potential risk to generate spray drift at the time of application. Although there is no specific droplet size range that is liable to drift under all conditions, droplets featured by diameter less than 100 μm are universally considered highly driftable,[67-70] because especially likely to be blown away by the environmental wind currents.[71]A lot of authors, mainly explain the relation between the drift and the droplets size linked to the V_{100} indicator.[57,58,72-77] Furthermore, based on the droplet size parameters measured, the droplet homogeneity was calculated according to the Equation 1 and it is expressed as the Relative Span Factor (RSF, Eq. 1).[78,79]

$$RSF = \frac{D90 - D10}{D50} \qquad [1]$$

Where *D50*, *D10* and *D90* are expressed in μm.

The order of the different combinations between LFR and AS was randomized. In order to take the measurement for every single combination of parameters, the spray was released, adjusting the spray pressure to 1 bar. Then, the laser system was automatically calibrated, function which is included in the data acquisition software included with the equipment. After each set of measurements was taken, the laser was switched off and the dataset was revised to detect possible mistakes or missing values, prior to exporting the file. When this process was complete, the whole dataset was exported to a text ‘.csv’ file.

The different individual files were then automatically comprised in a unique one by using an R-Software (v3.4.4 for Windows) script.[80]

2.5 Statistical analysis.

The statistical analysis were performed using IBM SPSS Statistics for Windows v20,[81] after importing the data matrix generated with every parameter combination. To properly present some data in form of heat colour map graphics, R-Software for Windows v3.4.4 was used,[80] with the packages ‘ggplot2’[82] and ‘RColorBrewer’.[83]

In order to evaluate the influence of each parameter tested and their interaction, a two-way Analysis of Variance (ANOVA) was used, being also useful to develop the linear models for each nozzle type and dependent variable (D50, D10, D90, RSF and V_{100}).

Linear regression models were obtained to express the effects of the liquid flow rate (LFR) and the air speed (AS) on the aforementioned dependent variables. It was also checked the effect of their interaction. Linear models were fitted according to Eq. 2.

$$DV = \beta_0 + \beta_1 \times LFR + \beta_2 \times AS + \varepsilon \qquad [2]$$

Where DV is the dependent variable, expressed in µm in the case of the droplet diameter, unit-less in the case of RSF and percentage (%) in the case of the V_{100} parameter. β_0 is the constant term of the model, where the rest of independent variables are zero. β_1 and β_2 are the correlation coefficients of LFR and AS, respectively, β_3 is the coefficient for the interaction between both factors, and ε is the residual error of the model.

The data normality and equality of variances were both checked by using the Shapiro-Wilk and Levene tests respectively ($\alpha = 0.05$).[83] Statistical significance was always considered when $P < 0.05$.

3 RESULTS AND DISCUSSION

3.1 Adjustment of the test bench to simulate a real sprayer

The relationship between test bench's fan rotary speed and Cima 50 Plus 400L sprayer's fan rotary speed, to obtain the same level of air pressure at the hand-type nozzle's outlet, is presented in Figure 6.

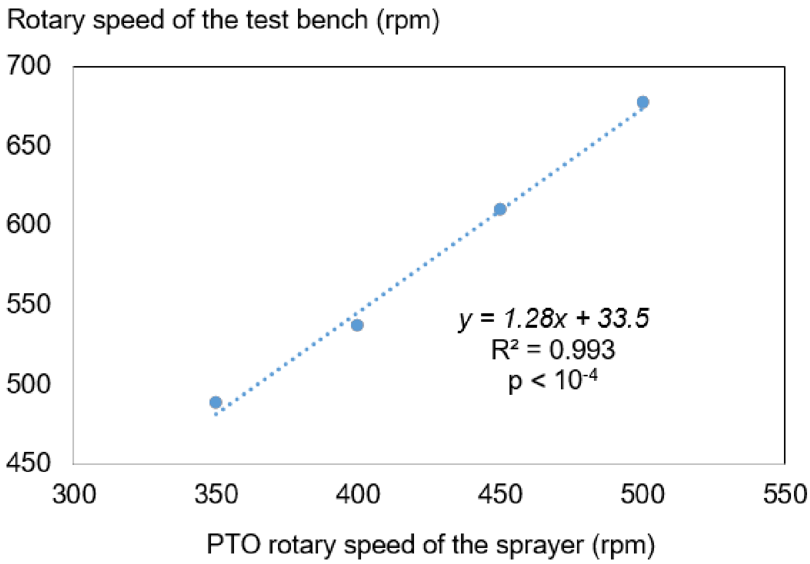


Figure 6. Relationship between test bench's fan and Cima 50 Plus 400L sprayer's fan rotary speeds to obtain the same level of air pressure at hand-type nozzle's outlet.

As it can be seen, there is a very strong relationship between both rotary speeds to keep air pressure constant. If comparing with the cannon's regression (Fig. 4), there is a high difference between the regression line's slope for both nozzles, with coefficients of 1.80 in the case of the cannon and 1.28 for the hand nozzle.

This difference, however, did not produce very important changes in the studied values, as it can be seen in the rotary speeds tested (Tab. 1). The reason why this happened lies on the fact that PTO speed values selected in the real sprayer are not very extreme values that would have made very difficult to have tested them, in the case of the cannon-type nozzle, with the test bench, as in the highest values there was very high speed needed (Tab. 1). It was also observed an appreciable difference in the independent term of the regression curve. Thus, in the case of the cannon nozzle, it presented a negative value (-168.12) and in the case of the hand nozzle, it was positive (+33.5).

3.2 Air speed drop along the spout's longitudinal axis: test bench measurements

The air speed reductions for the three measured positions along the spout's longitudinal axis for the different air flow rates are shown in Figure 7. In particular, Figure 7a shows the results obtained testing the cannon-type nozzle, and Figure 7b those obtained when testing the hand-type nozzle.

