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Nozzle spray quality and spray deposition in agricultural treatments

Salvatore Privitera
Doctor Scientiae

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Thesis submitted to the Agricultural Engineering Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

Adviser: Marconi R. Furtado Junior

Co-adviser: Giuseppe Ezio Manetto

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To myself,
for my determination
that pushed me beyond every obstacle.

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ABSTRACT

PRIVITERA, Salvatore, D.Sc., Universidade Federal de Viçosa, February, 2025. **Nozzle spray quality and spray deposition in agricultural treatments.** Adviser: Marconi Ribeiro Furtado Junior. Co-adviser: Giuseppe Ezio Manetto.

Within the current scenario of agriculture, Plant Protection Products (PPPs) have been recognized as one of the most effective and powerful tools for crop pest control, offering several benefits in controlling plant growth. However, improper handling of these products can inevitably lead to undesirable impacts on both human health and the surrounding environment. For this reason, it is required paying attention to several aspects during PPP application process, which will determine how effectively the crops are covered by the liquid mixture. Among these, the assessment of nozzle spray quality, evaluated in terms of droplet size spectrum, holds a significant role, as it has influence on the movement of the required dose to the target, on the unwanted off-target losses, as well as on the operator safety. In this context, the multidisciplinary research activities of this PhD thesis were focused on: (i) taking general understanding and reviewing the current available scientific literature regarding the most widespread techniques, both intrusive and non-intrusive, for droplet size measurement; (ii) evaluating the effects of image segmentation thresholding on droplet size measurement; (iii) comparing the performance of four droplet size measurements techniques employed for spray characterization, by measuring the droplet size spectrum produced by agricultural nozzles under identical operating conditions; (iv) studying the correlation between droplet diameters, foliar deposition on orange leaves and surface coverage measured on Water Sensitive Papers (WSPs) under laboratory conditions, so that allowing the development of a model capable of predicting foliar deposition in function of superficial coverage and droplet characteristic diameters; and (v) modelling the cumulative volume curves by using the logistic function, allowing to compute and forecast the volumetric diameters in a spray, as well as evaluate the effect of spray pressure on the model. Overall, the present research project has contributed to lay a valid base for an efficient PPP application, playing a fundamental role in increasing their benefits and driving farmers and researchers to better consolidate the state of knowledge about the optimal droplet size distribution and the resulting efficiency of the spray deposition process during phytosanitary treatments.

Keywords: plant protection product; nozzle; droplet size; surface coverage; deposit; digital image analysis; laser-based technology; spray characterization; spray modelling

RESUMO

PRIVITERA, Salvatore, D.Sc., Universidade Federal de Viçosa, fevereiro de 2025. **Qualidade da pulverização e deposição da pulverização em tratamentos agrícolas.** Orientador: Marconi Ribeiro Furtado Junior. Coorientador: Giuseppe Ezio Manetto.

No cenário atual da agricultura, os Produtos de Proteção de Plantas (PPPs) têm sido reconhecidos como uma das ferramentas mais eficazes e poderosas para o controle de pragas em plantações, oferecendo vários benefícios no controle do crescimento das plantas. No entanto, o manuseio inadequado desses produtos pode inevitavelmente levar a impactos indesejáveis na saúde humana e no meio ambiente. Por esse motivo, é necessário prestar atenção a vários aspectos durante o processo de aplicação de PPPs, que determinarão quão efetivamente as plantações são cobertas pela mistura líquida. Entre eles, a avaliação da qualidade da pulverização do bico, avaliada em termos de espectro de tamanho de gota, desempenha um papel significativo, pois influencia no movimento da dose necessária para o alvo, nas perdas indesejadas fora do alvo, bem como na segurança do operador. Nesse contexto, as atividades de pesquisa multidisciplinar desta tese de doutorado foram focadas em: (i) obter uma compreensão geral e revisar a literatura científica atual disponível sobre as técnicas mais difundidas, tanto intrusivas quanto não intrusivas, para medição do tamanho de gota; (ii) avaliar os efeitos do limiar de segmentação de imagem na medição do tamanho de gota; (iii) comparar o desempenho de quatro técnicas de medição de tamanho de gotas empregadas para caracterização de pulverização, medindo o espectro de tamanho de gotas produzido por bicos agrícolas sob condições operacionais idênticas; (iv) estudar a correlação entre diâmetros de gotas, deposição foliar em folhas de laranja e cobertura de superfície medida em Water Sensitive Papers (WSPs) em condições de laboratório, de modo a permitir o desenvolvimento de um modelo capaz de prever a deposição foliar em função da cobertura superficial e diâmetros característicos de gotas; e (v) modelar as curvas de volume cumulativo usando a função logística, permitindo calcular e prever os diâmetros volumétricos em uma pulverização, bem como avaliar o efeito da pressão de pulverização no modelo. No geral, o presente projeto de pesquisa contribuiu para estabelecer uma base válida para uma aplicação eficiente de PPP, desempenhando um papel fundamental no aumento de seus benefícios e levando agricultores e pesquisadores a consolidar melhor o estado do conhecimento sobre a distribuição ideal do tamanho de gotas e a eficiência resultante do processo de deposição de pulverização durante

tratamentos fitossanitários.

Palavras-chave: produto de proteção de plantas; bico; tamanho da gota; cobertura de superfície; depósito; análise de imagem digital; tecnologia baseada em laser; caracterização de pulverização; modelagem de pulverização

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Research Highlights

- Agricultural sector should be oriented towards the reduction of Plant Protection Products (PPPs) usage for making agriculture more competitive and sustainable.
- Droplet size, surface coverage and foliar deposition represent the main factors to study the quality of distribution during plant protection treatment.
- Studying the correlation between droplet size, surface coverage and foliar deposition helps predicting the foliar deposition starting from the fraction of surface covered on Water Sensitive Papers (WSPs).
- Droplet size is one of the most important variables affecting the biological effectiveness, environmental pollution, and operator safety during phytosanitary treatments.
- Droplet size can be assessed with intrusive and non-intrusive methods, both of which significantly affect the results.
- Selecting the threshold based upon the grey level of the image can allow to develop an automatic tool for segmentation process less dependent on the operator expertise and

to reduce its influence in the determination of the size of the droplets.

- Discrepancies in characteristic diameters observed with Liquid Immersion, Laser Diffraction, Phase Doppler Particle Analyzer and Shadowgraphy point out the necessity of always including reference nozzles in spray quality assessments to base classification in relative way rather than relying on absolute values.
- Analytical or empirical approaches are used to model the droplet size distribution in a spray. The applied approach based on the logistic function reveals a promising solution to fit cumulative volume curves of hollow cone ATR 80 nozzle, with high correlation coefficient.

Abstract

Within the current scenario of agriculture, Plant Protection Products (PPPs) have been recognized as one of the most effective and powerful tools for crop pest control, offering several benefits in controlling plant growth. However, improper handling of these products can inevitably lead to undesirable impacts on both human health and the surrounding environment.

For this reason, it is required paying attention to several aspects during PPP application process, which will determine how effectively the crops are covered by the liquid mixture. Among these, the assessment of nozzle spray quality, evaluated in terms of droplet size spectrum, holds a significant role, as it has influence on the movement of the required dose to the target, on the unwanted off-target losses, as well as on the operator safety.

In this context, the multidisciplinary research activities of this PhD thesis were focused on: (i) taking general understanding and reviewing the current available scientific literature regarding the most widespread techniques, both intrusive and non-intrusive, for droplet size measurement; (ii) evaluating the effects of image segmentation thresholding on droplet size measurement; (iii) comparing the performance of four droplet size measurements techniques employed for spray characterization, by measuring

the droplet size spectrum produced by agricultural nozzles under identical operating conditions; (iv) studying the correlation between droplet diameters, foliar deposition on orange leaves and surface coverage measured on Water Sensitive Papers (WSPs) under laboratory conditions, so that allowing the development of a model capable of predicting foliar deposition in function of superficial coverage and droplet characteristic diameters; and (v) modelling the cumulative volume curves by using the logistic function, allowing to compute and forecast the volumetric diameters in a spray, as well as evaluate the effect of spray pressure on the model.

Overall, the present research project has contributed to lay a valid base for an efficient PPP application, playing a fundamental role in increasing their benefits and driving farmers and researchers to better consolidate the state of knowledge about the optimal droplet size distribution and the resulting efficiency of the spray deposition process during phytosanitary treatments.

Keywords: Plant Protection Product; Nozzle; Droplet size; Surface coverage; Deposit; Digital Image Analysis; Laser-based technology; Spray characterization; Spray modelling.

Riassunto

Nell'attuale scenario dei mezzi disponibili per l'attività di difesa delle colture, i prodotti fitosanitari sono riconosciuti come uno degli strumenti più efficaci e potenti per il controllo dei parassiti delle colture, offrendo diversi vantaggi nel favorire la crescita delle piante. Tuttavia, una gestione impropria di questi prodotti può portare ad effetti indesiderati sulla salute umana e sull'ambiente circostante. Per questo motivo, è necessario prestare attenzione a diversi aspetti durante il processo di applicazione dei prodotti fitosanitari che, di norma, prevede la polverizzazione di una miscela di acqua e fitofarmaco e influisce sull'efficiente copertura delle colture con la miscela liquida irrorata.

Tra i diversi aspetti, lo studio della qualità dello spray prodotto dai comuni ugelli presenti nelle irroratrici, valutata in termini di spettro dimensionale delle gocce, svolge un ruolo significativo, poiché avrà effetto sul movimento della dose richiesta verso il bersaglio, sulle perdite fuori bersaglio e sulla sicurezza dell'operatore.

In questo contesto, le attività di ricerca multidisciplinari della presente tesi di dottorato si sono concentrate su: (i) conoscenza generale e studio della letteratura scientifica attualmente disponibile riguardante le tecniche, sia intrusive che non intrusive, per

determinare la dimensione delle gocce; (ii) valutazione degli effetti della soglia di segmentazione dell'immagine sulla misura della dimensione delle gocce; (iii) comparazione tra quattro tecniche di misura della dimensione delle gocce prodotte da ugelli nelle stesse condizioni di lavoro; (iv) studio della correlazione tra i diametri delle gocce, il deposito su foglie di arancio e la copertura della superficie misurata su cartine idrosensibili in condizioni di laboratorio, così da consentire lo sviluppo di un modello in grado di predire il deposito fogliare in funzione della copertura superficiale e dei diametri caratteristici delle gocce; (v) modellazione delle curve cumulative di volume utilizzando una funzione logistica attraverso cui calcolare e prevedere i diametri volumetrici in uno spray, nonché valutare l'effetto della pressione a cui si effettua la polverizzazione della miscela fitoiatrica.

In generale, il presente progetto di ricerca ha contribuito a porre una solida base per l'uso efficace dei pesticidi, svolgendo un ruolo fondamentale nell'aumentare i benefici degli stessi e nel guidare gli agricoltori a migliorare lo stato della conoscenza sull'applicazione ottimale del volume distribuito e sull'efficienza del deposito dello spray durante i trattamenti fitosanitari.

Parole chiave: Prodotto fitosanitario; Ugello; Dimensione della goccia; Copertura della superficie; Deposito; Analisi dell'immagine digitale; Tecnologia laser; Caratterizzazione dello spray; Modellazione dello spray.

Chapter 1

Introduction

1.1 Preface

The content of this Thesis is presented as the main deliverable of the scientific path carried out during the International PhD Programme in “Agriculture, Food, and Environmental Science” – XXXVII Cycle at the Department of Agriculture, Food and Environment (Di3A), University of Catania, Italy.

As a whole, the PhD Thesis involves the research developed in the period between January 2022 and January 2025, on the issue related to the assessment of the nozzle spray quality and foliar deposition during the application of spray liquid plant protection products. The work was entirely funded by the Sicily Region through the “Avviso n. 1/2021 per il finanziamento di borse regionali di dottorato di ricerca in Sicilia – A.A. 2021/2022” (CUP: G69J21014520001).

As reported in *The future of food and agriculture: Trends and challenges* of the Food and Agriculture Organization (FAO) of the United Nations, a number of global trends are influencing food

security and the overall sustainability of agricultural systems, posing an ever-growing challenges to face. World's population is projected to reach around 10 billion people by 2050, leading to increasing of the demand for food production (FAO, 2017). To meet this rising exigency in global society, the crop protection industry primarily enables farmers to grow a plentiful food supply in a safe manner, ensuring productivity, usable crop yields and less persistence on the environment.

With pests being the major threat for many crops, controlling these harmful organisms, while promoting sustainable agriculture by 2030, is crucial to achieving of a number of Sustainable Development Goals (SDGs) according to the goal of 2030 *Agenda for Sustainable Development* of the United Nations (<https://sdgs.un.org/>).

Plant Protection Products (PPPs) have been extensively used as an undeniable tool for pest management to lower the pest and disease pressure, thus safeguarding the agri-food chain. As defined by FAO (<https://www.fao.org/>), a Plant Protection Product, also known under the broad term “pesticide”, is an active substance or a mixture of substances aimed at controlling or destroying pests, diseases and weeds, or regulating plant growth. In relation to the pests they kill, pesticides include a wide range of herbicides, insecticides, fungicides, rodenticides, plant growth regulators and repellents (Saravi and Shokrzadeh, 2011).

Nowadays, spraying PPPs remain an indispensable activity in modern agriculture for boosting agricultural production functionally in line with the market needs. This reflects that effective and rationale use is important to extend their usefulness and longevity in agriculture (Pogăcean and Gavrilescu, 2011). However, the improper and excessive use of these natural or synthetic

products can pose concomitantly significant risks to both human health and environment.

The repercussions on humans can involve a wide range of individuals, from farm workers and operators to consumers and the general population, especially in terms of inhalation, ingestion and dermal exposure. Therefore, human life would be at risk not only from pesticides in the environment but also from contaminated food chain.

The environmental consequences are essentially related to two phenomena, namely drift and run-off (Gil and Sinfort, 2005; Khan et al., 2023; Tudi et al., 2021; Van Der Werf, 1996). According to the ISO 22866 (ISO 22866, 2017), drift is defined as “the quantity of active substance delivered by a sprayer during the phytosanitary treatment which, due to the action of the air currents, is moved away from the target site”. Meanwhile, run-off refers to the movement of the pesticide on the surface ground and underground layer by the action of rainwater or irrigation (Pericherla et al., 2020). These phenomena can lead to the pollution of surface water bodies (lakes, rivers), soil and air quality.

Given these detrimental effects, there is a pressing need to enhance the sustainability of PPP application and reduce the wastage of agrochemicals, even in alignment with the principles of precision agriculture (PA) (Bongiovanni and Lowenberg-Deboer, 2004; Zhang et al., 2002).

