A Brief Review of Nozzle Spray Drop Size Measurement Techniques

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2021 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor) | 978-1-6654-0533-1/21/$31.00 ©2021 IEEE | DOI: 10.1109/MetroAgriFor52389.2021.9628757

***Abstract*—Spray application of Plant Protection Products (PPP) is affected by many factors, among which drop size distribution is the most important. In fact, the correct spray spectrum ensures the required dose on the target, minimizes off-target losses due to evaporation, drift and run-off, and enhances the operator safety in terms of inhalation and dermal exposure. This study reports a brief review of the most common drop size measurement techniques present in the literature.**

Keywords—nozzle testing, drop pulverization, drop size distribution, image processing, laser diffraction, PDPA, Water Sensitive Paper.

I. INTRODUCTION

European Directive 2009/128/EC [1] recognizes that handling and application of PPPs in agriculture can cause undesirable effects on humans and the environment. Worker's exposure and environmental effects of pesticides are affected by a lot of factors, among which it can be mentioned the active substance and its formulation, the packaging, the task to be performed, the amount of pesticide to be handled, the duration of the activity, the Personal Protective Equipment (PPE) worn, the type of machinery and its maintenance status, the target structure (canopy, fruit, leaves, ground), the environmental conditions (temperature, relative humidity, wind speed), and, above all, the operator's expertise. The assessment and quantification of pesticide impact require to choose proper variables and suitable models [2], [3].

For spray liquid applications, drop size spectrum plays a key role as it affects biological efficacy of a phytosanitary treatment [4], environmental pollution [5], [6], and operator safety [7], [8], [9]. According to the International Standard ISO 25358 [10], the droplet size spectrum can be measured with any non-intrusive measuring system, appropriate for the range of droplet size and velocity. Examples of non-intrusive systems are Phase Doppler Particle Analyzers (PDPA) [11], laser diffraction [12], [13], or imaging principles [14], [15].

Intrusive measurement techniques are also widespread, among which it can be mentioned the liquid immersion method [16], [17] and the use of Water Sensitive Papers (WSP) [18], [19], [20].

The aforesaid techniques, either intrusive and non-intrusive, used for the evaluation of spray droplet size, allow measurements with different degrees of uncertainty and therefore fully fall within the scope of the metrology, which refers to quality assurance methods to improve measurements accuracy, precision, and traceability.

A. Contribution

Each measurement method produces results significantly different, depending on measuring protocol, settings and type of measuring equipment. A study of [21] aimed at comparing four different methods for measuring droplet size distributions (image analysis technique, stroboscopic imaging method developed in-house, PDPA, and laser diffraction), reports that the larger the droplets, the bigger the differences between the results obtained by the different methods. Even considering reference nozzles, pre-screened for laboratory testing, wide range of absolute measurements may be obtained [22].

In this study, after defining some mean characteristic diameters, useful for a basic description of drop populations, a brief review of the most common methods, both intrusive and non-intrusive, is presented.

II. STATISTICS ON DROP SIZE DISTRIBUTION

Each nozzle, depending on its mechanical construction, liquid properties, and working pressure, produces a range of drop sizes, which can be described by means of several characteristic diameters and theoretical distributions.

Under the hypothesis that all the droplets in the spray are spheres, and knowing the individual diameter of a significant sample of droplets (about 2000), some mean characteristic diameters of the distribution may be calculated with (1):

$$D_{pq}^{p-q} = \frac{\sum_{i=1}^{N} D_i^p}{\sum_{i=1}^{N} D_i^q}, \tag{1}$$

where p and q are indices describing the moments of the drop size distribution and N is the number of drops in the sample. The moment of order k about the origin of a statistical variable assuming raw scores X_i is defined as:

$$M_k = \frac{1}{N} \sum_{i=1}^{N} X_i^k . \tag{2}$$

This research was financed by the University of Catania with the research project "Contributo della meccanica agraria e delle costruzioni rurali per il miglioramento della sostenibilità delle produzioni agricole, zootecniche e agro-industriali. WP1: Impiego sostenibile di macchine irroratrici in serra e in pieno campo", Linea di intervento 2-dotazione ordinaria per attività istituzionali dei dipartimenti-2016-18-II annualità.