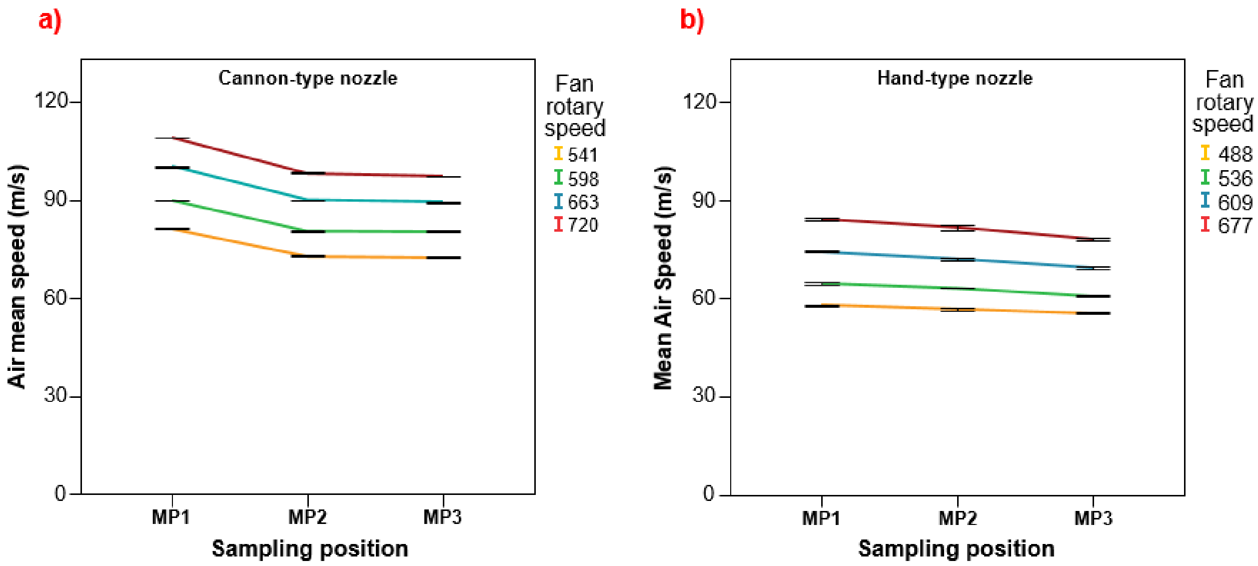


Figure 7. Mean air speed values measured in every sampling position (Fig. 5) are shown both for a) cannon-type nozzle and b) hand-type nozzle. The results are split based on test bench's fan rotary speed. The error bars indicate the SE.

As it can be seen, there is a strong decrease in the air speed value along the spout, but this decrease did not follow the same pattern in both nozzles. Thus, in the case of the cannon, there was a marked reduction between MP1 and MP2, but these values kept constant from MP2 to MP3. In the case of the hand nozzle, there was a much more regular behaviour, obtaining a practically constant decrease from MP1 to MP3. This fact can be due to the difference in the shape of both nozzles (Fig. 3b and 3c). The relationship between the spout diameter and length in both nozzles was different, as it was also the convergent section.

The influence of the test bench's fan rotary speed was different in both cases. Thus, in the case of the cannon nozzle, there was a constant absolute decrease independent of the air speed of about 10 m s^{-1}. As the fan rotary speed changed, the relative decrease did vary in proportion to the rotary speed and, therefore, to the AFR.

If the efficiency in the air speed reduction, i.e., the total percentage air speed reduction per linear cm from MP1 to MP3, is evaluated, both nozzles behave similarly independently of the PTO speed. Thus, the mean reduction obtained was 0.834 % cm^{-1} in the case of the cannon-type nozzle and 1.184 % cm^{-1} in the case of the hand-type nozzle.

3.3 Droplet size spectra

The droplet size parameters D50, D10, and D90, along with V_{100} and RSF for both nozzles, namely cannon-type and hand-type, and for all combinations of AS and LFR tested, are shown in Figure 8.