In the agricultural sector, conventional spray application machineries (ground-based sprayers) have long been employed for PPPs application and continue to be a predominant choice among farmers for their familiarity and minimal training requirements, balancing efficiency with practicality. These systems, typically mounted on or towed by tractors or designed as self-propelled

units, are equipped with a high-capacity tank, pump, and a series of nozzles arranged on booms. The technology behind these systems offers flexibility in spray application volumes through pressure changes and customization of the nozzle-pressure settings for various spray needs. This capability enables the operator to control the flow, thereby making them indispensable tools for large-scale farming operations due to the optimization of droplet size distribution. Despite that, their efficiency is inherently compromised by inability to adapt to the varying needs of different crop zones.

As agricultural spraying modernization progressed, the need of adopting new modern technologies for precise PPP spraying has led to the development of innovative spraying systems (drone systems with advanced sensors and GPS, robotic sprayer platform, Pulse Width Modulation (PWM) system) capable of adjusting the dosage based on the specific needs of the crops. In this context, growing research and continued investment have involved the use of Unmanned Aerial Vehicle (UAV) for crop parameters monitoring and site-specific application in the field, allowing to treat large surfaces in short period of times and achieving a reduction in inputs compared to conventionally used machinery (Baltazar et al., 2021; Cantelli et al., 2019; Meshram et al., 2021; Mogili and Deepak, 2018). Additionally, the promotion of the Integrated Pest Management (IPM) for crop protection is becoming increasingly vital for farmers in modern agriculture. This approach relies on promoting ecologically-sound agricultural practices by combining biological (using microbiological pesticides or natural enemies), cultural (crop rotations), physical (mating disruption using pheromone traps), and chemical methods (using vegetable insecticides or insect growth regulators) to

limit the reliance on chemical pesticide treatments, while reducing the sprayed quantity and maintaining crop productivity and profitability. Each of these strategies works synergistically within the IPM framework to manage pest populations (Baker et al., 2020; Ryalls et al., 2024).

Despite of the use of PPPs has contributed to agricultural production and food security, remarkable efforts have been made within European Union (EU) to attain a more sustainable use of these compounds, regulating the marketing and their residues in food. For this purpose, the EU has adopted in 2009 a precautionary approach, known as Pesticides Package, towards the use of PPPs. The EU's regulatory framework for PPP is primarily governed by Regulation (EC) No 1107/2009, which sets out the pesticide approval procedures on the market. Specifically, this Regulation mandates that active substances must be approved at the EU level and then authorized at national level. In the support of this, Directive 2009/128/EC (Sustainable Use Directive – SUD), establishes a framework for collective action to achieve the sustainable use of pesticides. It imposes a series of actions, among which a periodic inspection of pesticide application equipment is required to improve the distribution quality by minimizing their hardships. The SUD requires to EU Member States to develop a National Action Plan (NAP) aimed at reducing the risks and impacts of pesticide usage, so encouraging the adoption of IPM strategy. Directive 2009/127/EC introduces essential environmental safeguarding requirements regarding machinery for pesticide application. In addition, Regulation (EC) No 1185/2009 concerns statistics on pesticides, providing information on the quantities placed on the market and used in each Member State (Doussan et al., 2024).

In the common agricultural spraying practices, evaluating the efficacy of PPP applications require deep knowledge, with particular emphasis on the droplet size distribution, the resulting spray deposition and surface coverage, as these metrics affect the success of a phytosanitary treatment and all the aspects relating to environmental and operator safety (Srinivasarao et al., 2021). The optimal biological efficacy of a phytosanitary treatment, environmental effects and occupational exposure are affected by several factors, including the type of nozzle and its quality status, the appropriate spray volume released, diversified droplet size produced by nozzles, type of sprayers, their maintenance status and their operating parameters, the environmental conditions (temperature, relative humidity, wind speed) and the operator expertise (Damalas and Eleftherohorinos, 2011; Kramm et al., 2023; Nuyttens et al., 2007).

Among these numerous parameters, spray nozzles are of paramount importance and require careful consideration for attaining effective control. With their unique features, such as type, orifice size, atomization capabilities, working pressure and flow rate, nozzles generate a wide range of droplet sizes depending mainly on these variables. Typically, fine droplets are produced by conventional hollow cone nozzles operating at high pressure, whereas coarser droplets are produced by air induction nozzles, exploiting the impact of a high-speed air stream with the low-pressure liquid jet (Li et al., 2021b; Schick, 2008; Yuan et al., 2023). Therefore, the assessment of spray quality and the appropriate selection of nozzle type should be regarded as a benchmark to attain desired spray quality during PPP application for the basis of the uniformity of volume distribution and for obtaining the expected and effective spraying effects on crop productivity and

overall sustainability (Lodwik et al., 2020; Prado et al., 2023).

Within spray liquid applications, the droplet size distribution and its uniformity hold a meaningful role as an optimal droplet size spectrum allows to promote the transfer of the required dose to the target (leaf, fruit, etc.), to minimize the off-target losses due to evaporation, drift and run-off, and also to reduce risks for operator safety (ingestion, inhalation and dermal exposure). Notably, finer droplets are more suitable for applying contact pesticides because they are more capable to reach the inner parts of the canopy, ensuring the greater coverage on the desired target (leaf surfaces, fruit, etc.) but, on the other side, if they become too small, they are more prone to drift away and evaporate before reaching the target. In turn, larger droplets, being heavier and having higher kinetic energy, are less prone to deflection by air currents and can easily reach the external parts of the canopy, but are less retained on plant foliage, increasing the risk of run-off and rebound effect.

Taking in mind this, the choice of the right nozzle is essential in achieving successful pest management in the crops, which should be also linked to the specific mode of action of the active ingredient being used (Prokop and Veverka, 2006).

Recognizing the importance of droplet size (expressed in micrometers, μm) upon spray performance and drift minimization, the American Society of Agricultural and Biological Engineers (ASABE) developed since 2009 the ASABE S572 standard (ASABE S572, 2020). This standard interprets and categorizes the spray quality of a nozzle based on volumetric diameters ($D_{v\alpha}$). In general terms, the $D_{v\alpha}$ is the diameter at which the α fraction of the total volume is carried by droplets with a diameter less than $D_{v\alpha}$.

In this sense, the S572 standard uses the Volumetric Median Diameter (VMD) to define the spray quality of a given nozzle referring to its average droplet size in relation to the volume sprayed. The VMD divides the spray into two identical parts and represents the droplet size at which the 50 % of the total volume is contained in droplets smaller than this value and the other 50 % of the volume in droplets larger than this value.

According to the S572 standard, in accordance with the ISO 25358 standard (ISO 25358, 2018), the spray quality is described by eight class boundaries as follows: Extremely Fine (XF), Very Fine (VF), Fine (F), Medium (M), Coarse (C), Very Coarse (VC), Extremely Coarse (XC) and Ultra Coarse (UC). These above-mentioned spray droplet size classes are based on a set of certified reference nozzles operating at given pressure values, following guidelines outlined in the ISO 25358 standard (ISO 25358, 2018).

Spray deposition (generally expressed in $\mu\text{L}/\text{cm}^2$ or $\mu\text{g}/\text{cm}^2$) refers to the amount and distribution of the active substance per unit surface area that remains on the target area after the PPP application, from which depends on the proper dose and then the efficacy of the agricultural treatment. An inadequate spray deposition can result in insufficient treatment, so leading to improper crop growth or pest control. Conversely, excessive spray deposition can lead to unnecessary wastage of product and potential environmental harm due to run-off.

Currently, deposit assessment is measured by adding suitable tracers to the mixture to be sprayed and then measuring the amount of the tracer deposited on the target. Some widely used tracers are water-soluble dyes, such as *Red Ponceau*, yellow tartrazine, fluorescent products or metal chelates (e.g., copper, manganese, zinc). The measurement procedure of spray deposit

is usually performed using spectrophotometer or colorimeters and may be quite complex and time-consuming (Ferguson et al., 2016; Pascuzzi and Cerruto, 2015).

Spray surface coverage (%) is defined as the percentage of the total surface area wetted by the spray. It is especially essential when contact pesticides are used, which control pest once it enters in direct contact with the active ingredient. They require a sufficient coverage of the target area, and consequently pests are killed when enough of the surface area is covered by pesticide. Currently, surface coverage is usually assessed by means of Water Sensitive Papers (WSPs) (Syngenta, 2002), which consist of semi-rigid papers with one side covered with a yellow surface layer that changes its colour to dark blue when interacts with water particles. This property allows assessing the quality of droplet stain distribution in field tests, by relying on suitable image processing procedures (Mangado et al., 2013; Özlüoymak and Bolat, 2020).

Conclusively, in this current scenario, it becomes imperative for farmers, researchers and practitioners to pay close attention to the quality of the spray distribution and the resulting foliar deposition. These factors have a direct influence on the effectiveness of the treatment, as well as on the quality of production, thus ensuring a prosperous and sustainable future for the modern agriculture.

1.2 Aim of the Thesis

The general aim of this Thesis was to improve the understanding and provide novel advancements on the assessment of nozzle spray quality and the resulting spray deposition during agricul-

tural treatments, relying mainly on techniques based on Digital Image Analysis (DIA) (Liquid Immersion method and High-Speed Imaging involving specifically the Shadowgraphy technique) and on laser-based instruments (Laser Diffraction and Phase Doppler Particle Analyzer).

The assessment of the nozzle spray quality is considered an important aspect as a basis for volume distribution and plays an important role in obtaining the expected spraying effects. Thus, this PhD project would set the basis for contributing to an efficient PPP application in the field, playing a pivotal role at better increasing their benefits, reducing the risk of environmental and human contamination, and producing high-quality and safe food in a sustainable way. It also would serve for ensuring, in effective pesticide distribution, the proper amount of active substance on the target and increasing the probability of contact between pest and pesticide.

The following research activities addressed in the different Chapters focused to:

- (i) Take general understanding and review the current available scientific literature of the most widespread techniques, both intrusive and non-intrusive, for droplet size measurement.
- (ii) Evaluate the effects of the threshold values used for image segmentation procedure on the measurement of the main spray droplet diameters.
- (iii) Compare the performance of four common droplet size measurement techniques employed for droplet size characterization, by measuring the droplet size spectrum pro-

duced by four nozzle-pressure combinations under identical operating conditions.

- (iv) Study the correlation between droplet diameters, foliar deposition on orange leaves and surface coverage measured on Water Sensitive Papers (WSPs) under laboratory conditions, in order to develop a model capable of predicting foliar deposition in function of superficial coverage and droplet characteristic diameters.
- (v) Model the cumulative volume curves by using a mathematical model described by the logistic function, in such a way to compute and forecast the volumetric diameters in a spray, as well as evaluate the effect of spray pressure.

1.3 Outline of the Thesis

The content of the Thesis is made up by seven single and self-standing Chapters, which include a compendium of scientific papers that meet the specific objectives of the Thesis, besides an opening introduction (*Chapter I*) and a general conclusion (*Chapter VII*). It includes three original scientific articles and two conference contributions. Particularly, the introductory Chapter includes the theoretical framework of the study context related to the importance of assessing nozzle spray quality and the related quality of deposition in the scenario of agricultural PPP application; whereas, the concluding Chapter summarizes the main findings obtained in the various research activities involved in the PhD path and future research perspectives.

The full specific citation of the articles is reported at the bottom of the first page of each Chapter. To make easier the reading,

a quick overview of the described studies is provided below:

- *Chapter II:* The content of this Chapter refers to a review article, which provided an updating of the state of art and carried out a critical analysis of the most widespread droplet size measurement techniques for characterizing agricultural sprays. In detail, the literature review was arranged in five sections. A preliminary discussion on the most important characteristic mean diameters and the main drop size distribution functions used for the description of sprays was provided (first section). Particular attention was given to the non-intrusive measurement methods (Laser Diffraction, Phase Doppler Particle Analysis and High-Speed Imaging) and intrusive methods (Water Sensitive Papers and Liquid Immersion) (second and third section, respectively). A brief focus addressed by the review was the application of Machine Learning approaches for drop sizing (fourth section). Peculiarities and limitations common to all these measurement techniques were briefly highlighted (fifth section). The literature review presented here has been published in the Journal Agronomy (MDPI). DOI: <https://doi.org/10.3390/agronomy13030678>.
- *Chapter III:* This Chapter reports a study that, consistently with the specific objective (ii), investigated how variations in threshold levels could affect the main spray droplet parameters calculation (volumetric diameters, mean diameters, and numeric diameters). Specifically, in this study, images of droplets of an air induction hollow cone nozzle TVI 8002 at four different pressures (0.3 MPa, 0.5 MPa, 1.0 MPa and 1.5 MPa) and trapped in three Petri dishes

containing silicone oil were acquired following the Liquid Immersion method. The experimental research comprised three steps. As a starting point, images were segmented by applying a “reference” threshold TV^r based on the operator expertise (step 1). Successively, TV^r values were correlated with the average grey level (AGL) of the corresponding images, ranging from 0 (black pixels) to 255 (white pixels) for 8-bit grey level images (step 2). This allowed to obtain a linear regression model capable to predict a threshold value TV^* to be used for image segmentation. Having found the model highly statistically significant, images were ultimately reprocessed with the threshold value TV^* predicted by the model, with variations of ± 5 units of TV^* , with step of one, for a total of eleven different threshold values (step 3). Results of the study suggested the possibility of adopting a threshold value based on objective characteristics of the image itself, so that to reduce operator subjectivity, measurement errors, as well as enable faster and more advanced image processing. The work presented here has been published in the Journal Agronomy (MDPI). DOI: <https://doi.org/10.3390/agronomy12071677>.

- *Chapter IV*: This Chapter was carried out in collaboration with the Agricultural Engineering Department of the Federal University of Viçosa (UFV – Brazil) and the Flanders Research Institute for Agriculture, Fisheries and Food (ILVO – Belgium), where I spent my period abroad. It deals with a study that, consistently with the specific objective (iii), evaluated thoroughly the droplet size distribution of four agricultural spray nozzles, exploiting four different measurement techniques, as applied in three research laborato-

ries, based on image analysis processing (Liquid Immersion and Shadowgraphy) and laser principles (Laser Diffraction and Phase Doppler Particle Analyzer (PDPA)). Specifically, spraying measurements were performed with three reference flat fan nozzles from TeeJet Technologies (TP 11001-SS, TP 11003-SS, TP 11006-SS) and one air-induction flat fan nozzle (AVI 11003) manufactured by Albus. The general aim was to compare and examine how these techniques quantified results in terms of droplet size characteristics under ordinary practical conditions. Additionally, in this comparative study, droplet velocities were also investigated using the PDPA system and the Shadowgraphy. To meet the main objective, an in-depth statistical analysis of the main spray droplet characteristics (volumetric, mean, Sauter, and numeric median diameters) was performed. Results coming from this research work allowed recognizing the potential challenges in acknowledging the discrepancies that may arise between measurements obtained using different types of equipment. The work presented here has been published in the Journal Agriculture (MDPI). DOI: <https://doi.org/10.3390/agriculture14071191>.