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The most used mean diameters in agricultural spray applications are:

- D_{10} (p=1, q=0): Arithmetic mean diameter;
- D_{20} (p=2, q=0): Surface mean diameter;
- D_{30} (p=3, q=0): Volume mean diameter;
- D_{32} (p=3, q=2): Sauter mean diameter.

Other diameters referring to the volume transferred by the droplets are:

- $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$: 10 %, 50 % or 90% of the total volume of liquid sprayed is made up of drops with diameters smaller or equal to these values, respectively.

Finally, a diameter referring to the number of droplets is the Number Median Diameter (NMD):

- $D_{n0.5}$ (NMD): divides droplet spectrum so that 50 % of the total number of droplets are of lesser and 50 % are of greater diameter to this value.

Volumetric diameters, especially $D_{v0.5}$ (also known as VMD, Volume Median Diameter), are used for nozzle classification purposes according to [10].

All mean and characteristic diameters can be calculated by knowing the theoretical drop size distribution function. Conversely, a theoretical distribution can be fitted to data collected from experimental measurements. The most used distribution functions to describe agricultural sprays are the log-normal, the gamma, and the Rosin-Rammler.

The log-normal number density distribution, with parameters σ_g and D_g, is (3):

$$f_0(D) = \frac{1}{\sqrt{2\pi}\ln\sigma_g D} e^{-\frac{1}{2}\left(\frac{\ln D - \ln D_g}{\ln\sigma_g}\right)^2}. \tag{3}$$

The gamma number density distribution, with parameters α and β, is (4):

$$f_0(D) = \frac{1}{\beta^\alpha \Gamma(\alpha)} D^{\alpha-1} e^{-D/\beta}. \tag{4}$$

The Rosin-Rammler distribution, with parameters n and D_m, is usually given as volume density (5):

$$f_3(D) = \frac{n}{D_m}\left(\frac{D}{D_m}\right)^{n-1} e^{-\left(\frac{D}{D_m}\right)^n}. \tag{5}$$

It is the default function for the Malvern analyzer, the most common laser diffraction instrument in use today.

III. Intrusive Measurement Methods

A. Water Sensitive Papers

WSPs are semi-rigid papers, with one side covered with a yellow film that turns deep blue in contact with water.

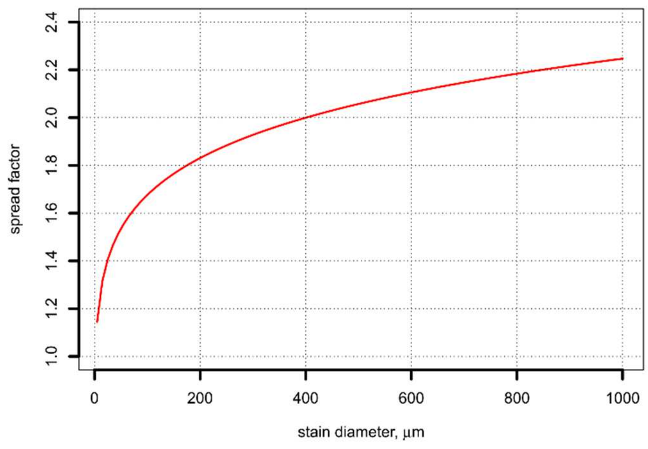

Fig. 1. Spread factor on WSP (adapted from [18]). Values refers to water at 20 °C and about 40 % relative humidity, and droplets reaching the WSP at sedimentation velocity.

Due to their quickly response in field, from over 30 years ago WSPs are usually used to evaluate the percentage of covered surface and the droplet density (number of droplets per unit surface).

Several studies have been carried out to determine the characteristic diameters of the spray by analysing the drop stains on WSPs by means of image analysis techniques, using commercial or freeware software, some of which implement dedicated functions or are App for smartphone [23]. Nevertheless, when the WSPs are used for this purpose, it should be considered that it is not possible to detect droplets with diameter less than 50 µm, they automatically turn to blue under high humidity conditions (>85 %), the achievable accuracy is reduced as the covered surface increases, the droplet spread varies with the physical property of the spray liquid (surface tension, angle of impact, energy of impact, pH, temperature) [19]. In fact, these parameters have influence on the spread factor (ratio between stain diameter and drop diameter) that must be known and verified, as recommended by the developer in technical data sheet [18] (Fig. 1).