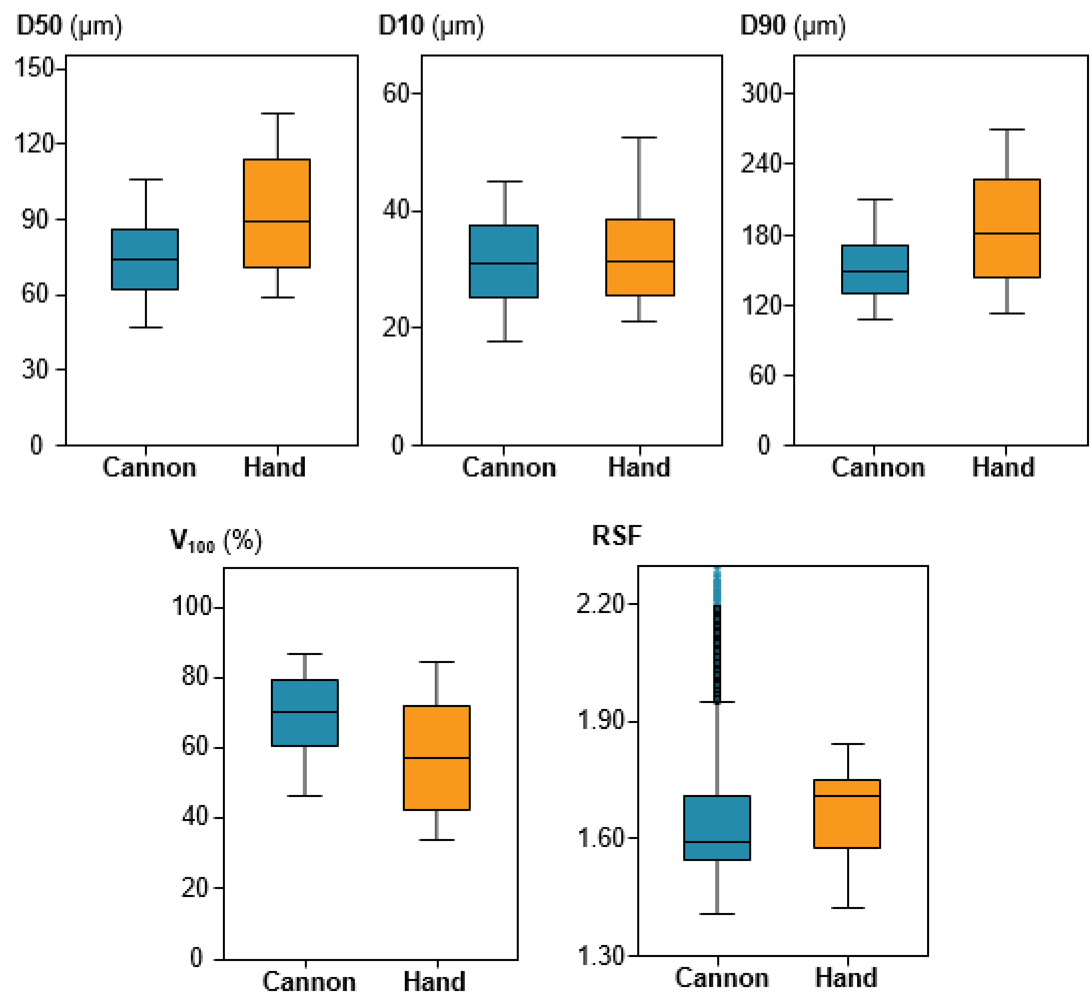


Figure 8. Boxplots for the variables D50, D10, D90, V_{100}, and Relative Span Factor —RSF—. The boxplots include every tested combination between air speed —AS— and liquid flow rate –LFR—.

As it can be seen, the mean values (including every parameter combination) obtained for the evaluated parameters markedly differed. In the case of D50, mean values for the cannon were 17% lower than those collected for the hand (74 μm and 89 μm, respectively). This result can be explained by the fact that the higher air speed achieved in the cannon nozzle produced lower droplet size in general, for every combination of LFR and AS tested (Fig. 7). It shall be remembered that, even when the rotary speed values were different in both cases, the air pressure conditions at the spout outlet were identical. D10 parameter was similar in both cases, with about 30 µm in diameter. The case of D90 presented a similar trend than D50, with a mean increase of 19% and values of 145 µm and 180 µm, respectively.

For the particular case of the cannon, the variations in droplet size are presented in Figure 9a for the evaluated parameters (D50, D10 and D90).

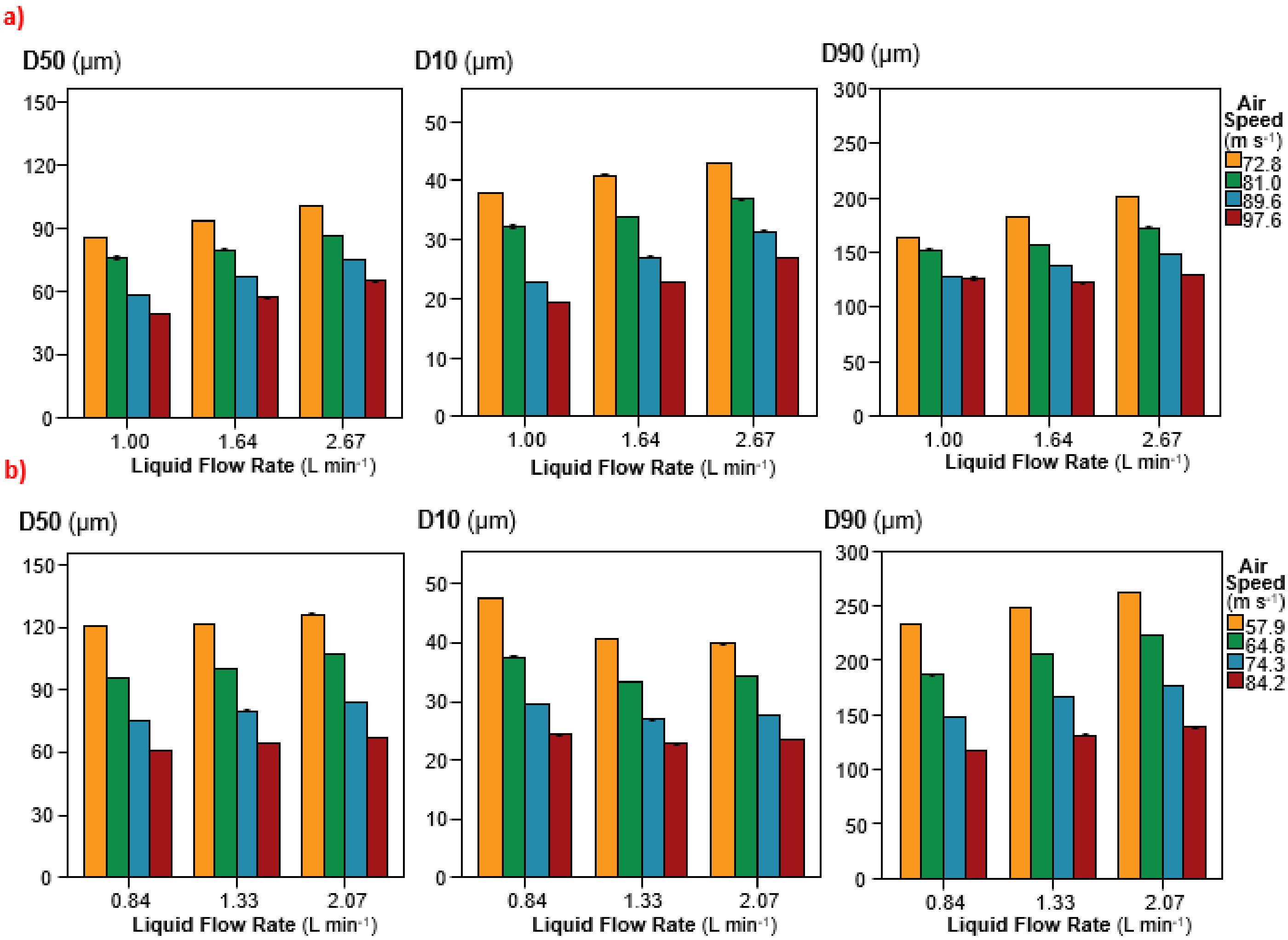


Figure 9. Droplet size parameters, namely D50, D10, D90, measured for different combinations between LFR and AS in a) cannon-type nozzle, and b) hand-type nozzle. Error bars represent the SE.