- *Chapter V*: In accordance with the objective (iv), the Chapter represents a preliminary study that aimed at correlating the foliar deposition ($\mu\text{L}/\text{cm}^2$) on orange leaves, droplet size (μm) and percentage of covered surface (%) on Water Sensitive Papers (WSPs) under specific laboratory conditions. The final goal was to develop a model able to predict foliar deposition in function of the superficial coverage and spray droplet parameters. More specifically, in this experimental activity, spraying tests were made with three

stainless steel flat fan nozzles (TP 11001, TP 11003 and TP 11006) tested at the nominal pressures established by the ISO 25358 (ISO 25358, 2018) (Crop protection equipment – Droplet size spectra from atomizers – Measurement and classification). Each nozzle was tested three times, for a total of nine Petri dishes to measure droplet diameters, nine WSPs to assess the surface coverage and eighteen orange leaves (nine with upper side surface and nine under side surface exposed) to measure foliar deposition. The first results showed that the foliar deposition per unit surface was positively and significantly correlated with the percentage of covered surface ($R^2 = 0.93$) and all main spray characteristic diameters (volumetric diameters, numeric median diameter and Sauter mean diameter). The research has been submitted as part of the book series Lecture Notes in Civil Engineering (LNCE), Springer Nature. DOI: https://doi.org/10.1007/978-3-031-63504-5_50.

- *Chapter VI*: With reference to the objective (v), the present Chapter deals with a study in using the logistic function to fit the cumulative volume curves of a given spray. Particularly, the research addressed the possibility of using a mathematical model that describes in a simple manner the cumulative curves, allowing to compute and forecast the volumetric diameters. Additionally, the effects of the spray pressure were considered on the model. Experimental data were obtained using an orange hollow cone nozzle ATR 80 (Albuz) at 0.3 MPa, 0.5 MPa, 1.0 MPa, and 1.5 MPa; for each pressure, three repetitions were made. Droplet size was measured through the Liquid Immersion method. The performance of the model was tested on two datasets,

which considered two repetitions for the training dataset (67% of the data) and the last one for the validation dataset (33% of the data). The training procedure consisted in determining the model parameters (m, n, D_0) based upon the measured cumulative volume values. The validation procedure regarded the calculation of three indices: RMSE (Root Mean Square Error), correlation coefficient (r) between the observed and the model predicted values, and the percentage of bias (%PBias). Results coming from this study showed that, when the model was tested on the training dataset, all the indices showed good fitting capabilities almost for all the pressures. Moreover, the proposed model, when used on validation dataset, fitted the experimental data with a high r value (on average 0.9992) and low percentage of bias values. The work has been submitted to 2023 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor). DOI: <https://doi.org/10.1109/MetroAgriFor58484.2023.10424378>.

In addition to the above, the Thesis includes further two chapters referring to the other activities and the annexes:

- *Other activities*: this section reports the other activities carried out during the PhD cycle, including two conference contributions, which only abstracts were reported. Both scientific contributions were presented at the International Conference AIIA (Italian Society of Agricultural Engineering) in 2022 and 2024.

The first contribution, titled *Effect of Image Binarization on Droplet Diameters Measurement* (https://doi.org/10.1007/978-3-031-30329-6_88), is a reduced version of the Chap-

ter III. It was carried out considering images of droplets of an air induction hollow cone nozzle TVI 8002 at a pressure of 1.0 MPa only. The manuscript has been submitted as part of the book series *Lecture Notes in Civil Engineering (LNCE)*, Springer Nature.

The second contribution, titled *Drop stain analysis on water sensitive papers*, deals with the study of the droplet stain patterns on Water Sensitive Papers through simulations, thus understanding the overlapping phenomena by varying the percentage of covered surface. It is still in pending to be published in Springer Nature.

- *Annexes*: The annexes section includes the scientific curriculum and provides a detailed background of the scientific activities, along with the academic and research achievements.

The bibliography section is organized in a unique list reported at the end of the document, with specific references for each chapter included.

Chapter 2

Drop Size Measurement Techniques for Agricultural Sprays: A State-of-The-Art Review

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Contribution	Author
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2.1 Abstract

Plant protection control based on the spray application of plant protection products is a very complex task depending on a series of factors, among which droplet size is the most influential for deposition and pesticide effectiveness. In fact, the adoption of the correct droplet size can ensure that the required dose reaches the target area and is not wasted, minimizes the off-target losses due to evaporation, drift and run-off and, at the same time, enhances the operator safety in terms of inhalation, ingestion and dermal exposure. In this paper, after defining some mean characteristic diameters helpful for the description of the drop population and focusing on the main drop size distribution functions for the statistical characterization of sprays, a critical analysis of known methods, both intrusive and non-intrusive, for drop size measurement is carried out by reviewing the literature. Among intrusive methods, the Liquid Immersion method and the use of Water Sensitive Papers are discussed, whereas, among non-intrusive methods, laser-based systems (Laser Diffraction, Phase Doppler Particle Analysis) and High-Speed Imaging (Shadowgraphy) are presented. Both types of method, intrusive and non-intrusive, can be used in machine-learning-based approaches exploiting regression techniques and neural network analysis.

2.2 Introduction

Despite the promotion of non-chemical methods of crop protection within the framework of integrated pest management, plant protection products (PPPs) are still used on a large scale. The environmental impact of the inappropriate use of the PPPs is a

major public concern (Gil and Sinfort, 2005; Tudi et al., 2021), so European Directive 2009/128/EC (European Union, 2009) recognizes their application in agriculture as an important issue to be properly managed to avoid undesirable effects on humans and the natural environment; in fact, in some cases, PPPs may not reach the target, causing serious economic losses and environmental risks (Roussel et al., 2000). The occupational exposure, environmental effects and efficacy of PPPs are affected by many factors, including the active substances and their formulations, the type of packaging, the task to be performed, the amount of pesticide to be handled, the duration of activity, the personal protective equipment (PPE) used, the type and quality of nozzles, the type of sprayers, their maintenance status and their operating parameters, the target structure (canopy, fruit, leaves, soil), the environmental conditions (temperature, relative humidity, wind speed) and the operator expertise (Damalas and Eleftherohorinos, 2011; Van Der Werf, 1996; Yarpuz-Bozdogan, 2018).

Within spray liquid applications, the droplet size spectrum plays a key role in determining the spray behaviour as it affects the biological efficacy of PPP treatment due to target coverage, the environmental pollution due to evaporation, drift and run-off and the operator safety due to ingestion, inhalation and dermal exposure. Therefore, agricultural nozzles have a remarkable impact on the treatment efficiency, and the types that provide a more homogeneous droplet spectrum give a higher quality of application. This means that an optimal droplet spectrum is crucial for obtaining desired spray performance and reducing spray drift in order to ensure the deposition of the required dose to the target (leaf, fruit, etc.), minimize the off-target losses and reduce the operator exposure. In agricultural PPP applications,

small droplets, carried by air currents, can more easily reach the inner parts of the canopy, increasing coverage on leaves; but, on the other hand, if they become too small, they are more often subjected to wind drift and evaporation before reaching their target, especially in hot conditions. Large droplets, being heavier and having higher kinetic energy, are less prone to deflection by air currents and reach the external parts of the canopy more easily, but run-off becomes high, and the risk of soil contamination increases (Derksen et al., 2008; Martins et al., 2021; Nuyttens et al., 2007).

Drop size primarily depends on the atomization device and on the operating parameters. Agricultural nozzles for PPP application are mainly based on hydraulic, pneumatic and centrifugal atomization. In hydraulic nozzles, pulverization is accomplished by forcing the liquid under pressure through a small opening or orifice. Drop size primarily depends on orifice diameter and spraying pressure; increasing the nozzle openings results in larger drops (and vice versa) and increasing the spraying pressure results in smaller drops (and vice versa). Another aspect that affects the drop size is the liquid viscosity; high-viscosity solutions tend to produce larger drops, whereas low-viscosity solutions produce smaller drops. Pneumatic atomization is obtained when the liquid is exposed to a stream of air flowing at high velocity. For a given air flow rate, the higher the liquid flow rate, the higher the drop diameter (and vice versa). In rotary atomizers, the liquid is released near the center of a high-speed rotating disk; the liquid flows radially outward across the disk and is discharged at high velocity in the form of droplets from its periphery due to the centrifugal force. Drop diameter depends on disk rotation speed and liquid flow rate; for a given liquid

flow rate, increasing the speed results in smaller drops (and vice versa), and, for a given rotating speed, increasing the liquid flow rate results in larger drops (and vice versa).

The effects of droplet size on treatment efficacy can also depend on the mechanism of action of the active substance. Pesticides with systemic action do not require complete and uniform coverage of the plant, and translocation in plant tissues may be ensured by larger droplets. They control pests when applied to one area of a plant or animal. In fact, a systemic herbicide, absorbed through a plant's roots or surfaces, moves throughout all parts of the plant and kills the entire plant. Conversely, drop size is of great importance for contact pesticides which control a pest because of direct contact with the plant outside layer (epidermis). They require good coverage of the target, and pests are killed when enough of the leaf surface area is covered with a contact PPP, ensured by smaller droplets on the target. In the Czech research of Prokop and Veverka (2006), the authors studied the influence of different droplet spectra on the efficiency of contact and systemic fungicides. They found that, with the same volume of sprayed mixture, smaller droplets allow coverage of a larger area, increasing efficacy with a higher droplet density per unit of leaf area (droplets/cm²) with products containing a contact active substance.

On this basis, an efficient spray application in terms of the droplet spectrum plays an important role in increasing the benefits of PPPs and in reducing the risk of environmental and human contamination, as well as in producing high-quality and safe food in a more sustainable way (Cerruto et al., 2018; Chen et al., 2020; De Cock et al., 2017; Lodwik et al., 2020; Matthews, 2004; Nuyttens et al., 2009).

All these aspects are typical of precision agriculture (PA), which has become an increasingly important topic. The importance that accurate and correct PPP spraying could have for a precise agronomic management of soil and plants is very high due to the use of the most modern technologies which meet the specific needs of individual crops. Precision spraying is an approach used within this context to control the amount of mixture distributed across the field only where needed. Many researchers across the world have contributed to smart technologies for precision spraying, developing innovative pesticide spraying systems (drone systems, robotic sprayer platforms) in order to enhance the soil productivity, reduce the wastage of pesticide and control dangerous effects on the environment (Baltazar et al., 2021; Cantelli et al., 2019; Danton et al., 2020; Meshram et al., 2021; Mogili and Deepak, 2018; Tellaeche et al., 2008). Research involving the use of drone systems (unmanned aerial vehicle (UAV) models) was reviewed in the Indian study of Mogili and Deepak (2018), where specific information for crop monitoring and pesticide spraying were summarized. A UAV is an aircraft able to fly without a human pilot, and its integration with sprayer systems, multispectral cameras and sensors enables accurate, site-specific application in the field. A related Indian study for the development of pesticide-spraying robotic systems was conducted by Meshram et al. (2021). The review paper described the robotic system categories (platform mobility and steering, localization and navigation control, sensing and target detection and pesticide spraying arrangement). Baltazar et al. (2021) developed a smart electric sprayer (precision robotic sprayer, PRySM) that can be assembled on a robot capable of operating autonomously on uneven ground and equipped with a crop perception system

to calculate the leaf density. In the Italian study of Cantelli et al. (2019), a system based on a reconfigurable vehicle with a high degree of automation for PPP application in environments where standard sprayers cannot operate (greenhouses and mountain areas) was presented.

Precision spraying in agriculture requires a proper choice and control of the spraying system, for which the correct drop size is fundamental. According to the International Standard ISO 25358:2018 (ISO 25358, 2018), drop size measurement is of particular importance for pesticide spraying in agriculture, because it makes the description of the spray easier and, therefore, enhances biological efficacy and spray drift management. However, the adopted measurement systems may produce different values for a given droplet spectrum with variations in the analyzed parameters, especially due to sampling effects and dynamic size range capabilities (da Cunha et al., 2019; Sijs et al., 2021).

Different methods to measure droplet size have been discussed in the literature, and several instruments exploiting different principles are available on the market. The droplet size spectrum can be measured with intrusive or non-intrusive methods (Pascuzzi and Cerruto, 2015). Examples of non-intrusive systems are Phase Doppler Particle Analysis (PDPA) (Nuyttens et al., 2006a), Laser Diffraction (LD) (Fritz and Hoffmann, 2016), and imaging principles, such as High-Speed Imaging (HSI), better known as Shadowgraphy methods (Castrejón-García et al., 2011; De Cock et al., 2015; Lad et al., 2011; Minov et al., 2016). PDPA and HSI methods also allow the measurement of drop velocity at the same time (Tuck et al., 1997). Among intrusive techniques, based on digital image analysis, the most popular available in the literature include the use of Water Sensitive Pa-

pers (WSPs) (Salyani and Fox, 1999) and the Liquid Immersion (LI) method (Fujimatsu et al., 2014). In addition, Machine Learning (ML) methods have recently been used to classify sprays and evaluate droplet size and deposition (Guo et al., 2020; Srikanth et al., 2021).

All the aforesaid techniques are widespread for the evaluation of spray droplet size, and all have a strong influence on the results, which may be significantly different depending on the settings and type of measuring equipment. For this reason, the ISO 25358:2018 (ISO 25358, 2018) standard recommends classification of spray droplet spectra by using reference sprays to define reference categories to increase uniformity in relative measures and classifications among different measurement systems and laboratories.

The main objective of this paper is to carry out a critical analysis of the most widespread methods for drop size measurement in the context of PPP application in agricultural systems by reviewing the literature. The paper is organized as follows:

1. The first section discusses the most important characteristic mean diameters and the main drop size distribution functions used for the description of sprays;
2. In the second section, non-intrusive measurement methods are presented, namely, Laser Diffraction, Phase Doppler Particle Analysis and High-Speed Imaging;
3. The third section discusses two widespread intrusive methods, namely Water Sensitive Papers and Liquid Immersion;
4. The fourth section presents some methods for drop sizing based on Machine Learning approaches;

5. In the last section, errors sources common to all the measurement methods are briefly discussed.

For each measuring technique, the main characteristics, peculiarities and limitations are highlighted, and some applicative examples are presented. Issues regarding the applications of the techniques and possible ways to overcome the problems are discussed.

2.3 Mean Characteristic Diameters and Statistical Characterization of Sprays

Considering the importance of droplet diameter (usually expressed in μm) in spray performance and drift minimization, a classification of sprays based on droplet size is used to classify nozzles in relation to spray efficacy and drift potential. Each nozzle, depending on its features, liquid properties and working pressure, produces a range of drop sizes which can be described by several mean characteristic diameter values. For this reason, it is necessary to know the technical characteristics of the spray nozzles to select those that produce droplets of the appropriate size under certain working pressure (Marangoni Junior and da Costa Ferreira, 2019; Schick, 2008).