Considering these variabilities and the comparison of the target supports carried out by [25], it can be concluded that the WSPs should be reserved for qualitative observations. However, [26] found that the analysis of WSPs could allow both to measure the unit deposit and to characterize droplet spectra even with high values of percentage of covered surface when the spray distribution is known.

B. Liquid immersion method

In the liquid immersion method, droplets are collected on a glass plate coated with lightly viscose liquids, such as Vaseline, light mineral oil, silicone oil, which prevent evaporation and condensation. The low viscosity and hydrophobic nature of the oil cause drops to form spherical shapes (Fig. 2). They are immediately photographed at high magnification or observed with a microscope, allowing drop counting and size measurement. Using a camera and microscope, this technique does not require calibration or special equipment [27].

The method is cost-efficient and easy to use, and it is one of the most fundamental mechanical techniques to measure droplet sizes and their distributions. It is also adopted to confirm adequacy of the data obtained by optical methods, such as the Phase-Doppler Particle Analyzer [28].

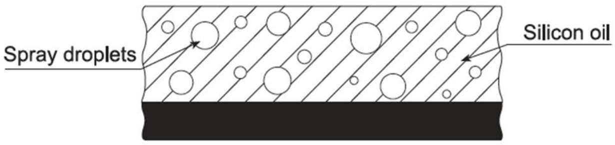

Fig. 2. Illustration of immersion sampling method (https://www.ikeuchi.eu/news/measurement-of-droplet-size/).

However, ultra-fine droplets, too small to break the surface tension of the oil, will evaporate. Thus, the droplet sizes of the fine and ultra-fine fog determined by the immersion sampling method are larger than the actual values.

IV. Non-Intrusive Measurement Methods

A. General aspects

The measurements of spray droplets in flight through their electromagnetic scattering is a powerful non-invasive method widely used in several scientific and technical fields. In this regard, there are two classes of problems involving electromagnetic scattering by small particles: i) the direct problem and ii) the inverse problem. The direct problem treats about the calculation or measurement of the scattering created by a known and well-defined system. Conversely, the inverse problem concerns the analysis of a system, such as the characterization of spray droplets, applying scattering data collected from laboratory measurements.

The analysis of spray droplets by the electromagnetic scattering, both spatial or temporal, is practically performed by various devices on the market based on a laser light beam through which the spray droplets are discharged (Fig. 3). The spatial analysis (to obtain the number of droplets per cubic meter) is carried out by quantifying contemporaneously the droplets within a defined space, inside the laser beam. Conversely, the temporal analysis (to obtain the number of droplets per cubic meter per second) is performed by measuring droplet flux crossing a defined sampling volume over a set time.

B. Laser diffraction

This method has been largely employed for pesticide spray droplet analysis [29], [30], [31], [32]. The laser beam is crossed by the spray within the working zone of a lens and a multi-element detector, placed in its focal plane, gathers the light diffracted by the spray droplets, considering that either the angle and the intensity of scattering are strictly connected to the droplet size (Fig. 4).


Fig. 3. Electromagnetic scattering (in red) produced by water droplets crossing a laser beam.

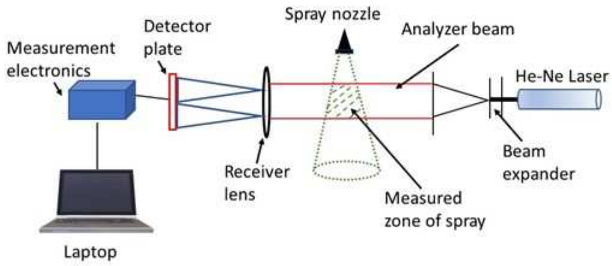

Fig. 4. Laser diffraction analyzer.