For every nozzle type, LFR and AS showed to have significant influence according to the ANOVA results ($p < 10^{-4}$). As it can be seen, cannon's mean D50 values for the different combinations of parameters ranged from 50 μm to 100 μm for the minimum LFR with the maximum AS and the maximum LFR with the minimum AS, respectively. For every value of LFR, notorious differences were found for the different AS tested. The mean increase obtained was higher than 50% in every disc position. The maximum relative difference was found for the 1.00 L min^{-1} LFR value (disc position '3'). Nevertheless, the LFR variation did not produce such an important droplet size increase, with mean values below 15% in every case. As to the D10, the increase of this parameter showed to follow a similar trend than D50, directly increasing with LFR and decreasing with AS. In this case, a minimum D10 mean value of 19 μm was collected, and the combination yielding the maximum value did not reach 50 μm. D90 showed an atypical behaviour in the case of the minimum LFR, where no decrease of D90 parameter was measured varying AS from 89.6 m s^{-1} to 97.6 m s^{-1}. There was another rare trend: for the maximum AS (97.6 m s^{-1}), no increase took place with the increase of LFR. This finding did not follow the aforementioned behaviour (for D10 and D50), but the rest of the AS did behave normally.

In the case of the hand-type nozzle, its droplet size parameters with respect to the LFR and AS are resumed in Figure 9b. The D50 parameter was directly influenced by the LFR and inversely influenced by the AS (Fig. 9b), in the same way of cannon spout case. The parameter ranged from 60 μm to 127 μm, for the minimum LFR and maximum AS and the opposite, respectively. Like it happened in the case of the cannon nozzle, there was a major influence of the AS for any given LFR, but this last parameter did not affect the droplet size in the same magnitude. D10 ranged, in this case, from 23 μm (in this case for the intermedium LFR) to 47 μm (minimum LFR). As it can be seen, there is an atypical behaviour in the influence of LFR on D10, what can be easily observed if comparing both Figures 9a and 9b. As it happened in the case of D90 for the cannon, LFR did not offer a homogeneous response in every case. Nevertheless, the fact that it occurred in the highest and lowest droplet size could indicate some kind of atypical function in the nozzle for working out of its optimal working range, which made difficult to achieve a coherent response in

D10 and D90. D90 did follow, in the case of the hand nozzle, a regular trend with values comprised between 122 μm and 268 μm.

When comparing both nozzles, it can be seen that the cannon spout achieved lower droplet size in every case except for D10 in the highest LFR values, where it was higher than the hand nozzle. The reason behind this fact must be some kind of constructive particularity that differs in both nozzle types.

As to the statistical analysis, the two-way ANOVA results showed significant effect of LFR and AS ($p < 10^{-4}$), and as their interaction ($p < 10^{-4}$) on D50, D10 and D90 for every nozzle type (Fig. 9).

In order to quantitatively assess the influence of each one of the factors on the dependent droplet size variables (D50, D10 and D90), linear models were fitted for each one. This also allows for the prediction of these variables when setting both working parameters. The fitted models for the calculation of the D50 parameter for both the cannon-type and the hand-type nozzles from the LFR and AS are included in Table 3.

Table 3. Coefficients for the calculation of droplet size parameters — D50, D10, D90 — according to the fitted linear models.

		Adjusted model for every dependent variable $DV = \beta_0 + \beta_1 \times LFR + \beta_2 \times AS + \varepsilon$					
Dependent parameter		**Cannon nozzle**			**Hand nozzle**		
DV		β_0	β_1	β_2	β_0	β_1	β_2
D50	(μm)	184.690	8.397	−1.470	237.502	6.605	−2.206
D10	(μm)	85.927	3.838	−0.722	86.129	−2.487	−0.716
D90	(μm)	327.852	12.438	−2.322	466.669	22.657	−4.442

D50 models fit almost perfectly (R^2 = 0.963 and R^2 = 0.972 for both cannon and hand spout, respectively). This is not strange as the independent parameters considered (LFR and AS) are known to have a major influence on the droplet size.[64] Therefore, both models (that for cannon-type and that for hand-type nozzles) seem to explain almost every change in the D50 parameter, what has a major importance when advising applicators who have to control droplet size in their treatments, especially when the environmental wind speed is notorious, as in these situations droplet size is a major concern from the drift point of view.[13] The two fitted models are consistent with the data represented in both graphics (Fig. 9a and 9b), as LFR presented a positive coefficient and AS a negative one. When tested, both models presented a very accurate predictive response, what was expected from their high determination coefficients. It should be noticed that there are strong differences in the coefficients obtained in both nozzles, as LFR affected D50 more importantly in the case of the cannon (8.397 vs 6.605, Table 3) and the opposite occurred with the AS, which affected more importantly in the case of the hand (-2.206 vs -1.470, Table 3). In the case of the intercept, it was higher in the case of the hand (237.502) than in the cannon (184.690). This is not strange if taking into account that the D50 values reached were significantly higher in the spout of hand-type nozzle. In the case of the cannon, with lower droplet size than the hand, a D50 graph could be represented for the different combinations between LFR and AS (Fig.10), so that any technician/farmer could predict the minimum D50 achieved with any of them.