In light of this, the specific standard S572 was developed and approved by the ASABE (American Society of Agricultural and Biological Engineers) for the purpose to measure and interpret the spray quality in terms of volumetric diameters and to aid in the selection of the most appropriate spray size (ASABE S572, 2020). According to this standard, aligned with the ISO 25358:2018 standard (ISO 25358, 2018), spray droplets are classi-

fied into eight quality categories in increasing order as follows: extremely fine (XF), very fine (VF), fine (F), medium (M), coarse (C), very coarse (VC), extremely coarse (XC) and ultra coarse (UC). The definition of the spray droplet size classes is based on a set of certified reference nozzles operated at given spray pressures while spraying clean water (free of particulates) (Table 2.1).

Table 2.1: Reference nozzles and pressure combinations for class boundary definition (adapted from ISO 25358:2018).

Reference Nozzle	Pressure (MPa)	Flow Rate (mL/min)	Class Boundary
Mee Fog IP-16 impaction pin	0.550	8.1	XF/VF
TeeJet TP 11001-SS	0.450	8.2	VF/F
TeeJet TP 11003-SS	0.300	19.6	F/M
TeeJet TP 11006-SS	0.200	32.3	M/C
TeeJet TP 8008-SS	0.220	45.1	C/VC
TeeJet TP 6510-SS	0.120	42.2	VC/XC
TeeJet TP 6515-SS	0.100	56.8	XC/UC

Classification is based upon volumetric diameters. In general terms, the volumetric diameter $D_{v\alpha}$ is the diameter at which the α fraction of the total volume is carried by droplets with a diameter lower than $D_{v\alpha}$. The most used parameter to evaluate the droplet size is the volumetric diameter $D_{v0.5}$, also known as the “volume median diameter” (VMD), which divides the spray into two equal parts in terms of sprayed volume; 50% of the total volume is carried by droplets lower than the VMD and the other 50% by droplets larger than the VMD. The volume median diameter is used to define the spray quality of a nozzle

in terms of its average droplet size in relation to the volume sprayed. According to the S572 ASABE standard (ASABE S572, 2020), VMD values (μm) vary as follows: XF: < 60 ; VF: 60–105; F: 106–235; M: 236–340; C: 341–403; VC: 404–502; XC: 503–665, UC: > 665 . These VMD ranges may vary widely based upon the type of measuring equipment used.

The information given by the VMD gives an indication of the risk of drift and of the nozzle to select for a particular application. As an example, very fine droplets are collected efficiently by flying insects, but they tend to remain in the air stream, which carries them around the stems and leaves of weeds. Fine and medium-sized droplets deposit efficiently on stems and narrow vertical leaves if applied when there is some air movement (fungicide in foliar protective or curative applications, insecticide in foliar contact and herbicide in foliar/post-emergent contact applications). Coarse or larger droplets deposit efficiently on large, flat surfaces such as the leaves of broad-leaved weeds or the soil (insecticide in foliar and soil-applied systemic applications, herbicide in foliar/post-emergent and soil-applied/pre-emergent systemic applications).

Two additional diameters that are commonly used are $D_{v0.1}$ and $D_{v0.9}$: 10% and 90%, respectively, of the total volume consisting of drops with diameters smaller or equal to these values (Cerruto et al., 2021a; Schick, 2008). The $D_{v0.1}$ diameter refers to the drift potential of individual drops and then it can be used for nozzle classification for drift reduction purposes. If the value of $D_{v0.1}$ is large, then the spray contains many droplets that are prone to drift. Conversely, the $D_{v0.9}$ diameter is best suited when complete evaporation of the spray is required. In addition, high values of $D_{v0.9}$ indicate that too much of the volume of spray

may be taken up by a few large droplets. Spray coverage and efficiency may be reduced as there are not enough droplets to cover all treated surfaces, leading to an increased risk of reduced effectiveness due to poor coverage.

A dimensionless parameter indicative of the uniformity (i.e. width) of the drop size distribution is the relative span factor (*RSF*), defined by:

$$RSF = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \quad (2.1)$$

The higher the *RSF* value, the wider the drop size distribution and vice versa. Then, the lower the *RSF* value, the lower the variation among drop sizes, resulting in less drift potential and greater coverage. The *RSF* provides a practical means for comparing various drop size distributions and should be used when possible.

Other mean diameters of special interest in agricultural spray application and their equations are listed below, with D_i representing the droplet diameter and N the total number of droplets.

- D_{10} : Arithmetic mean diameter. It is the diameter of a drop which, multiplied by the number of drops, equals the sum of all drop diameters:

$$D_{10} = \frac{\sum_{i=1}^N D_i}{N} \quad (2.2)$$

- D_{20} : surface mean diameter, best suited for surface controlling applications such as absorption. It is the diameter of a drop, the surface of which, multiplied by the total droplet

number, equals the sum of all droplet surfaces:

$$D_{20} = \sqrt{\frac{\sum_{i=1}^N D_i^2}{N}} \quad (2.3)$$

- D_{30} : volume mean diameter, best suited for volume-controlling applications such as hydrology. It is the diameter of a drop, the volume of which, multiplied by the total droplet number, equals the sum of all droplet volumes:

$$D_{30} = \sqrt[3]{\frac{\sum_{i=1}^N D_i^3}{N}} \quad (2.4)$$

- D_{32} : Sauter mean diameter (also known as SMD), best suited to calculating the efficiency and mass transfer rates in chemical reactions, such as the fuel injection in combustors. It is the diameter of a drop with the same volume/surface area ratio as the total volume of all the drops to the total surface area of all the drops:

$$D_{32} = \frac{\sum_{i=1}^N D_i^3}{\sum_{i=1}^N D_i^2} \quad (2.5)$$

Considering the definition of the SMD, the same equation can be written in a simpler way as follows:

$$D_{32} = \frac{D_{30}^3}{D_{20}^2} \quad (2.6)$$

Finally, a diameter referring to the number of drops is the number median diameter (NMD or $D_{n0.5}$), i.e., the diameter at which 50% of the total number of droplets is smaller than this

value. The NMD is usually smaller than the VMD because most PPP sprays often contain a large number of very small droplets. The VMD is influenced by relatively few large droplets, whereas the NMD is more affected by small droplets. So, the more uniform the size of the droplets, the closer to unity is the ratio of VMD and NMD.

All mean and characteristic diameters discussed above can be calculated by knowing the drop size distribution (DSD) function. According to Déchelette et al. (2011), there are two categories of droplet distribution functions for describing droplet characteristics in different process, such as atomization or spraying: analytical and empirical functions. The atomization process consists of the disintegration of a liquid mixture into a multiplicity of small drops from a specific nozzle which has different shaped orifices and produces various spray patterns. A simple explanation of this process is that the potential energy (measured as liquid pressure for hydraulic nozzles or air and liquid pressure for pneumatic nozzles) of the spray liquid, along with the geometry of the nozzle, causes the liquid to emerge like small ligaments and then the breakup of these ligaments leads to the formation of further small drops (Mohandas et al., 2021; Schick, 2008). Such a process is particularly important in agricultural “spraying” since it refers to an effective method where drops, resulting from atomization, are applied to the target by means of sprayers in order to obtain an adequate deposition, allow security against diseases and pests and increase productivity.

In the book of Lefebvre and McDonell (2017a), the authors provided a summary of the main probability distribution in each group (analytical and empirical). Theoretical atomization models for agricultural spray nozzles used for PPP applications are

rare in the literature; conversely, according to the empirical approach, fitting theoretical curves to measured data is much more common. A wide variety of distribution functions have been proposed in the literature to describe agricultural sprays, such as the normal, log-normal, gamma, Nukiyama-Tanasawa and Rosin-Rammler distributions, able to fit experimental data with different levels of accuracy. The equations usually depend on two parameters, the first representing the mean diameter and the second indicating a measure of the droplet size range; in the empirical approach, their values are determined by fitting the function to the experimental data (Cerruto et al., 2021b; González-Tello et al., 2008; Jurado et al., 2007; Majewski, 2013). They have also been used to simulate the DSD as a function of the particle size to produce data on the droplet characteristics.

The normal distribution function is based on the random occurrence of a given drop size, and it is usually expressed in terms of a number distribution function $f_0(D)$ that gives the number of particles of a given diameter D :

$$f_0(D) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(D-\bar{D})^2}{2\sigma^2}} \quad (2.7)$$

where σ is the standard deviation, σ^2 is the variance and \bar{D} is the mean value. The normal distribution is considered when the range of drops is narrow, but it does not usually show a good fit to experimental results since natural distributions are rarely symmetrical.

If the logarithm of the particle diameter is used as the variable,

the corresponding distribution function is the log normal:

$$f_0(D) = \frac{1}{\sqrt{2\pi}D\sigma_g} e^{-\frac{(\ln D - \ln \bar{D}_g)^2}{2\sigma_g^2}} \quad (2.8)$$

where \bar{D}_g is the geometric mean drop size, and σ_g is the geometric standard deviation. The log-normal distribution is used because it provides a satisfactory correlation with experimental data, even if it is less popular than the normal distribution.

The probability density function of the gamma distribution has the general form:

$$f_0(D) = \frac{1}{\beta^\alpha \Gamma(\alpha)} D^{\alpha-1} e^{-D/\beta} \quad (2.9)$$

where α is the shape parameter, β is the scale parameter and $\Gamma(\alpha)$ is the gamma function. According to the French study of Van Der Werf (1996), the atomization process involves the fragmentation of ligaments into droplets, and the gamma probability distribution function reasonably fits experimental data distribution.

The Nukiyama-Tanasawa probability density function has the general form:

$$f_0(D) = aD^p e^{-(bD)^q} \quad (2.10)$$

This expression contains four independent constants, the simultaneous optimization of which is often difficult to apply and can lead to measurement errors. Most of the commonly used size distribution functions represent either simplifications or modifications of this function.

Finally, The Rosin-Rammler distribution, also known as the Weibull distribution, is one of the most well-known and -used

empirical functions for droplet size distribution analysis. The general equation, expressed as cumulative volume, is the following:

$$F_3(D) = 1 - e^{-(D/D_m)^n} \quad (2.11)$$

where $F_3(D)$ is the fraction of the total volume contained in drops with a diameter of less than D , D_m is a representative diameter where 63.2% of the total liquid volume is in drops of smaller diameter and n is an adjustable parameter characteristic of the distribution that provides a measure of the spread of the drop. The higher the value of n , the more uniform the spray. The advantage of this expression is its simplicity, and it enables data to be extrapolated into the range of very fine drops, where measurements are typically more difficult. These features are the reason for its popularity (Alderliesten, 2013; González-Tello et al., 2008).

Regardless of which drop size distribution function is used, all functions perform the same task. However, the discussion as to why a certain distribution function might fit better than another is still open for further study by researchers (Alderliesten, 2013; González-Tello et al., 2008; Jurado et al., 2007; Lefebvre and McDonell, 2017a; Majewski, 2013; Panão et al., 2020; Villermaux et al., 2004).

2.4 Measuring Techniques for Spray Characterization

Spray drop size measurement is a very complex task that has been faced in many ways over the years. In this sense, knowledge of the drop size distribution has for a long time been known as

a fundamental factor for the research and development of new techniques relating to measuring drop size since a precise droplet size has a direct impact on biological efficacy and reduction of environmental contamination (Lefebvre and McDonell, 2017a).

According to the study of Schick (2008) from Spraying Systems Co. (USA, 2008), when discussing drop size distributions, it is preliminarily necessary to distinguish spatial and flux (or temporal) sampling methods. Typically, with spatial techniques, a collection of drops occupying a given volume is sampled instantaneously by using holographic means (for example, high-speed photography or light-scattering instruments). Drop size analyzers that implement a spatial technique include image analysis and Laser Diffraction. Conversely, with temporal techniques, the flux of drops is examined during an interval of time with the aid of optical instruments that are capable of detecting individual drop characteristics. Thus, not only the density of drops is important but also the velocity of the particles in the spray; in fact, it is used to obtain the number of droplets per cubic meter per second. Phase Doppler Particle Analysis (PDPA) is an example of a technique producing temporal distribution (Lefebvre and McDonell, 2017b; Schick, 2008).

In more detail, Figure 2.1 shows a diagram of the various methods used to measure drop size and distributions in the agricultural sector, classified as non-intrusive and intrusive (or mechanical). The first category gathers methods based on light-scattering properties, which do not interfere with the droplet flow, while the second involves the collection of drops on slides (Petri dishes) or artificial collectors, such as Water Sensitive Papers. Some methods of both categories are based upon Digital Image Analysis (DIA) principles. In addition, more recent ap-

proaches are based upon machine learning methods that exploit regression techniques and neural network analysis. All measuring methods, whether simple or sophisticated, are susceptible to various errors and ambiguities, some of which are debated below. Cited references have been systematized, as reported in Table 2.2, according to the measurement method treated.

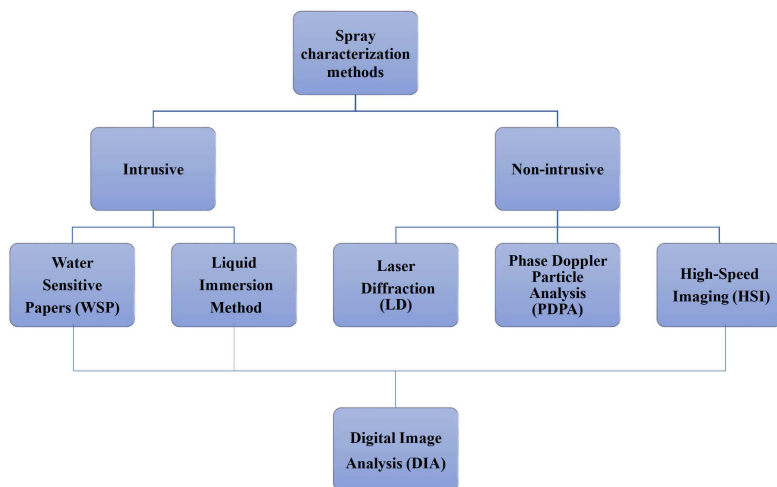


Figure 2.1: Scheme of the main spray characterization methods.