In particular, the scattering angle increases as droplet size decreases, whereas the scattering intensity reduces as droplet volume increases, that is, small particles scatter at wider angles but with low intensity whereas great droplets scatter light at narrow angles with high intensity [33].

The measurement of the size distribution of spray droplets is based on Lorenz-Mie theory, in far-field conditions, which provides an accurate solution for this type of calculation from light scattering data [34]. This measurement principle can be understood considering that the droplets scatter the incident light, generating, due to the wave interference, a central forward scattering lobe flanked by a succession of lateral lobes of decreasing amplitude. Fig. 5 reports an example of the scattering created inside a plane wave with wavelength λ=0.63 µm by a circular particle with diameter 1.26 µm and refractive index m=1.33.

The lobes constitute a diffraction pattern in which the amplitude and location of each of them depends on the ratio between the wavelength of the incident field and the diameter of the scattering spherical particle. If the spray were made up of droplets all the same size, the diffraction patterns would be superimposed giving rise to a macroscopic diffraction pattern which would allow the common particle size to be calculated with high precision. Conversely, considering a spray formed by droplets of different sizes (polydisperse distribution), the density function $n = n(r)$ is introduced, which represents the number n of droplets, having radius between r and $r + dr$, per volume unit. The aim is the measurement of this function $n(r)$.

In a polydisperse spray, droplets of different sizes generate different diffraction patterns which are composed in the overall intensity in a weighted way according to the $n(r)$ function. In short, an incident radiation of intensity I_0 and wavelength λ passing through a spray composed of droplets with relative refractive index m and distributed according to the function $n = n(r)$, generates, in far-field conditions, a diffuse intensity profile expressed by:

$$I_s(\Omega,\lambda,m) = I_0 \int_0^{\infty} C_{sca}(\Omega,\lambda,r,m) \cdot n(r)dr \,, \tag{6}$$

where Ω is the solid angle towards which the field has been scattered and C_{sca} is the differential scattering section (which contains the information on the diffraction pattern).

In equation (6) I_s is measured by the multi-element detector, C_{sca} is evaluated by the Lorenz-Mie theory, $n = n(r)$ is the unknown function, that can be solved by referring to the Fredholm integral equation of the first kind:

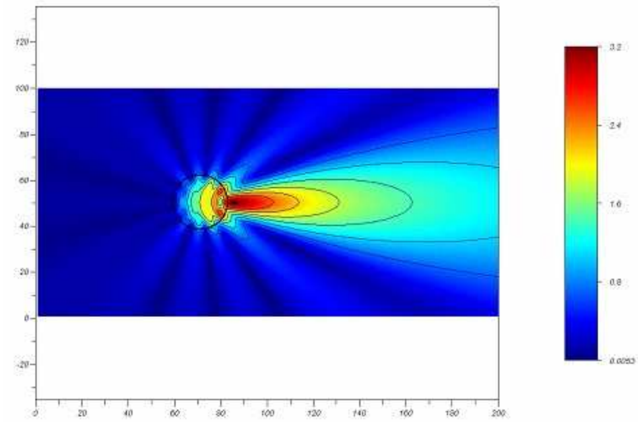

Fig. 5. Electric field diffused by a circular particle with diameter 1.26 μm and refractive index m=1.33 hit by a plane wave of wavelength λ=0.63 μm. The black circle is the perimeter of the particle. The color represents the amplitude of the total electric field (V/m) according to the chromatic scale on the side.

$$f(x) = \int_a^b K(x,t)\phi(t)dt \,, \qquad (7)$$

where $f(x)$ is a known function, $K(x, t)$ is the known "kernel" function, and $\phi(t)$ the function to find.

C. Phase Doppler Particle Analyzer

The system is formed by an unbroken laser, which is split into two beams by means of a beam-splitter and lenses. These beams intersect so producing interference fringes [35], [36]. The method measures droplets one by one and then it is relatively less influenced by droplet density. Furthermore, it can measure droplet velocity simultaneously. Really, the passage of a droplet in the intersection zone of the two beams produces a diffused light modulated in space and time. The spatial frequency is proportional to the size of the droplet, whereas the temporal one to its speed (Fig. 6).