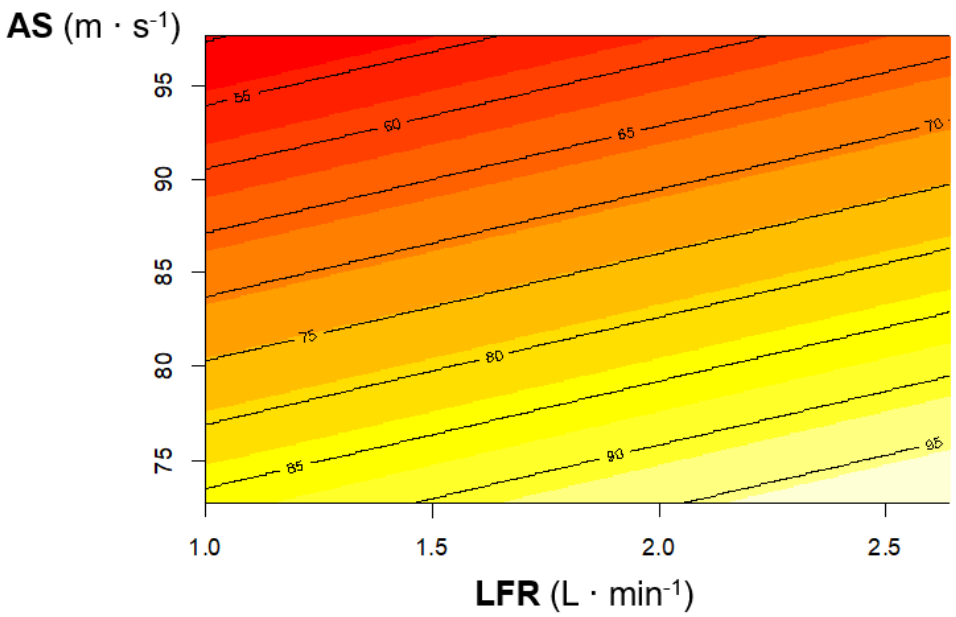


Figure 10. D50 graph in function of the most usual LFR (liquid flow rate) and AS (air speed) in the cannon nozzle.

The models for D10 parameter in function of the LFR and the AS are also presented in Table 3. As it happened with D50, there were very high determination coefficients (R^2 = 0.946 and R^2 = 0.903 for the cannon-type and hand-type nozzle, respectively). It was noticeable that LFR had a negative coefficient in the case of the hand spout (Tab. 3). This fact was in line with the unusual response observed in Figure 9b and previously commented. It can be also pointed out that the coefficients obtained in both cases for D10 (Tab. 3) were significantly lower than the ones obtained in the D50 model, as it is logical if taking into account that D10 values were much lower. Taking into account the affection of both evaluated parameters, excluding the sign, they differed in the case of the LFR, which affected more decisively in the case of the cannon, but the influence of AS was found to be very similar (Tab. 3). As a consequence, higher D10 values were obtained for the high AS in the cannon (Fig. 9a). The intercept was also very similar in both cases (Tab. 3).

In the case of D90 (Tab. 3), the determination coefficients, even still being very high, were not as much as in the previous cases (R^2 = 0.839 and R^2 = 0.974 for the cannon and hand nozzle, respectively). In this case, the determination coefficient for the cannon was slightly lower due to the fact that there was an atypical response in D90 in the case of the cannon (Fig. 9a), as previously explained. The coefficients for every independent variable had the convenient sign according to the general trend commented throughout the paper. The coefficients of the model, in this case, were both superior in the case of the hand nozzle, where they nearly doubled those obtained by the results of the cannon. This affection is well represented in Figure 9, where it can be seen that the values obtained by the hand nozzle in terms of D90 were significantly higher than those obtained by the cannon.

3.4 Droplet driftability.

Although there is no specific droplet size range that is liable to drift under every condition,[68,70,74,75,85] droplets with diameters smaller than 100 μm are considered highly driftable.[67,86] Many authors have proved the existence of a relationship between spray drift and droplet size linked to the V_{100} parameter.[57,58,72-77,87] Therefore, as to the driftability of the drops, V_{100} was calculated split by nozzles for the different combinations of LFR and AS tested during the trials (Fig. 11a and 11b). In general, it can be stated that the results show higher values for the cannon-type nozzle (Fig. 11a), as expected by the smaller droplet size generally obtained as compared to hand-type nozzle (Fig. 9a and 9b). It is interesting to remark that mean V_{100} values obtained by testing cannon-type nozzle were above 50% for any given LFR and AS configuration, what can be understood, if following the aforementioned criterion, as the possibility to have potentially drifted more than half of the spray in windy days.

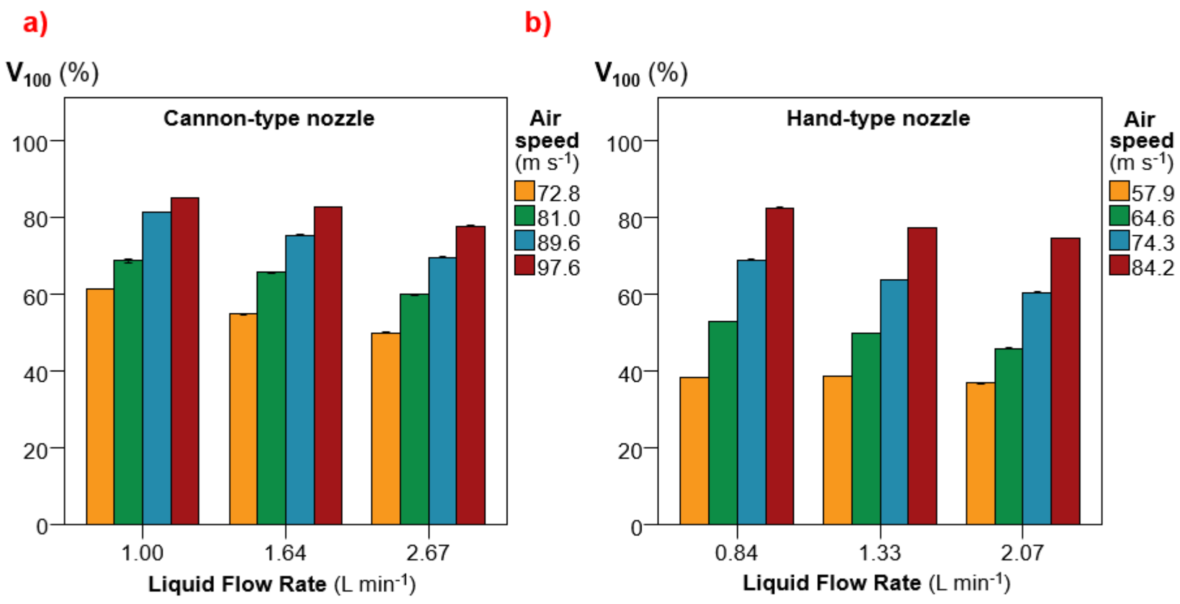


Figure 11. V_{100} parameter values derived from the combination of different AFR and AS in a) cannon-type nozzle and b) hand-type nozzle. The error bars show the SE.