Table 2.2: *Systematization of cited bibliographic references according to the drop size measurement method treated.*

Laser-based	LD	Dodge et al. (1987); Dorr et al. (2013); Eshel et al. (2004); Fritz and Hoffmann (2016); Fritz et al. (2012); Lefebvre and McDonell (2017b); Merkus (2009); Pascuzzi et al. (2021); Pieloth et al. (2023); Schick (2008); Sijs et al. (2021); Sirmour and Verma (2019)	Total = 12
	PDPA	Bachalo and Houser (1984); Dodge et al. (1987); Lefebvre and McDonell (2017b); Nuytens et al. (2006a,b); Pascuzzi et al. (2021); Schick (2008); Sijs et al. (2021); Tian et al. (2010)	Total = 9
Digital Image Analysis (DIA)	HSI	Asgarian et al. (2020); Castanet et al. (2013); Castrejón-García et al. (2011); Cerruto et al. (2022); De Cock et al. (2015, 2016); Hijazi et al. (2012); Kathiravelu et al. (2016); Kumar et al. (2019); Lad et al. (2011); Lefebvre and McDonell (2017b); Manetto et al. (2022); Minov et al. (2016); Pascuzzi et al. (2021); Pieloth et al. (2023); Schick (2008); Sijs et al. (2021)	Total = 17
	WSP	Abramoff et al. (2004); Cerruto et al. (2019); Cunha et al. (2013, 2012b); Ferguson et al. (2016); Gargari et al. (2019); Guler et al. (2012); Hoffmann and Hewitt (2005); Kathiravelu et al. (2016); Manetto et al. (2022); Mangado et al. (2013); Marçal and Cunha (2008); Özlüoymak and Bolat (2020); Pascuzzi et al. (2021); Salyani et al. (2013); Zhu et al. (2011)	Total = 16
	LI	Cerruto et al. (2022); Eigel and Moore (1983); Fujimatsu et al. (2014); Hulburt and Hanratty (2002); Kathiravelu et al. (2016); Longo et al. (2020); Pascuzzi et al. (2021)	Total = 7
Machine learning	ML	Chlingaryan et al. (2018); Dong et al. (2023); Eli-Chukwu (2019); Gargari et al. (2019); Guo et al. (2020); Liao et al. (2019); Pieloth et al. (2023); Rehman et al. (2019); Srikanth et al. (2021); Talaviya et al. (2020)	Total = 10

2.5 Non-Intrusive Measurement Methods

The development of modern technologies such as powerful computers and laser systems has led to the introduction of new techniques for obtaining non-intrusive spray characterization information. Over recent years, several laser-based techniques have been developed to determine droplet features, such as Laser Diffraction (Dorr et al., 2013) and Phase Doppler Particle Analysis (Bachalo and Houser, 1984; Nuyttens et al., 2006b). The recent improvements in digital image processing have increased the interest in High-Speed Imaging methods for agricultural applications in general, specifically for PPP application (De Cock et al., 2016; Hijazi et al., 2012).

In general terms, a potential feature of these methods is that they do not influence spray behaviour during tests, allowing full analysis of the spray in a non-intrusive way.

2.5.1 Laser Diffraction (LD)

Laser Diffraction devices have been largely adopted by the agricultural application community for spray droplet analysis (Fritz and Hoffmann, 2016; Sirmour and Verma, 2019). The most widely used commercial laser diffraction instrument used today by researchers is the Malvern analyzer, which consists of a transmitter unit, a receiving system and a computer. The principle of diffraction by laser beam is applied; when the droplets intersect the laser beam, they scatter the direction of the laser rays, creating a diffraction pattern. The laser beam is crossed by the drops within the working zone of a lens, and a multi-element detector gathers the light diffracted by the spray droplets (Figure 2.2).

Both the angle and intensity of scattering are strictly con-

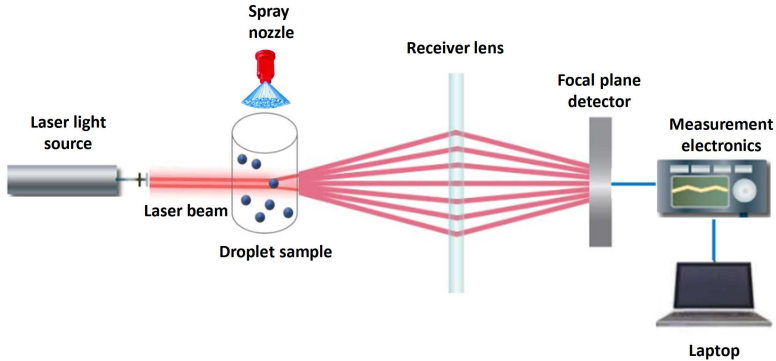


Figure 2.2: *Scheme of the Laser Diffraction measurement system.*

nected to the droplet size. The scattered light intensity is measured using a series of semi-circular photodiodes housed in the receiver unit. Later, a specific curve-fitting software is used to convert the light intensity into any of several empirical function, typically the Rosin-Rammler distribution function. In particular, the scattering angle is inversely proportional to the size of the droplet, and so it increases as droplet size decreases and vice versa (Merkus, 2009; Pascuzzi et al., 2021; Schick, 2008; Sijs et al., 2021).

Other manufacturers of Laser Diffraction devices have emerged. As an example, a Sympatec analyzer was used in the study of US researchers (Fritz et al., 2012) for investigating a set of reference nozzles under three concurrent air flow velocities (0.7 m/s, 3.1 m/s and 6.7 m/s). The system used a 623 nm He-Ne laser and was fitted with a lens capable of detecting particles in the range between 0.5 μm and 3500 μm .

The study of Fritz and Hoffmann (2016) described the methods used in making spray droplet size measurements with Laser Diffraction equipment for both ground and aerial application sce-

narios. The authors configured the equipment in such a way as to have a dynamic size range from 18 μm to 3500 μm for ground nozzle testing and from 9 μm to 1750 μm for aerial nozzle testing. The authors provided some guidelines that can be used to ensure inter- and intra-laboratory precision while minimizing the sampling bias associated with laser diffraction systems. A Sympatec Helios laser diffraction particle size analyzer was also used in a study by Dorr et al. (2013) to compare the initial spray characteristics, including drop size, produced by several types of agricultural nozzles. Finally, in the Indian study of Sirmour and Verma (2019), a Malvern Spraytec laser diffraction system was used to detect the drop size distribution of agricultural nozzles in the range of from 1 μm to 2500 μm .

The measurement of the size distribution of spray droplets is commonly based on Lorenz-Mie theory or Fraunhofer diffraction light theory. They both assume that particles have a spherical shape. The Fraunhofer theory is based on the approximation that the laser beam is parallel, and the detector is at a distance that is very large compared with the size of the diffracting particle. The Lorenz-Mie principle can be understood by considering that the drops scatter the incident light, producing, due to the wave interference, a central forward scattering lobe flanked by a succession of lateral lobes of decreasing amplitude. In addition, it requires the proper choice of refractive index for ensuring the accuracy of the computed size distributions Eshel et al. (2004).

Even if they require a little knowledge of their basic principles for operation, laser diffraction instruments have been widely used by researchers for drop size measurements due to their ease of use, capacity to rapidly measure high-number density sprays with a high degree of precision and the large measure-

ment range. Despite that, their use is not free from problems and can produce considerable errors in results, affecting the size measurements. The most significant limitation associated with this method is called multiple scattering; this effect occurs when the concentration of the drops in the spray is remarkably high, and, consequently, there is a dispersion of light before it reaches the detector since the light that is scattered by a drop may be scattered by another drop. This introduces errors in computing the drop size distribution and should be corrected empirically. Another limitation to consider concerns the correct alignment of the laser and the detector, which introduces significant complexity in droplet size distribution measurement. About this, experience has shown that a good alignment of the laser is crucial, and, to obtain accurate measurements, it should be perpendicular to the spray axis at a suitable distance from the spraying point (Fritz and Hoffmann, 2016; Lefebvre and McDonell, 2017b; Schick, 2008). Although many non-intrusive techniques have been developed for the measurement of drop size distribution, Laser Diffraction system and the Malvern instrument remain a reference for many researchers.

2.5.2 Phase Doppler Particle Analysis (PDPA)

PDPA is another commonly used method for droplet size measurement. It falls into the category of flux-sampling instruments and, together with the laser diffraction method, is considered a powerful tool for non-intrusive investigations of sprays. In comparison to Laser Diffraction, PDPA is a single-droplet technique in which the phase difference of scattered light at multiple angles is measured and inverted to obtain the size and velocity of individually detected drops (Sijs et al., 2021). In general terms,

it is equipped with transmitter and receiver units, a signal processor and a computer. The principle of operation is based on the creation of an unbroken laser that is split through a beam splitter into two beams with the same wavelength; these laser beams intersect again at a point named “the probe volume”, and the measurement point is defined by this intersection, producing a set of parallel equidistant interference fringes. When a droplet passes through the intersection zone of the two beams (sampling area), a diffused light modulated in space and time is produced. The spatial frequency is proportional to the size of the droplet, whereas the temporal one is proportional to its speed. Hence, the method measures droplet size one by one and also the speed of the droplets at the same time (Figure 2.3).

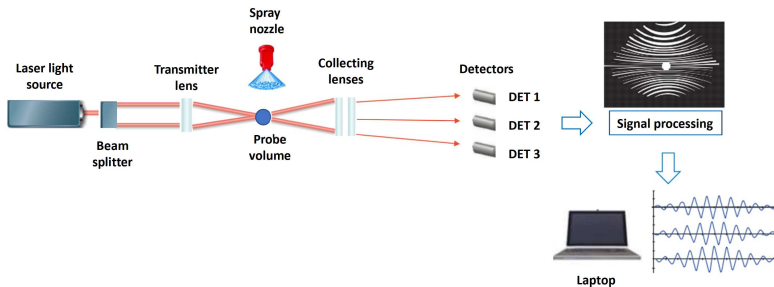


Figure 2.3: *Scheme of PDPA measurement system.*

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. 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 range for these instruments can vary from 1 μm even to 8000 μm . However, the PDPA technique is strictly limited to homogeneous and spherical droplets since the measured signal depends on the radius of curvature of the droplet. Therefore, the presence of inhomogeneous droplets, due to air inclusions inside droplets, may be interpreted as smaller drops and can adversely affect the results (Nuyttens et al., 2006a; Pascuzzi et al., 2021; Schick, 2008; Tian et al., 2010).

In the US study of Bachalo and Houser (1984), a theoretical analysis of the method was carried out, and experimental verification of the theory was obtained by using monodisperse droplet streams. Simulated spray environments and fuel spray nozzles were used in the evaluation of the method. The measurements of the monodispersed drops showed complete agreement with the theoretical predictions.

A particular comparison of drop sizing results obtained using an Aerometrics Phase Doppler Particle Analyzer and a Malvern laser diffraction instrument was proposed in the study of US researchers Dodge et al. (1987), where, after an appropriate conversion procedure from temporal to spatial sampling, they demonstrated that average drop sizes measured in different points of a sample showed similar trends during spraying with both systems, but those produced by the phase Doppler values were generally larger.

A detailed description of the PDPA measuring system was given in a more recent study by Nuyttens et al. (2006a). The laser used in this study was an Aerometrics PDPA 1D system, which was used to test 32 nozzle-pressure combinations for a total of 288 measurements. The experiment was performed in a controlled

climate room with defined dimensions and was provided with temperature and humidity control. The results showed the effect of nozzle type and flow rate on droplet size and velocity.

2.5.3 High-Speed Imaging (HSI)

Over the years, the rapid development of imaging techniques has made High-Speed Imaging even easier to use and a cheaper alternative to scatter- or diffraction-based measurement methods for the characterization of agricultural sprays. In general terms, High-Speed Imaging analyzers are spatial sampling techniques consisting of a light source (generally a strobe light), a high-speed camera and a computer with image processing software able to identify the in-focus droplets in the image and determine their sizes and velocities (Figure 2.4).

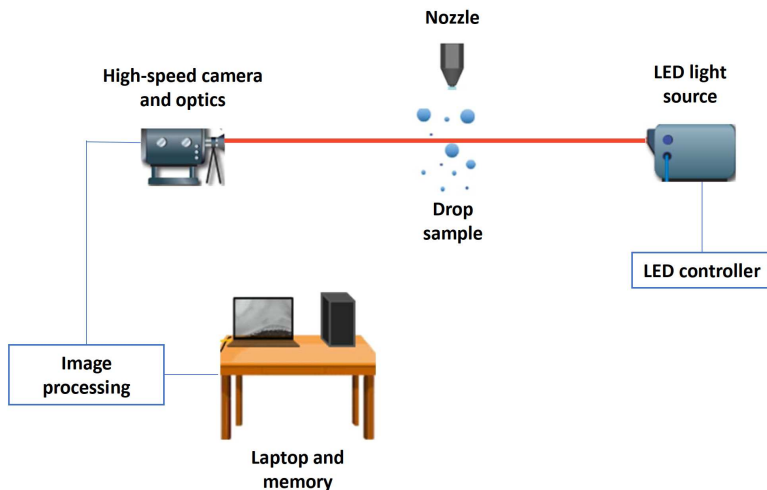


Figure 2.4: Scheme of HSI measurement system.

The illumination source spreads uniform light on the spray, and, consequently, part of the light is refracted by the spray, leaving a shadow on the bright background (De Cock et al., 2016; Hijazi et al., 2012; Kumar et al., 2019; Minov et al., 2016). This methodology, usually performed in a back-lighted arrangement for image acquisition, is often known as the Shadowgraphy technique (Castrejón-García et al., 2011). In detail, the system consists of a camera equipped with high-magnification optics used to acquire images of the drops and synchronized with a light-emitting diode (LED) light source for irradiating the spray. In addition, an LED controller provides intensity control of the light source. The droplets appear on the images as darker shadows on a brighter background, so, for each acquisition, two frames are recorded within a small time lapse. The droplet diameter and velocity are retrieved by using an advanced image analysis algorithm on each pair of frames. Then, the drop size distribution is obtained by gathering the data retrieved from all the images that are visible on the monitor of the computer.

In the work conducted by the Belgian researchers De Cock et al. (2016), the drop size distribution of a set of reference nozzle/pressure combinations defined in the ISO 25358 (ISO 25358, 2018) was measured by using a High-Speed Imaging method. The results proved how the method can be a real alternative to the laser-based technique, emphasizing the fact that the spray quality categories were well distinguished. An investigation conducted by the French researchers Castanet et al. (2013), aimed at studying drop impact on heated surfaces, showed many advantages resulting from the combination of size and velocity measurements.

In absolute terms, the Shadowgraphy method stands out

among the other droplet sizing techniques as a powerful and versatile tool with a low cost. The main source of error in this technique relates to the limited Depth of Field (DOF); in fact, during the imaging processing, not all droplets appear sharp or in focus, making those that are unfocused larger than their real size. This leads to an overestimation of the droplet size distribution (Asgarian et al., 2020).