The light diffusion angle is usually 30° and three detectors collect the scattered light from the individual particles that pass through the sample volume, assessing their phase shifts. An ad hoc software, capable of providing real-time displays of droplets spectra, constantly evaluates and adjusts the sample volume to be analyzed, which is affected by the probability that larger droplets cross the edge producing an inadequate signal. The system can evaluate a range of droplet diameters from 1 to 8000 μm.

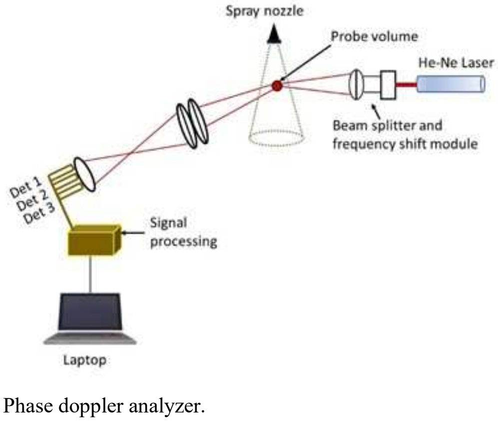

Fig. 6. Phase doppler analyzer.

D. High speed imaging

The rapid development of imaging equipment and image processing capabilities makes high speed imaging an ever easier and cheaper alternative to scattering- or diffraction-based measurement methods for low density sprays as agricultural sprays. In [21] the Authors propose a measuring system consisting of a laser, a magnification lens, a digital camera, and a specific software. The laser illuminates a screen that is photographed such that droplets show up as dark spots against a bright background. The digital camera after a proper magnification, captures two snapshots of the particles. The image analysis software allows to identify the in-focus droplets in the image and determine their sizes and velocities. This methodology is currently known as shadowgraph technique [37], [38] and some companies are now providing shadowgraph tools equipped with laser to study the behavior of sprayer nozzles.

A similar system is used in [15]. A camera coupled with high magnification optics provides a field of view with spatial resolution of 9.7 μm/pixel, allowing to measure droplets with a diameter ranging from 40 to 3500 μm. A custom-made LED array is placed in front of the camera. Using the double exposure mode of the camera, two consecutive images are acquired so to allow the computation of both droplet size and velocities.

In both systems, to ensure an accurate sizing, a critical aspect is the depth of field, the rejection of out-of-focus particles, and the background elimination, all aspects managed via appropriate software procedures.

V. Conclusion

Several methods and techniques are applied to measure drop size distribution of agricultural nozzle sprays. Each sampling technique, spatial or temporal, and measurement method produce different results. In addition, the results are affected by type of nozzle, capacity, spraying pressure and liquid properties. The measuring technique should be appropriate for the range of drop size and velocities. Due to these differences, the ISO standard [10] recommends basing nozzle classification on the comparison of the spray droplet size spectrum produced by nozzle under certain operating conditions with reference spectra produced by reference nozzles under standard conditions.

The standard ISO 25358 [10] recommends measuring droplet size spectrum with non-intrusive systems, and from this point of view the PDPA is the most widespread system, thanks also to its ability to measure the droplet velocity at the same time. On the other hand, the liquid immersion method is efficient, easy to use, and does not require complex or high-cost equipment. In addition, although the non-contact optical method provides much information on droplet size measurement, it requires occasional confirmations to ascertain the measurement accuracy and the immersion liquid method is the classic calibration for the optical method [28].

References

[1] European Union, "Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides," Off. J. L 309, pp. 71–86, 24/11/2009.

[2] O. Roussel, A. Cavelier, and H.M.G. der Werf, "Adaptation and use of a fuzzy expert system to assess the environmental effect of pesticides applied to field crops," Agriculture, Ecosystems and Environment, pp. 143-158, 80, 2000.

[3] H.M.G. der Werf, "Assessing the impact of the pesticides on the environment," Agriculture, Ecosystems and Environment, pp. 81-96, 60, 1996.

[4] G.A. Matthews, "How was the pesticide applied?," Crop Protection, 23, pp. 651-653, 2004.

[5] N. De Cock, M. Massinon, S.O.T. Salah, and F. Lebeau, "Investigation on optimal spray properties for ground based agricultural applications using deposition and retention models," Biosystems Engineering, 162, pp. 99-111, 2017.