As it can be seen in both Figures 11a and 11b, the V_{100} values obtained in both nozzles were very high, especially if taking into account that the hydraulic hollow-cone nozzles usually generate much lower V_{100}. In fact, the reference values for this nozzles (ATR Lilac operated at 0.7 MPa pressure) are 23.1%.[49,88] In the present study, every single value obtained was much higher than the reference value, as the minimum V_{100} value obtained was 36% for the maximum LFR with the minimum AS in the hand nozzle. In this sense, the values ranged from 50% to 86% (Fig. 11a) in the cannon nozzle and from 36% to 83% in the hand (Fig. 11b). It can also be checked that the cannon spout is more likely to produce high drift rates for having higher V_{100} values than the hand-type nozzle. This is very relevant in practice because this cannon is responsible for spraying the row which is farther from the sprayer, as previously explained (Fig. 3a), with its droplets being more exposed to the effect of the environmental wind. The longer distance combined with the smaller droplet size is a suitable combination to have an important part of the spray lost before reaching its target, causing in addition an asymmetrical deposition pattern, as one side will be sprayed with the hand and the other one with the cannon.

If comparing the different configurations available for the farmers, it can be easily observed that there can be important differences in terms of driftability. Thus, there is the possibility to nearly halve the driftable portion of the spray (Fig. 11), according to the formula proposed by van de Zande et al.,[88] in which the drift reduction percentage between two sprays is directly proportional to the reduction in the V_{100} parameter.

The cumulative sprayed volume curves, obtained in both type of nozzles by testing the more drift prone configuration and the less drift prone configuration, compared with American Society of Agricultural and Biological Engineers (ASABE) nozzles classifications (ASABE S572.1)[89] (Fig. 12) showed that an appropriate selection of pneumatic sprayer operational parameters, namely LFR and AS, allows to move from very fine (VF) to fine (F) spray quality.

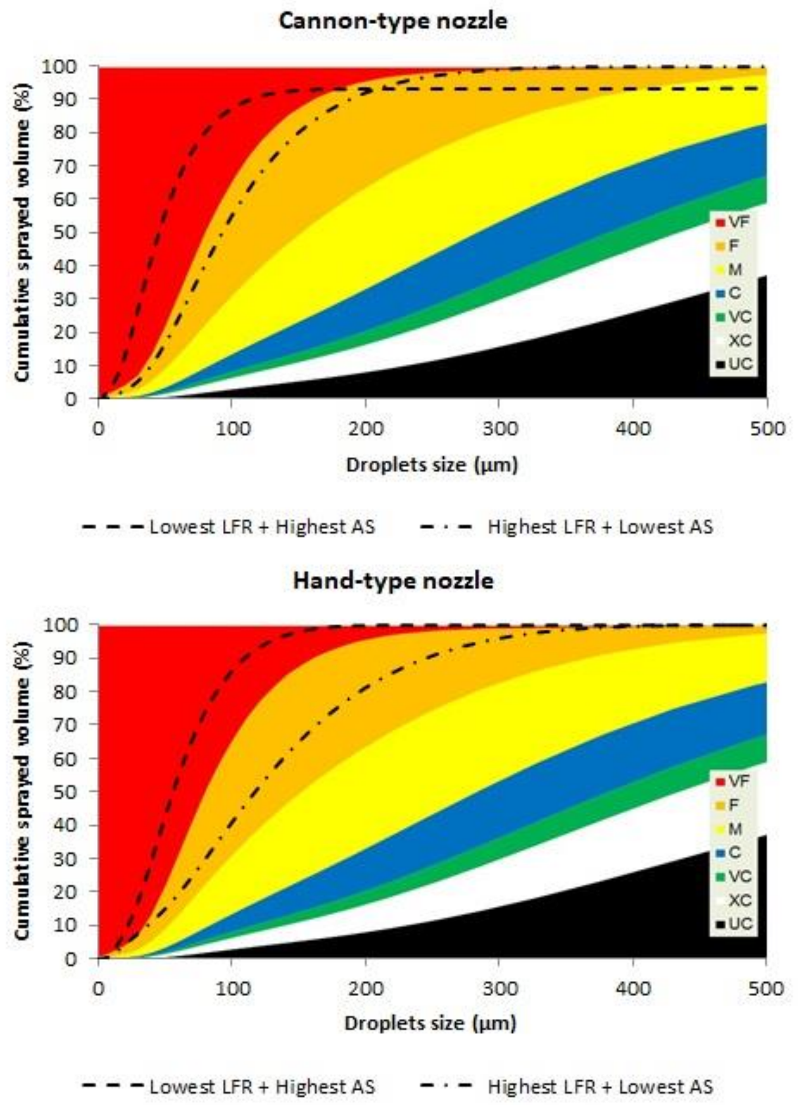


Figure 12. Cumulate sprayed volume curves as a functions of droplets size measured by Malvern Spraytec system for spray jet generated by: hand-type nozzle, and cannon type nozzle. In both graphs the configurations' curves deriving from the combinations of i) lowest LFR and highest AS, and ii) highest LFR and lowest AS were presented. Hand-type nozzle: 0.84 and 2.07 L min^{-1} respectively lowest and highest LFR, and 57.9 and 84.2 m s^{-1} respectively the lowest and highest AS. Cannon-type nozzle: 1.00 and 2.67 L min^{-1} respectively lowest and highest LFR, and 72.8 and 97.6 m s^{-1} respectively the lowest and highest AS. Furthermore was provided the comparison with ASABE classification: VF = very fine; F = fine; M = medium; C = coarse; VC = very coarse; XC = extremely coarse; UC = ultra-coarse/unclassified.[89]

Thus, at the time of application, the selection of the lowest LFR along with the highest AS allowed for the generation of very fine (VF = VMD < 100μm)[89] spray quality characterized by VMD of 50 μm for cannon-type nozzle and by VMD of 61 μm for the hand-type nozzle (Fig. 9). On the contrary the selection of the highest LFR combined with the lowest AS gave droplets that moved towards fine (F = VMD 100 – 175 μm)[89] spray quality in the classification, characterized by higher VMD: equal to 100 μm for the cannon-type nozzle and 126 μm for hand-type nozzle (Fig. 9). Even when the hand-type nozzle generated averagely larger droplets than the cannon-type (Fig. 9), the spray quality produced by both of them, for the same tested configuration, was very similar (Fig. 12). In practice, no substantial difference in prospective coverage of the leaves and fruit, could be noted between both nozzle types.