Many researchers have proposed some corrections to improve this limitation. For instance, the Franco-Belgian study of Minov et al. (2016) applied Shadowgraphy imaging for measuring droplet size and velocity from different nozzle types used in spray applications. To minimize the error due to unfocused droplets, the authors introduced an in-focus parameter as a function of the gray level gradient at the droplet edge, droplet diameter and gray level intensities of the background and droplet. Consequently, an in-focus criterion based on the droplet diameter was established to correct the measurement of droplet diameter and reject unfocused droplets. The US researchers Kumar et al. (2019) proposed a different approach based on digital inline holography (DIH), able to ensure high-resolution imaging of the sample over an extended depth of field typically several orders of magnitude larger than that of traditional imaging.

In an exploratory study by Sijs et al. (2021), the authors compared three methods for measuring droplet size in the range from 10 μm up to 2000 μm , namely, image analysis (commercial VisiSizer and developed in-house stroboscopic imaging), a Phase Doppler Particle Analyzer and a Laser Diffraction tool (Malvern Spraytec), using several nozzles and a surfactant-based adjuvant in such a way as to obtain fine, medium, very coarse and ultra-coarse sprays. They found that the larger the droplets,

the bigger the differences between the results obtained by the different methods (Figure 2.5).

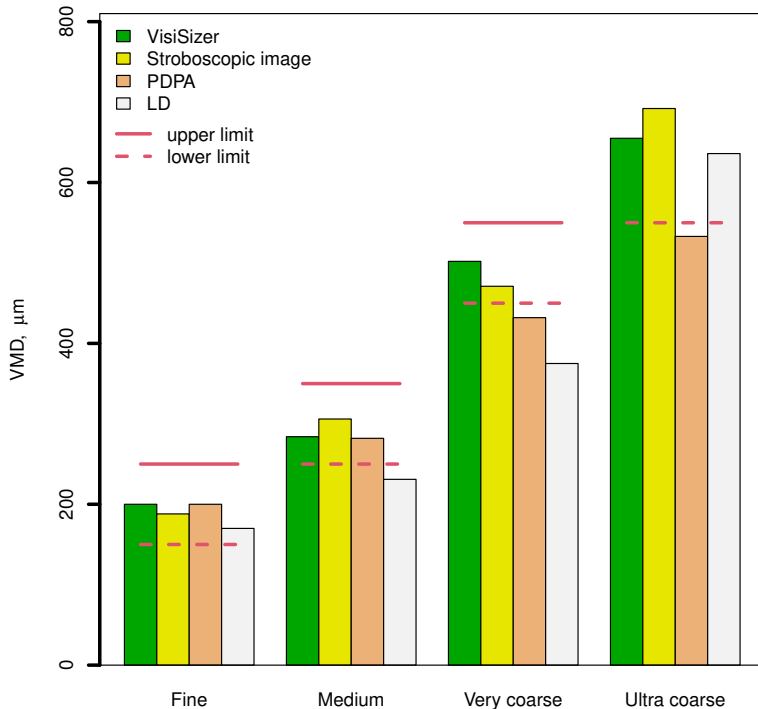


Figure 2.5: Comparison between non-intrusive measurement methods based on the research of Sijs et al. (2021). Upper and lower limits refer to the expected range for each spray quality.

In more detail, the commercial VisiSizer technique provided the same results as the in-house stroboscopic imaging when using the raw data (diameter of each single droplet) to calculate the probability density distribution, but differences were observed when the default software output was used, which

suggests that there is a bias toward counting bigger droplets due to their greater probability of being in focus. The PDPA technique requires homogeneous, transparent and spherical droplets. Non-spherical and inhomogeneous droplets due to the presence of air bubbles may be interpreted as slightly smaller drops, thus resulting in a finer drop size spectrum. The Laser Diffraction technique overestimates the contribution of small droplets due to their low velocity and then higher concentration in the sample volume, resulting in lower VMD measurements (Figure 2.5). In addition, since it uses a fitting method during measurements to obtain the drop size spectrum, distributions that deviate from the expected shape are misinterpreted.

Overall, the results emphasized how the limitations of each method can influence the droplet size measurements and also the need for selecting the size measurement method to fit the expected range of droplet parameters. In the Belgian study of Nuyttens et al. (2007), the authors compared their PDPA measurements with results from 17 references for the British Crop Protection Council (BCPC) reference nozzles and deduced that absolute results vary considerably between different investigators depending on the settings and type of measuring tool.

2.6 Intrusive Measurement Methods

Various intrusive methods based on image analysis have been used in the literature for spray characterization in agricultural treatments in order to provide accurate information on droplet size. Among these, in this section, we focus our attention on the use of Water Sensitive Papers (WSPs) and the Liquid Immersion (LI) method, which appear to be the most useful. They usually

involve the capture of a droplet sample on a solid surface or in a cell containing a special liquid. Then, the drops are photographed or observed with the aid of a camera or microscope. In general, these methods use a light source that is as diffused as possible to illuminate a collection of droplets, followed by software analysis of the images to determine all the droplet spray parameters. These methods, even if intrusive, have the virtues of simplicity and low cost, but the extraction and collection of representative droplet samples should be considered. Another aspect to be considered regards the resolution of the image, to be chosen according to the size of the particles to be extracted (Cerruto et al., 2022; Manetto et al., 2022).

2.6.1 Water Sensitive Papers (WSPs)

The use of WSPs is considered an important tool for the evaluation of agricultural spray parameters. They are semi-rigid papers of various sizes with one side covered with a yellow surface layer that changes its color to dark blue when in contact with water droplets, allowing the assessment of the droplet stains in spray tests. Being the most popular artificial targets used in agricultural spray applications, WSPs have been on the market for over 30 years. Due to their quick response in field, they are commonly used by farmers to evaluate the amount of covered surface (spray coverage) and the quality of deposition in terms of number of droplets per unit area (droplet density). They are normally placed at specific points for a given crop to check the spray coverage of a certain treatment. In addition, it is also recommended to place a large number of these targets to obtain a representative sample (Castrejón-García et al., 2011; Guler et al., 2012; Mangado et al., 2013).

Calculation of droplet size by using WSPs is heavily affected by the spread factor, i.e., the ratio between the stain diameter and the droplet diameter, which varies with physical properties of the liquid such as surface tension and with the direction and energy of the impact on the cards. Moreover, with a high degree of coverage, a halo grows around the stains that increases the area processed during the image analysis.

Several studies have been carried out to determine the characteristic diameters of spray by analyzing drop stains on WSP through image analysis techniques using commercial or freeware software based on the image processing of scanned WSPs or an app for smartphones (Cunha et al., 2013, 2012b; Ferguson et al., 2016; Marçal and Cunha, 2008). All these tools produce significant indicators related to the spray quality. However, as demonstrated by Cunha et al. (2012b), comparing the results obtained from seven software packages after the analysis of nine Water Sensitive Papers, there was a great difference among the results in terms of the calculated spray parameters. In the US study of Salyani et al. (2013), the authors, operating in a citrus orchard, assessed spray distribution and deposition using WSPs and analyzed them with three different image analysis systems. They found a good correlation among the three imaging systems in measuring the amount of area coverage of WSPs but concluded that WSPs cannot be used to quantify the amount of spray deposit in most field applications.

Although it is possible to visually determine if a treatment has been either insufficient or correct by counting the stains using a lens, it is advisable to analyze the cards using an image analyzer to obtain reliable results and to accurately verify the effectiveness of the treatment. *ImageJ* software, an easily accessible package,

is one of the most used during experimental tests because it can operate on any operating system, it is easy to use and it can perform a full set of imaging manipulations (Abràmoff et al., 2004) (Figure 2.6).

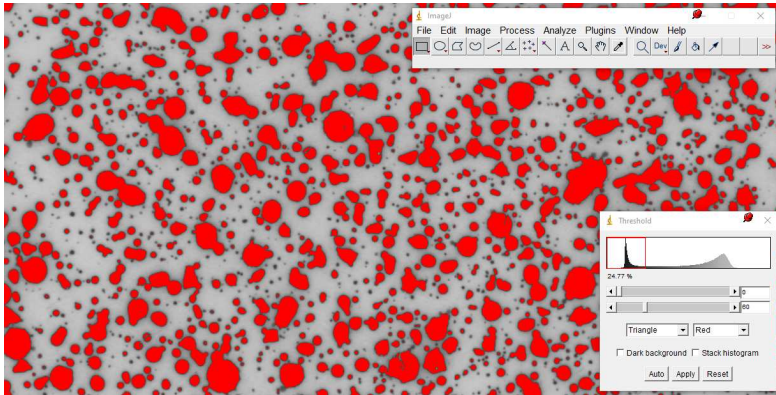


Figure 2.6: Example of a WSP image processed with ImageJ software. *Overlap between stains must be properly managed during drop size measurements.*

When WSPs are used, some negative aspects should be considered, such as the difficulty and slowness of analyzing them manually or in high-humidity environments ($> 85\%$), because, in this condition, the cards become unreadable, and there is a limitation in detecting drops with a diameter of less than $50\ \mu\text{m}$ as they do not generally contain enough water to create a detectable stain. Furthermore, the droplet spread varies with the physical properties of the spray liquid, such as the surface tension and temperature, and kinematics of the impact, such as the angle and energy of impact. Finally, using WSPs to determine droplet size may not be as accurate as other techniques, e.g., Laser Diffraction,

because larger droplets may coalesce after they impact on the cards, while small droplets may not be deposited. In general terms, WSPs show a quite good applicability for evaluations carried out in the field, representing a simple and low-cost tool for improving PPP application (Cerruto et al., 2019; Hoffmann and Hewitt, 2005; Özlüoymak and Bolat, 2020; Zhu et al., 2011).

2.6.2 Liquid Immersion (LI)

The Liquid Immersion method is considered one of the most popular mechanical techniques to measure droplet sizes and their distributions. According to this method, droplets are captured within a glass plate (or slide), usually a Petri dish, covered with a suitable fresh mixture of lightly viscose liquids, for instance, Vaseline, light mineral oil or silicone oil, which, due to their hydrophobic nature, cause drops to form almost perfectly spherical shapes. After Petri dishes are exposed to the spray, they are immediately photographed in situ with high-resolution cameras or observed with a microscope for subsequent scanning, allowing drop counting and size measurement. This step is performed to obtain magnified photographs, and, due to use of a camera and microscope, the method does not require special equipment (Eigel and Moore, 1983; Kathiravelu et al., 2016).

The method was applied by Eigel and Moore (1983) to develop a direct technique for measuring raindrop size and distribution for both laboratory and field use. Another application is described by Hulburt and Hanratty (2002) to obtain measurements of drop diameter in a horizontal annular flow of air and water in a pipe. Drop samples were captured in a high-viscosity oil, and photographic images of the samples were used to measure the distribution of diameters. A more recent application

of this method was described in an experimental study carried out in Italy by Longo et al. (2020) to construct a low-cost test bench useful for evaluating agricultural spray nozzles with hydraulic atomization under effective work conditions. In this trial, the droplets were collected within three Petri dishes containing silicone oil of suitable density and viscosity, photographed with a digital single-lens reflex (DSLR) camera and then their images were analyzed with *ImageJ* software to calculate the usual spray parameters (Figure 2.7). The results showed a good agreement with other measurement systems, even if some aspects still needed improvements.

When using the Liquid Immersion method, it must be said that there are several associated problems. Among these, one common limitation regards the determination of what fraction of the liquid surface area should be covered by droplets. In fact, if too many drops are collected, the probability of error due to overlap is high, and, consequently, drop counting is difficult; alternatively, if too few drops are collected, the sample may not be representative of the spray. Other important considerations are related to drop evaporation and drop coalescence. The evaporation effects are very significant in the measurement of fine droplets because, being too small to break the surface tension of the oil, they evaporate. Instead, regarding drop coalescence phenomenon, a solution could be the use of an immersion liquid with low viscosity and surface tension. This remedy may be applied satisfactorily for the problem of droplet breakup since the risk of disintegration of the largest droplets is relevant to the impact with the liquid. In addition, the Liquid Immersion method, even if it falls within the category of intrusive methods, is efficient, easy to use and does not require complex or high-cost

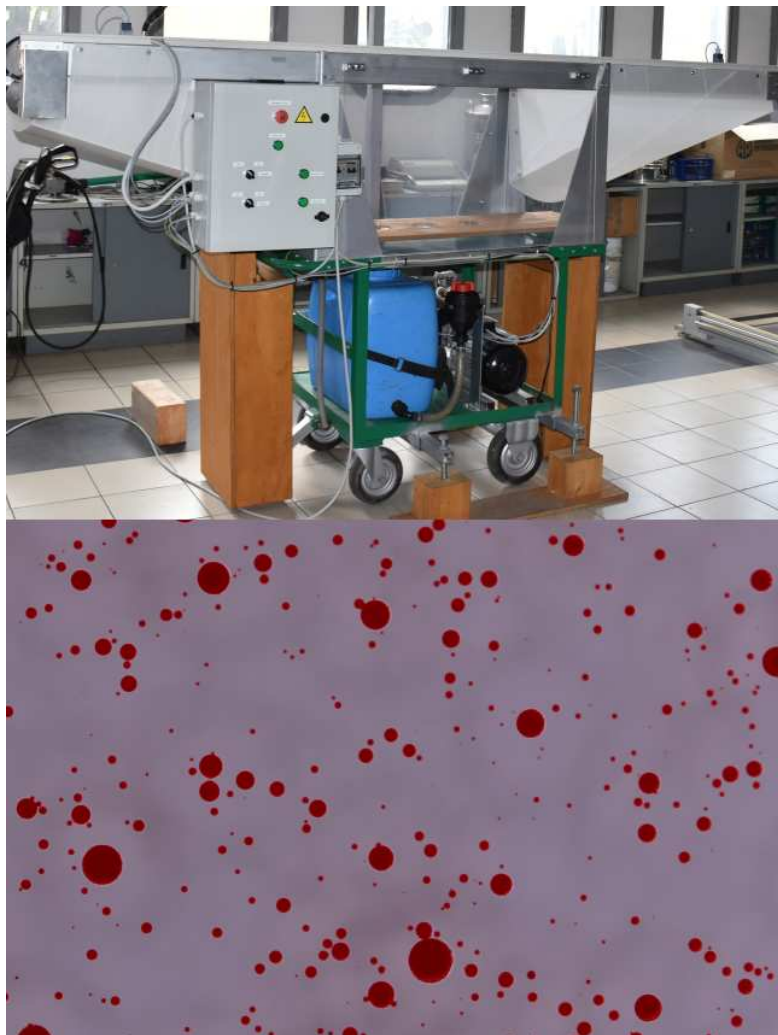


Figure 2.7: Test bench exploiting the Liquid Immersion method and example of drops (water solution with soluble red tracer) captured in Petri dishes containing silicone oil. Red color simplifies drop feature extraction during image processing with ImageJ.

equipment; it is also adopted to confirm the adequacy of the data obtained by optical methods, such as Phase Doppler Particle Analysis (Eigel and Moore, 1983; Kathiravelu et al., 2016).