[6] S. Chen, Y. Lan, Z. Zhou, F. Ouyang, G. Wang, X. Huang, X. Deng, and S. Cheng, "Effect of droplet size parameters on droplet deposition and drift of aerial spraying by using plant protection UAV," Agronomy, 10, 195, 2020.

[7] D. Nuyttens, P. Braekman, S. Windey, and B. Sonck, "Potential dermal pesticide exposure affected by greenhouse spray application technique," Pest Manag. Sci., 65, pp. 781-790, 2009.

[8] L. Cao, H. Zhang, F. Li, Z. Zhou, W. Wang, D. Ma, L. Yang, P. Zhou, and Q. Huang, "Potential dermal and inhalation exposure to imidacloprid and risk assessment among applicators during treatment in cotton field in China,", Science of the Total Environment, 624, pp. 1195-1201, 2018.

[9] E. Cerruto, G. Manetto, F. Santoro, and S. Pascuzzi, "Operator dermal exposure to pesticides in tomato and strawberry greenhouses from hand-held sprayers," Sustainability, 10, 2273, 2018.

[10] ISO (International Organization for Standardization), "ISO 25358, Crop protection equipment — Droplet-size spectra from atomizers — Measurement and classification," ISO: Geneva, Switzerland, 2018. Available online: https://www.iso.org/standard/66412.html (accessed on 14 June 2021).

[11] D. Nuyttens, K. Baetens, M. De Schampheleire, and B. Sonck, "PDPA laser based characterisation of agricultural sprays," Agricultural Engineering International: the CIGR Ejournal. Manuscript PM 06 024. Vol. VIII. December, 2006.

[12] B.K. Fritz and W.C. Hoffmann, "Measuring spray droplet size from agricultural nozzles using laser diffraction," J. Vis. Exp. (115), e54533, 2016.

[13] J. Liao, X. Luo, P. Wang, Z. Zhou, C.C. O'Donnell, Y. Zang, and A.J. Hewitt, "Analysis of the influence of different parameters on droplet characteristics and droplet size classification categories for air induction nozzle," Agronomy, 10, 256, 2020.

[14] M. Massinon and F. Lebeau, "Experimental method for the assessment of agricultural spray retention based on high-speed imaging of drop impact on a synthetic superhydrophobic surface," Biosystems Engineering, 112, pp. 56-64, 2012.

[15] N. De Cock, M. Massinon, D. Nuyttens, D. Dekeyser, and F. Lebeau, "Measurements of reference ISO nozzles by high-speed imaging," Crop Protection, 89, pp. 105-115, 2016.

[16] ISO (International Organization for Standardization), "ISO 5682-1, Equipment for crop protection — Spraying equipment — Part 1: Test methods for sprayer nozzles," ISO: Geneva, Switzerland, 2017. Available online: https://www.iso.org/standard/60053.html (accessed on 16 May 2021).

[17] D. Longo, G. Manetto, R. Papa, and E. Cerruto, "Design and construction of a low-cost test bench for testing agricultural spray nozzles," Applied Sciences, 10, 5221, 2020.

[18] Syngenta, "Water-sensitive paper for monitoring spray distribution", Technical data sheet, available at https://www.agroconsultasonline.com.ar//ticket.html/Water%20Sensitive%20Paper%20Syngenta%20Agro.pdf?op=d&ticket_id=2388&evento_id=4891 (accessed on 16 May 2021).

[19] M. Cunha, C. Carvalho, and A.R.S. Marcal, "Assessing the ability of image processing software to analyse spray quality on water-sensitive papers used as artificial targets, "Biosystems Engineering, 111, pp. 11-23, 2012.

[20] E. Cerruto, S. Failla, D. Longo, and G. Manetto, "Simulation of water sensitive papers for spray analysis," Agricultural Engineering International: the CIGR Ejournal, 18, pp. 22-29, 2016.

[21] R. Sijs, S. Kooij, H.J. Holterman, J. van de Zande, and D. Bonn, "Drop size measurement techniques for sprays: Comparison of image analysis, phase Doppler particle analysis, and laser diffraction," AIP Advances, 11, 015315, 2021.