On the other hand, the possibility to increase the droplet size at the time of application allows to enhance the retention for direct spray on target (e.g. for contact-acting fungicides and insecticides where usually the fine (F) spray quality is recommended), improving at the same time the spray performance and efficacy, as reducing spray drift leads, necessarily, to an increase in the spray proportion that reaches the target canopy, acting over the pest or disease.[22,23,89] However, when a very fine spray quality is suggested and the environmental conditions are favourable, the AS increase could allow the applicator to accomplish the application aim.

In hydraulic nozzles, the four major factors affecting droplet size are: nozzle type and size, spraying pressure and spray pattern type.[49,79,88-90] In accordance to the ASABE classification generally the smallest droplet sizes are produced by hollow-cone nozzles, the most widespread for orchard and vineyard applications.[49] Generally, the hollow-cone nozzle in accordance to spray pressure variation and nozzle size selection produce droplets that vary from VF to F spray quality, with some exception in treatments with low pressure (unusual) that can reach the Medium (M) category. A similar result can be achieved, in terms of classification category, with pneumatic nozzles, according to the present study. Nevertheless, pneumatic spraying tends to generate more small droplets (higher V_{100}) than hydraulic ones and, therefore, it can be considered more susceptible to drift.

In any case, the possibility to predict the spray driftability as a consequence of the droplet size by simply adjusting the operational parameters, LFR and AS, is a very important opportunity for both farmers and technicians to match the environmental requirements, balancing at the same time the treatment specifications for every spray application while using pneumatic spraying in vineyards. In this way, correlations between VMD, the parameter most usually employed to classify nozzles based on spray quality, and V_{100}, parameter that mainly explain the relationship between the drift and the droplet size was determined for both nozzles separately. Very significant correlations between D50 and V_{100} parameters for both nozzles were found (Fig. 13a and 13b).

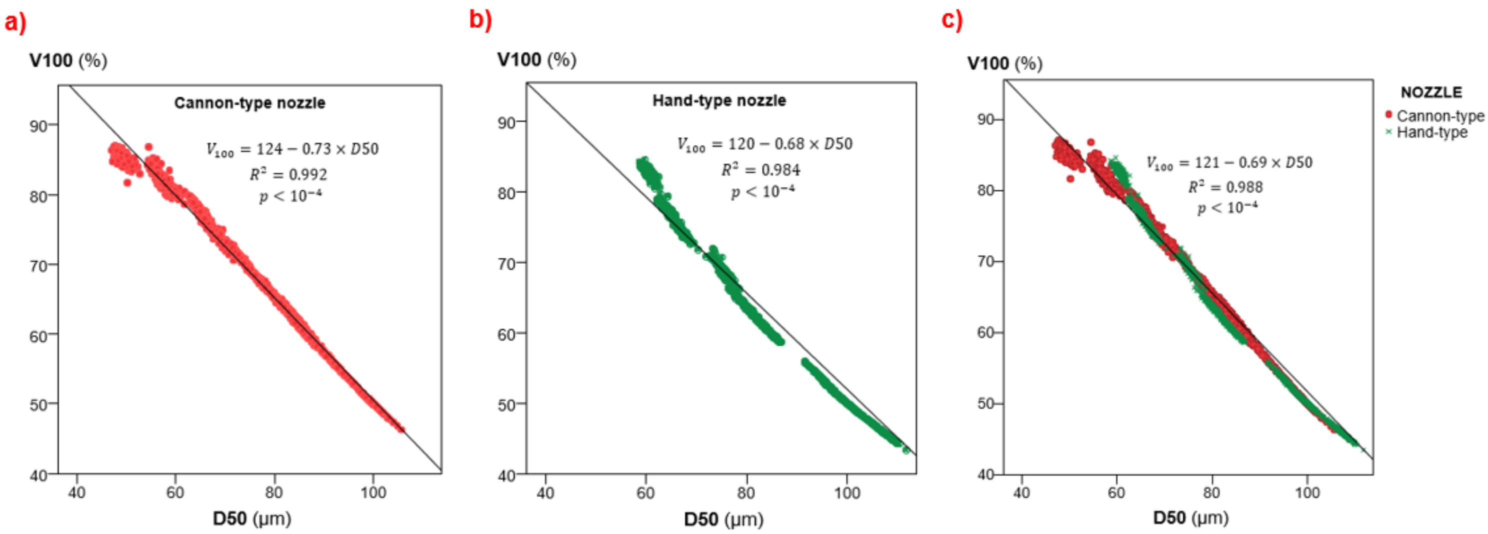


Figure 13. Linear correlations between D50 and V_{100} parameters for a) the cannon-type nozzle, b) the hand-type nozzle, and c) both nozzles combined.

It is noticeable that the determination coefficients were very high in both cases ($R^2 = 0.992$ for the cannon-type nozzle and 0.984 for the hand-type nozzle, Figure 13). In addition, the regression lines were very similar in slope in both cases, with coefficients of −0.73 and −0.68 respectively for cannon-type and hand-type nozzles (Fig. 13a and 13b). The intercept (x = 0) was also very similar in both cases. Therefore, these results revealed that the regressions obtained were valid independently of the pneumatic spout considered. As it was previously seen, the two nozzles evaluated presented different values in every single studied dependent variable, as they were not affected in the same way by the factors considered (Fig. 9 and 11). Nevertheless, when studying the relationship between D50 and V_{100}, which could lead to predict the driftable spray portion of a given pneumatic nozzle, there is a very similar trend (Fig. 13a and 13b). This fact suggests that a unique regression line, showed in Figure 13c which combines both nozzle types, could be used to predict the driftability of the whole pneumatic sprayer. This affirmation will be validated in future studies, as it needs to be tested with more spout types to set an universal drift prediction reference line for pneumatic spraying. The two main nozzles used in pneumatic spraying in vineyards, evaluated in this study, showed to have their V_{100} accurately estimated by the well-fitted models proposed for D50 (Tab. 3) and the regression curves obtained for V_{100} (Fig. 13).