Based on the research of Cerruto et al. (2019), the percentage of covered surface and stain density on WSPs were compared to the deposit and drop density on Petri dishes with silicone oil (Figure 2.8). Both targets (WSPs and Petri dishes) were simultaneously sprayed by means of an ATR 80 orange hollow cone nozzle (Albuz, France) at the pressures of 0.3 MPa, 0.5 MPa, 1.0 MPa and 1.5 MPa. Images of WSPs were acquired using a scanner at 600 dpi resolution, and images of drops on Petri dishes were acquired using a DSLR camera at 6000 pixels \times 4000 pixels; both images were processed using *ImageJ* software (Abràmoff et al., 2004).

The results showed that the droplet density and unit deposit measured on Petri dishes increased when the pressures increased due to the increase in both the flow rate and in droplet pulverization. On the contrary, the analysis of WSPs showed that, when the pressure increased, the mean percentage of covered surface also increased, but mean stain density decreased due to the overlap of stains. The authors concluded that the spray qualities of the ATR 80 orange hollow cone nozzle at the four pressures measured by adopting the Liquid Immersion method were in accordance with nozzle producer information. In addition, the spray deposit measured on Petri dishes was found to be highly significantly correlated to the covered surface measured on the WSPs.

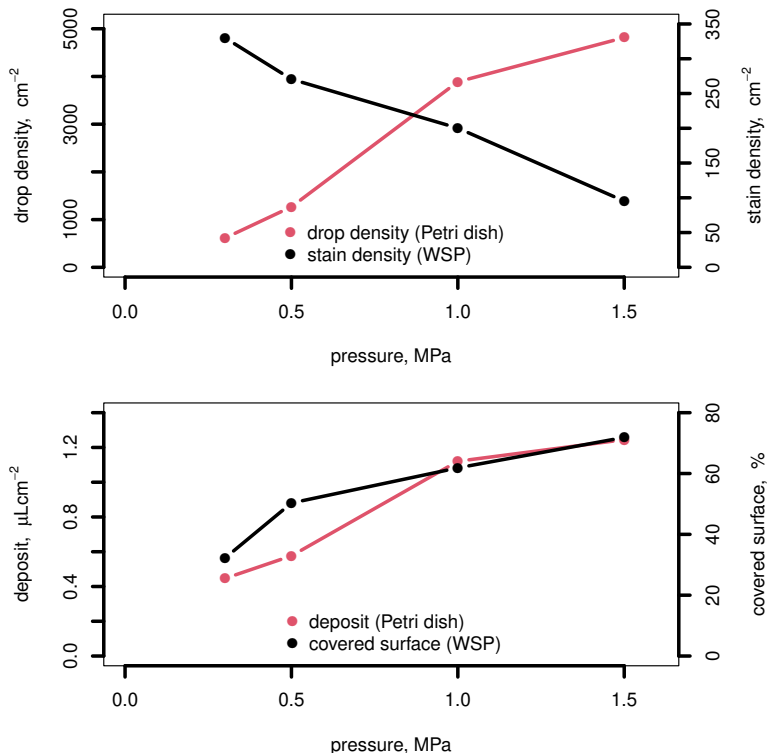


Figure 2.8: Comparison between Petri dishes and WSPs in terms of drop density, stain density, deposit and covered surface.

2.7 Machine Learning (ML)

In simple terms, the main task of Machine Learning is to develop learning algorithms that build models from data. Modern digital agriculture is characterized by great availability of data from a variety of sources (satellites, drones, cameras, sensors), and these data can be properly analyzed (artificial intelligence, deep learning, machine learning, Internet of Things) to build models able to guide decisions to optimize many agricultural

practices. As an example, the study of Rehman et al. (2019) surveyed the current applications of statistical machine learning techniques for agricultural machine vision systems able to ensure an increase in crop production by using automated, non-destructive and cost-effective techniques. The Indian study of Talaviya et al. (2020) discussed the implementation of artificial intelligence in agriculture for optimizing some agricultural tasks, such as irrigation, application of pesticides and herbicides, crop monitoring and guidance of drones and robots. Another study conducted by Australian researchers (Chlingaryan et al., 2018) carried out a review on ML approaches for crop yield prediction and nitrogen status estimation. The authors concluded that the rapid progress in sensing technologies and ML techniques provides cost-effective and comprehensive solutions for better crop yielding and decision making. A review of applications of artificial intelligence in agriculture was also reported in the Nigerian study of Eli-Chukwu (2019). The paper discussed the potentialities of artificial intelligence in soil, crop, disease and weed management.

Applications of ML methods to measurements and classifications of spray drop size are also common in the literature. The Iranian researchers Gargari et al. (2019) developed a piezoelectric sensor for detecting the vibration signals from the impact of droplets onto the active surface of the sensor. Vibration signal analysis allowed the building of a model able to classify spray droplets based on their VMD, previously detected by using WSPs. Another Chinese study by Guo et al. (2020) discussed different machine learning methods used to build mathematical models able to predict droplet size (VMD) and deposition in function of sampling location coordinates and for different types of noz-

zles. In the study of Pieloth et al. (2023), convolutional neuronal networks (CNN) were used to categorize sprays by analyzing the spray cone images. The authors reported that deviation from laser diffraction was less than 1.5%. Multiple regression models were used in the study of Liao et al. (2019) to predict several spray parameters (volumetric diameters, RSF, coefficient of variations) for different air-induction nozzles in the function of nozzle flow rate and spray pressure. Finally, a Chinese study carried out by Dong et al. (2023) on electrohydrodynamic atomization systems proposed the use of an artificial neural network model to efficiently and accurately correlate the relationship between the process variables (nozzle diameter, flow rate, liquid properties, distance between the nozzle and the grounding electrode, applied voltage) and droplet diameter, reaching determination coefficients near to unity.

All these recent techniques have been increasingly used in digital agriculture to address challenges in terms of productivity and sustainability. Their application in several sectors is expected to revolutionize many modern agricultural practices.

2.8 Final Considerations

Drop size measurement is a complex process that can be affected by various factors, and all measuring techniques are susceptible to various errors and ambiguities, the nature and importance of which depend on the particular method employed. A number of potential sources of error are common to almost all methods and include the sampling method, the sample size, the sampling location, the drop saturation, evaporation and coalescence and environmental conditions.

The sampling method (spatial or temporal) and sampling location affect results due to the different drop velocity. Pressure atomizers produce sprays with a high concentration of smaller drops near the atomizer because the smaller drops decelerate more quickly than larger ones. As a result, measuring the mean drop diameter using spatial sampling in this area produces smaller values than measurements taken using flux-based sampling. In sampling regions where all the drops are moving at the same velocity, the results obtained by both methods should be the same.

A spray from an agricultural nozzle contains a fraction of small drops much higher than that of large drops, but a few large drops predominate in determining the average volumetric diameter. Thus, if a sample of drops must be representative of the whole spray, the inclusion of large drops is vitally important. The ISO standard 5682-1 (ISO 5682-1, 2017) recommends computation of the spray parameters on at least 2000 droplets, but, in the absence of a stated confidence interval on a particular mean value, the sample size can even be greater.

Drop saturation occurs when the drop flux exceeds the capability of the sizing instrument or method. The problem is most evident when drops are collected on WSPs or Petri dishes. If the sample is too large, the probability of error due to overlapping and/or coalescence of drops (or their stains) is high. The evaporation effect, depending on environmental conditions, is very important in the measurement of fine sprays, as the lifetime of small drops is extremely short. This leads to an increase or decrease in mean drop size in the function of the initial drop size distribution.

While instrument designers strive to minimize these errors,

it is important to recognize that all measuring techniques come with some level of uncertainty. To accurately quantify the size of drops, it is necessary to consider these potential sources of error and their impact on the results.

In general, by controlling the VMD, farmers can reduce the amount of spray that is wasted or deposited in unintended areas, minimizing harm to the environment and surrounding crops. In addition, precision spraying with an optimized VMD can help farmers to reduce the amount of chemical they need to apply, leading to cost savings. Overall, the use of the VMD in precision spraying helps farmers to achieve more effective and efficient application of their sprays while reducing waste and potential harm to the environment.

New approaches based on artificial intelligence and machine learning methods may have impact on precision spraying. Applications of artificial intelligence in agriculture for irrigation, weeding, crop spraying and monitoring with the help of sensors and other means embedded in robots and drones allow the saving of water, pesticides and herbicides, maintenance of soil fertility and improved productivity and quality.

2.9 Conclusions

This review paper illustrated several techniques used for agricultural spray measurements, highlighting the importance of droplet size in PPP application. The droplet size spectrum has to be as uniform as possible to reach the target, avoiding very coarse or very fine droplets. Overall, in light of the recent introduction of precision agriculture principles, it helps to have a better deposit on the target to reduce both environmental contamination

and population risks (risks to farmers, consumers, bystanders). Measurement techniques were conveniently grouped into two main categories, namely, non-intrusive and intrusive systems. Some methods of both categories are based on digital image processing and on sophisticated Machine Learning techniques (multiple regression, neural network). Laser systems provide fast measurements but are unable to give reliable droplet size and distribution values. On the other hand, image analysis techniques can give accurate measurements of droplet size, but more time is needed to analyze droplets from a lot of images. Machine Learning methods have proven to be very reliable in providing deeper insights and precise predictions but require large amount of complex data during the training stages, with which it is impossible to cope with all the problems arising from agricultural cropping systems.

It has been shown in the literature that each measuring technique produces different results in terms of range of droplet sizes, depending primarily on type of nozzle and its orifice size, spraying pressure, mixture properties and, not least, the technique itself. All these factors should be considered when the atomizing capabilities of a nozzle are studied, and the measuring technique should be appropriate for the expected range of drop size and velocities.

Although there are various techniques able to measure droplet size distributions, information on their accuracy and on how they compare with each other is limited yet and has to be deepened. Hence, further studies and measuring campaigns should be aimed at comparing different working conditions while using the same technique, thus providing relative results. Absolute results are affected by the limiting factors spe-

cific to each technique, whereas relative sizes with respect to the reference nozzles always allow correct classifications. Finally, the potentialities of the latest available technological solutions (machine learning, artificial intelligence) should be better exploited and included in the precision agriculture principles to intensify agricultural production while limiting input requirements.

Chapter 3

Effect of Image Segmentation Thresholding on Droplet Size Measurement

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Validation	Emanuele Cerruto, Giuseppe Manetto
Formal analysis	Emanuele Cerruto, Giuseppe Manetto, Salvatore Privitera, Rita Papa, Domenico Longo
Investigation	Emanuele Cerruto, Giuseppe Manetto, Salvatore Privitera
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3.1 Abstract

Droplet size spectrum is a key factor in pesticide application because it affects the biological efficacy of a treatment in terms of target coverage, environmental impact in terms of evaporation, drift and run-off, and operator safety in terms of inhalation and dermal exposure. Droplet measurement methods based upon image analysis have to face the “binarization” or “segmentation” process, by which the objects of interest (the droplets) are extracted from the background. Segmentation is carried out by choosing appropriate threshold values, mostly based on the operator experience. In this study, images of droplets of an air induction nozzle TVI 8002 at four pressures (0.3, 0.5, 1.0, and 1.5 MPa) were obtained using the Liquid Immersion method. Each image was processed multiple times, firstly by using a “reference” threshold value based on the operator experience and then by using 11 different threshold values, chosen in the range of around $\pm 5\%$ of the reference threshold and based upon the average gray level of the image. For each threshold value, the corresponding spray parameters (volumetric diameters, mean diameters, Sauter diameters, and numeric diameters) were analyzed. The results showed that spray parameters had a statistically significant linear trend with respect to the threshold values in most cases. However, in absolute terms, variations were almost always less than 1.0% of reference values. This result allows considering the image acquisition system used in the present study as an automatic tool able to select the threshold according to the gray level of the image, making the whole segmentation process faster, more objective, and less dependent on the operator experience.

3.2 Introduction

Nowadays, in the field of pesticide application, the correct use of Plant Protection Products (PPPs) is the most common and powerful tool for crop pest control, and, for this reason, it is necessary to satisfy the growing demand for agricultural productivity in a more sustainable way (Blandini et al., 2008; Caffi et al., 2017; Grella et al., 2022; Hillocks, 2012; Maghsoudi et al., 2015; Miranda-Fuentes et al., 2017; Papa et al., 2018; Pérez-Ruiz et al., 2015; Pertot et al., 2017; Salcedo et al., 2021). According to the European Directive 2009/128/EC (European Union, 2009) for spray application, the handling of PPPs is considered an important aspect to avoid undesirable effects on the population and the environment, because, when pesticides are applied to crops, part of the spray may not reach the target, causing serious economic and environmental problems (Gil and Sinfort, 2005; Levitan, 2000; Roussel et al., 2000; Van Der Werf, 1996). Worker exposure, environmental effects, and biological efficacy are affected by several factors, including, but not limited to, amount and type of active substance, sprayer settings, types of nozzles and their maintenance status, and crop structure, which determine how well the targets are covered with liquid.

The droplet size spectrum plays a key role because it affects the biological efficacy of a treatment in terms of target coverage, environmental contamination in terms of evaporation, drift and run-off, and operator safety in terms of inhalation and dermal exposure (Cerruto et al., 2018; Cunha et al., 2012a; Hilz and Vermeer, 2013; Nuyttens et al., 2009; Tsakirakis et al., 2014; Wong et al., 2018). An optimal droplet size distribution has positive effects on the deposition process efficiency in order to simulta-

neously increase the benefits of PPPs and to reduce the risks of environmental and human contamination (Lodwik et al., 2020; Matthews, 2004). As an example, Ferguson et al. (2016), testing nozzles with different spray qualities in an oat canopy, found that droplet number densities were inversely related to the droplet size, yet coverage was increased more by application volume rate than droplet size. An exploratory study by Zwertvaegher et al. (2014) showed that droplet size also affects spray retention, influencing efficacy, economic losses, and environmental contamination.

As it is well documented in the literature (Bouse, 1994; Butler Ellis and Tuck, 1999; Butler Ellis et al., 1997; Dafsari et al., 2021; Kooij et al., 2018; Liao et al., 2020; Lin et al., 2016; Minov et al., 2016; Nuyttens et al., 2007; Parafiniuk et al., 2015; Prokop and Veverka, 2006; Vallet and Tinet, 2013), droplet size is affected by several factors, among which nozzle features, liquid properties, working pressure, air speed, climatic conditions, position, and technique of sampling. All these factors should be considered when the atomizing capabilities of a nozzle are studied. The International Standard ISO 25358 (ISO 25358, 2018) recognizes that the measurement and classification of droplet size spectra for applications of pesticides and other chemicals facilitate the description of sprays and therefore enhance efficacy and spray drift management. However, measurement systems and laboratories can produce different absolute values for a given droplet spectrum, due primarily to sampling effects, dynamic size range capabilities, data processing, and reporting (Sijs et al., 2021). Even if some of these differences can be minimized using appropriate sampling techniques, discrete differences in absolute values of droplet size spectra can still remain between measurement sys-

tems. An approach that has been successfully used for describing spray droplet size spectra involves the use of reference sprays to define reference categories, in order to increase uniformity in relative measures and classifications among different measurement systems and laboratories.