[22] D. Nuyttens, K. Baetens, M. De Schampheleire, and B. Sonck, "Effect of nozzle type, size and pressure on spray droplet characteristics," Biosystems Engineering, 97, pp. 333-345, 2007.

[23] J. Connor Ferguson, R.G. Chechetto, C.C. O'Donnell, B.K. Fritz, W.C. Hoffmann, C.E. Coleman, B.S. Chauhan, S.W. Adkins, G.R. Kruger, and A.J. Hewitt, "Assessing a novel smartphone application – SnapCard, compared to five imaging systems to quantify droplet deposition on artificial collectors," Computers and Electronics in Agriculture, 128, pp. 193–198, 2016.

[24] J. Sánchez−Hermosilla and R. Medina, "Adaptive threshold for droplet spot analysis using water-sensitive paper," Applied Engineering in Agriculture, 20(5), pp. 547-551, 2004.

[25] A. Degré, O. Mostade, B. Huyghebaert, S. Tissot, and C. Debouche, "Comparison by image processing of target supports of spray droplets," Transactions of the ASAE, 44(2), pp. 217-222, 2001.

[26] E. Cerruto, G. Manetto, D. Longo, S. Failla, R. Papa, "A model to estimate the spray deposit by simulated water sensitive papers," Crop Protection, 124, 104861, 2019.

[27] G. Kathiravelu, T. Lucke, and P. Nichols, "Rain drop measurement techniques: A review," Water, 2016, 8, 29.

[28] T. Fujimatsu, M. Kito, and K. Kondo, "Droplet size measurement of liquid atomization by the immersion liquid method (droplet coalescence and solution into the immersion liquid)," WIT Transactions on Engineering Sciences, Vol. 82, 2014, WIT Press.

[29] J. Swithenbank, J.M. Beer, D.S. Taylor, D. Abbot, and G.C. Mc Reath, "Laser diagnostic technique for the measurement of droplet and particle size distribution," Progress in Astronautics and Aeronautics, 53, 1979.

[30] A.C Arnold, "Comparative droplet spectra for three different-angled flat fan nozzles," Crop Protection, 2, pp. 193-204, 1983.

[31] A.C. Arnold, "The dropsize of the spray from agricultural fan spray atomisers as determined by a Malvern and the Particle Measuring System (PMS) instrument," Atomisation and Spray Technology 3, pp. 155-167, 1987.

[32] J.H. Combellack and G.A. Matthews, "Droplet spectra measurements of fan and cone atomisers using a laser diffraction technique," Journal of Aerosol Science 12, pp. 529-540, 1981.

[33] G.A. Matthews, "Pesticide application methods," Blackwell Science Third Edition, 2000, London, UK.

[34] ISO (International Organization of Standardization), 2020. Particle size analysis — Laser diffraction methods. ISO 13320:2020. Geneva: International Organization for Standardization Publications; 2020. Available online: https://www.iso.org/obp/ui/#iso:std:iso:13320:en (accessed on 15/06/2021).

[35] W.D. Bachalo, M.J. Houser, and J.N. Smith, "Behaviour of sprays produced by pressure atomizers as measured using a phase-doppler instrument," Atomisation and Spray Technology 3, pp. 53-72, 1987.

[36] L. Lading and K. Andersen, "A covariance processor for velocity and size measurements," in: Laser Anemometry in Fluid Mechanics (eds R.J. Adrian and D.F.C. Durad), Vol. 4, pp 454-472, Springer-Verlag, Berlin, 1987.

[37] N. De Cock, M. Massinon, S. Ouled Taleb Salah, B.C.N Mercatoris, and F. Lebeau, "Droplet size distribution measurements of ISO nozzles by shadowgraphy method," Commun. Appl. Biol. Sci. 80, pp. 295-301, 2015.

[38] G. Castanet, P. Dunand, O. Caballina, and F. Lemoine, "High-speed shadow imagery to characterize the size and velocity of the secondary droplets produced by drop impacts onto a heated surface," Exp Fluids, 54, 1489, 2013.