3.5 Droplet homogeneity

The results about the droplet homogeneity, indicated by Relative Span Factor (RSF) parameter, showed to adopt different values in both nozzles for the selected combinations of LFR and AS (Fig. 14a and 14b). As it can be seen, in general, the cannon nozzle produced a higher homogeneity for having a lower RSF (1.59 vs 1.71 of the hand-type nozzle). Nevertheless, there were several atypical points (outliers) that can be observed in the graph (Fig. 8e), possibly due to unusual coarse droplets produced in some particular cases.

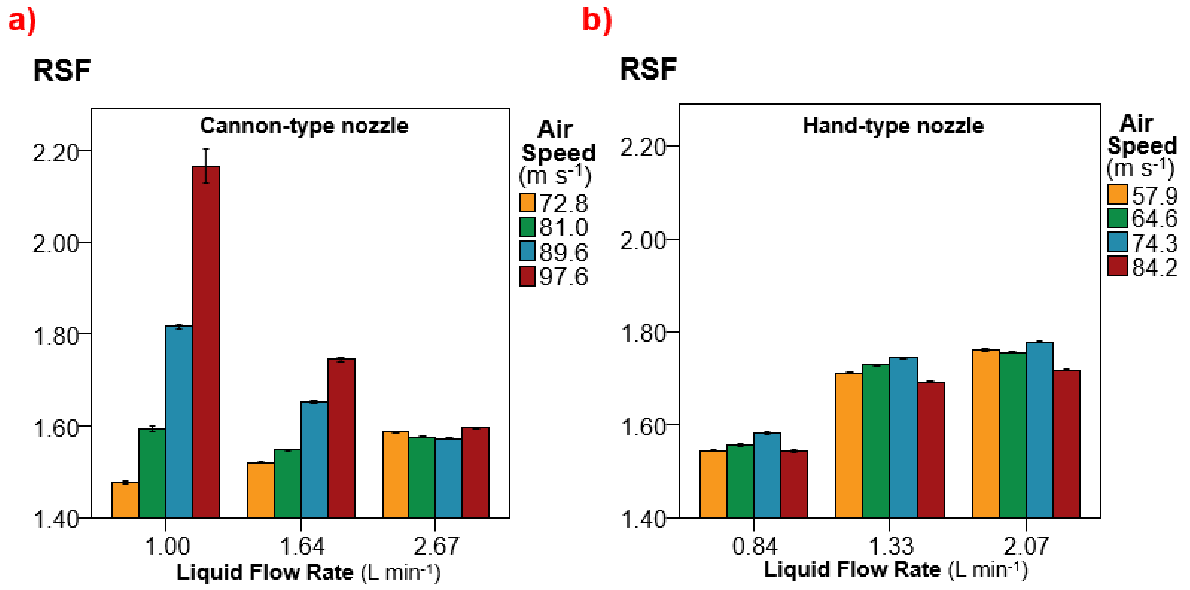


Figure 14. RSPAN Factor (RSF) values derived from the combination of different LFR and AS in a) cannon-type nozzle and b) hand-type nozzle. Error bars show the SE.

As it can be seen, the spray homogeneity did not vary much in any of the studied nozzles / parameters, with most values ranging from 1.50 to 1.70 in the cannon and from 1.55 to 1.80 in the hand nozzle. The ANOVA test showed statistically significant effect of every studied variable ($p < 10^{-4}$) and their interaction ($p < 10^{-4}$) on RSF, but unlike the case of the droplet size parameters, clear increase trends were not found for this parameter in any nozzle. Thus, in the case of the cannon, a superlative heterogeneity (RSF = 2.17) was shown for the combination between minimum LFR and maximum AS, i. e., for the smallest droplet size spectra (RSF = 1.48) (Fig. 14a and 9a), while the highest homogeneity was also shown for the minimum LFR value combined, in this case, with the minimum AS. In general, in cannon-type nozzle, the maximum homogeneity (given by the lowest RSF) was found for the minimum AS values, existing some evidence that high ones result in higher heterogeneity (Fig. 14a). The LFR did not seem to follow a clear trend in this nozzle type.

As to the hand spout, the minimum RSF values (higher homogeneity) were found in the minimum LFR value, whilst the medium and high values gave more important heterogeneity (Fig. 14b). In this case, AS did not show a clear trend on RSF, only a decrease in this parameter for the highest AS value for every LFR configuration. On the other hand, and as it was mentioned, LFR did show a clear trend to increase RSF. In general, no practical advice can be given to farmers to increase droplet homogeneity, but in every case RSF values are not alarmingly high, except for the aforementioned case in the cannon spout.

4 CONCLUSIONS

The main factors affecting droplet size in pneumatic spraying, LFR and AS, were combined to check their influence on the droplets size spectra, homogeneity and driftability during droplets generation process. It was shown that these factors have major influence on every evaluated parameter and, therefore, they are enough by themselves to accurately explain most of their variations by fitting linear models with very high determination coefficients. It was seen that pneumatic spraying produced very fine droplets whose D50 parameter rarely reached the value of 100 μm. These values were, generally, lower than those provided by hydraulic nozzles, especially regarding the lower diameter spray fraction. The droplet classification according the ASABE S572 Standard, on the other hand, was similar, giving a fine 'F' droplet size in the case of the biggest drops. Some strange trends were found in the extreme parameters (D10 and D90) depending on the nozzle type, what had influence on the fitted models. The droplet driftability was higher in the case of the cannon spout, for having a lower droplet size, what can have a major impact not only on the efficiency of the application, but also on its efficacy, as the required spray portion to control the disease agent could not reach the target canopy. The relationship between D50 and V_{100} was determined, being very significant and similar in both nozzle types, what could lead to use the regression curve to accurately predict spray drift as a consequence of the droplet size in pneumatic spraying. If better results in terms of drift reduction are wanted, additional strategies need to be implemented, as the droplet driftability always resulted high for every tested combination of parameters. The droplet homogeneity was similar in both cases, but did not follow regular trends and was more constant in the case of the hand spout, but generally lower in the cannon nozzle.

5. ACKNOWLEDGEMENTS

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