Several methods to measure droplet size are reported in the literature and several instruments exploiting different principles are available in the market. Droplet size spectrum is usually measured with intrusive or non-intrusive systems (Pascuzzi et al., 2021), which both have a strong influence on the results. Examples of non-intrusive systems are Phase Doppler Particle Analyzer (PDPA) (Lodwik et al., 2020; Nuyttens et al., 2006a, 2007), Laser Diffraction (LD) (Fritz and Hoffmann, 2016; Liao et al., 2020), and imaging principles (High-Speed Imaging (HSI), Shadowgraphy methods) (De Cock et al., 2015, 2016; Kapulla et al., 2006; Lad et al., 2011; Massinon and Lebeau, 2012; Minov et al., 2016).

Among intrusive techniques, based on digital image analysis, the most popular available in the literature include the use of Water Sensitive Papers (WSP) and the Liquid Immersion method. WSPs are one of the simplest and lowest-cost tools used by farmers to check the spray coverage of a certain treatment applied to any crop (Mangado et al., 2013). They consist of artificial targets with a yellow surface layer that turns dark blue when in contact with water (Syngenta, 2002); the analysis of droplet stains by means of image processing software, allows measuring the droplet diameters (Cerruto et al., 2013, 2019; Cunha et al., 2012b; Salyani and Fox, 1999; Sánchez-Hermosilla and Medina, 2004). Salyani et al. (2013), operating within a citrus orchard, reported somewhat weak correlations between WSP area coverage and

spray deposition, so they concluded that WSPs may provide a reasonably accurate estimation of area coverage, but could not be used to quantify the amount of spray deposits in most field applications.

In the Liquid Immersion method, droplets are collected on Petri dishes containing lightly viscose liquids, such as Vaseline, light mineral oil, or silicone oil, which, due to their hydrophobic nature, cause droplets to form almost spherical shapes. They are immediately photographed in situ by high-resolution cameras or observed with a microscope, allowing droplet counting and size measurement (Fujimatsu et al., 2014; Kathiravelu et al., 2016). The Liquid Immersion method, even if intrusive, is cost-efficient, 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 the adequacy of the data obtained by optical methods, such as the Phase Doppler Particle Analyzer (Fujimatsu et al., 2014). In general, these methods use as diffused as possible light sources to illuminate a collection of droplets, avoiding shadows formation, followed by software analysis of the images to determine the main characteristics of the spray droplets.

A common problem with these measurement methods concerns the “binarization” or “segmentation” of the image, which allows producing a binary image with only two values: one for droplets and another one for the background, in which it becomes possible to separate the droplets from the background. Other aspects to be addressed concern the resolution of the image, to be chosen appropriately in relation to the size of the objects to be extracted (Manetto et al., 2022), or the in-focus image identification when High-Speed Imaging, Shadowgraphy, particle/droplet

image analysis, or holography methods are used (De Cock et al., 2015, 2016; Kapulla et al., 2006; Kashdan et al., 2007; Kumar et al., 2019; Lad et al., 2011; Massinon and Lebeau, 2012; Minov et al., 2016).

Thresholding is one of the most common image segmentation methods for binarization, in which objects of interest are extracted from the image by assigning a pixel brightness as the threshold, which varies from 0 to 255 for an 8-bit gray-scale image. The accuracy of information that is extracted from digital images strongly depends on the success in selecting an appropriate threshold that becomes fundamental during segmentation (Al-amri and Kalyankar, 2010; Kapulla et al., 2006; Ozen and Guler, 2014). The choice of the proper threshold value is crucial for the image evaluation since it separates the pixels of interest from the background in such a way that it influences all subsequent measurements (Surový et al., 2014).

Several thresholding methods are available in the literature, among which the Huang method, based on Shannon entropy function (Huang and Wang, 1995), the isoData algorithm based on an iterative process that provides increasingly cleaner extractions of the object region (Ridler and Calvard, 1978), the mean method, that uses the mean of gray levels as the threshold (Glasbey, 1993), and the Otsu threshold clustering algorithm, that searches for the threshold that minimizes the intra-class variance (Otsu, 1979).

The basic problem of deciding if a threshold value or an extraction method is appropriate is ultimately user dependent. The final decision on which algorithm to apply under specific conditions or a specific experiment is necessarily subjective and application dependent. In general, the threshold value neces-

sary to obtain an informative binary image is correlated with the gray level of the image itself, so this correlation enables the selection of an adequate threshold when analyzing samples (Sánchez-Hermosilla and Medina, 2004). Unfortunately, using manual thresholding methods has several limitations, among which low reproducibility, higher user bias, tediousness and time-consuming, and high intra- and inter-user variability. Instead, there are multiple advantages to using automatic binarization methods over manual ones, among these: full reproducibility, reduction in preprocessing treatments, possibility of automation in macros, plugins, etc. On the other hand, even if automatic methods are used, the final choice of the method to be used is user dependent and the results may vary significantly.

The main objective of this study was to evaluate the effects of the threshold values used for image binarization on droplet diameter measurement. More specifically, we assessed how much variations of about $\pm 5\%$ in the choice of the segmenting threshold affect the computation of volumetric, mean and numeric diameters. The result may provide information useful for an automatic thresholding process, able to reduce the operator subjectivity and the measurement errors.

3.3 Materials and Methods

3.3.1 The Image Acquisition System

Spray droplets were captured by means of a custom-made test bench, built at the Section of Mechanics and Mechanization of the Di3A (Cerruto et al., 2017; Longo et al., 2020). The test bench allows analyzing nozzle sprays with hydraulic atomization ac-

ording to the procedure established by ISO 5682-1 standard (ISO 5682-1, 2017), based upon the Liquid Immersion method.

The test bench reproduces test conditions similar to those present in a standard sprayer with hydraulic atomization (Figure 3.1). The test liquid is contained in a 70 L main tank, from where it is pumped to the nozzle under test by means of a diaphragm pump (AR 30, Annovi Reverberi, Reggio Emilia, Italy), driven by a 2.2 kW, 230 V AC induction motor. The required pressure value may be adjusted by means of a manual pressure regulating valve. The nozzle is applied to a mobile support that moves along two horizontal rails, with travel speed controlled by a closed-loop position/speed controller, applied to a 240 W, 24 V DC brushed motor. Liquid pressure at the nozzle and flow rate are measured in real time by means of a piezoresistive pressure transmitter (Series 22 S, Keller Italy Srl, Milano, Italy) and an infrared flow sensor (SF800-6, Swissflow, Maarheeze, The Netherlands). The whole system (sensor signal acquisition, starting and stopping spraying, nozzle speed, data logging) is managed by a suitable self-made software user interface designed to run on a Windows 10 PC operating system.

The nozzle under test, while moving up to 1.5 m/s, sprays in a single pass the test liquid (clean water with soluble coloring agent *Red Ponceau*, Novema Srl, Turin, Italy, at the concentration of 2 g/L) above three Petri dishes (55 mm diameter, centers spaced 195 mm), each containing 5 mL of silicone oil (AR200, Sigma-Aldrich, Milano, Italy). The distance between the nozzle and Petri dishes is 0.5 m, chosen according to the ISO 5682-1 standard (ISO 5682-1, 2017), on which the construction of the test bench for the measurement of the droplet size is based. To reduce the effects of unwanted vibrations, the Petri dishes are placed

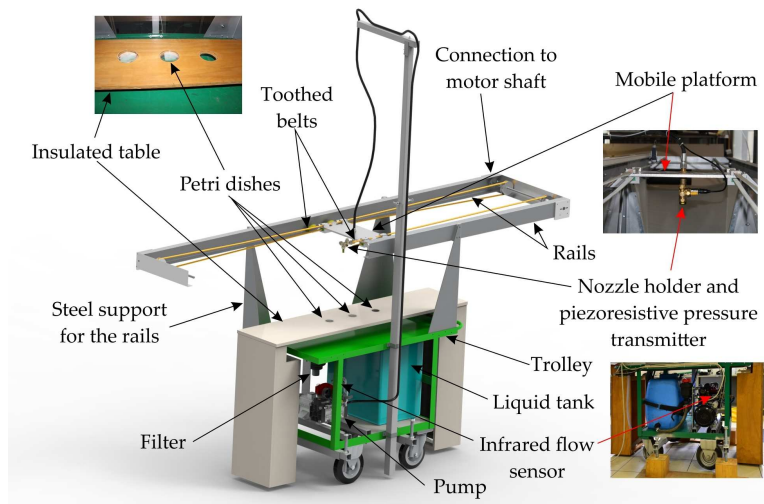


Figure 3.1: *Main components of the test bench.*

on a wood table, distinct and mechanically insulated from the whole apparatus.

The images of the droplets trapped by the silicone oil were acquired by using a high-resolution (6000 pixels \times 4000 pixels) DSLR camera (Nikon D5500, Nikon Corporation, Tokyo, Japan) equipped with a macro lens (Nikon Micro Nikkor AF-S 60 mm f/2.8 G ED, Nikon Corporation, Tokyo, Japan) and an electronic flash (Neewer 48 Macro LED Ring Flash, Shenzhen, Guangdong, China) and saved as high-quality color JPEG files. Figure 3.2 shows an example of the droplets trapped by the silicone oil. The red color of the tracer added to the water was functional for the subsequent recognition of the droplets in the image.

Images were spatially calibrated by taking photos of a known object (a 10 mm \times 10 mm grid pattern, 1 mm step, engraved on a glass disc, placed at the three positions of the Petri dishes). This

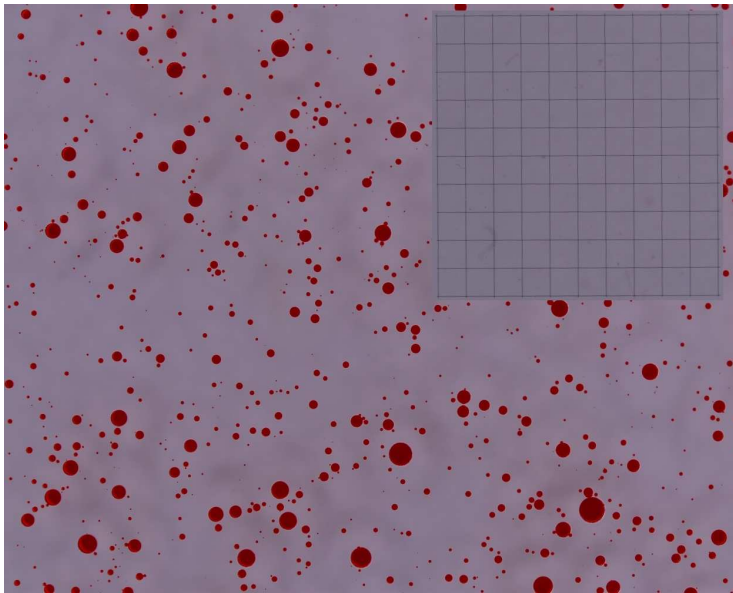


Figure 3.2: Example of image with the droplets captured by the silicone oil with superimposed the grid pattern for spatial calibration.

assured that the camera focal plane had the same distance for both droplets and pattern grid, and therefore it was possible to measure in pixels a known length (10 mm) along two orthogonal directions. Relating real length to pixel length, the average calibration factor C_f was $5.33 \mu\text{m}/\text{pixel}$.

Experiments were carried out with an air induction hollow cone nozzle TVI 8002 (Albus, France) at the pressures of 0.3 MPa, 0.5 MPa, 1.0 MPa, and 1.5 MPa, with a nozzle speed of 1.5 m/s. The corresponding flow rates were 0.80 L/min, 1.05 L/min, 1.47 L/min, and 1.76 L/min, respectively. Pressure values were chosen according to the manufacturer information so as to cover the usual range of use of the nozzle. Three repetitions were carried out per each pressure, so a total of 36 images ($4 \text{ pressures} \times 3$

repetitions/pressure \times 3 Petri dishes/repetition) were captured.

3.3.2 The Image Analysis Procedure

Droplet features extraction from images was based on the segmentation principle. Image analysis was carried out by means of the image processing software *ImageJ* (Abràmoff et al., 2004). The segmentation algorithms available as plugins in *ImageJ* were judged unsatisfactory for the present application, so a global thresholding based on the average gray level of the image was exploited. Original color JPEG images were converted into 8-bit gray-level images, segmented by applying the chosen threshold value, processed with the “watershed” binary filter to separate some touching particles (Li et al., 2021a), and then carefully inspected at a suitable zoom factor to manually remove some unrelated particles arising from the segmentation process or to separate some particles not separated by the watershed filter. Finally, all particles present in the images, except those touching the edges of the image, were extracted and for each particle the following items were considered (all data in pixel): area, primary and secondary axis of the best fitting ellipse, aspect ratio (ratio between primary and secondary axis), and maximum and minimum caliper (Feret diameters). These shape descriptors (best fitting ellipse axes and Feret diameters) were used to discharge particles strongly deviating from circularity, mainly deriving from the overlapping and subsequent separation of stains. In this study particles with aspect ratio and Feret diameters ratio greater than 1.50 were ignored. All particles lower than 5 contiguous pixels were considered as noise and then were also ignored. All data were saved in excel spreadsheets and then imported into R (R Core Team, 2021) for subsequent analyses.

3.3.3 The Experimental Activity

The experimental activity was organized in three steps:

1. Segmentation of all 36 images by using an “optimal” or “reference” threshold value (TV^r) based on the operator experience. More in detail, the operator adjusted the threshold value in such a way the droplet diameters in segmented images were as close as possible to real diameters, visually established by comparing the segmented images to the original ones, both carefully inspected at a suitable zoom factor. Results coming from this step were assumed as a reference for successive comparisons.
2. Study of the correlation between the “reference” threshold value (TV^r) and the average gray level (AGL) of the corresponding images so to explore the possibility of using a threshold value based on the objective characteristics of the images rather than on the operator subjectivity. This allowed to obtain a linear model (Equation 3.8 in the Results section) whose predicted value TV^* was significantly correlated to the average gray level of the image.
3. Reprocessing of each of the 36 images with 11 threshold values so to assess how much the choice of the threshold affects the calculation of the spray parameters. In detail, each image was segmented with the threshold value TV^* predicted by the linear model (step 2) based upon its average gray level, with five thresholds greater than TV^* and five thresholds lower than TV^* , with a step of one. A total of 396 segmented images were analyzed. Figure 3.3 shows the flow chart of the whole procedure.

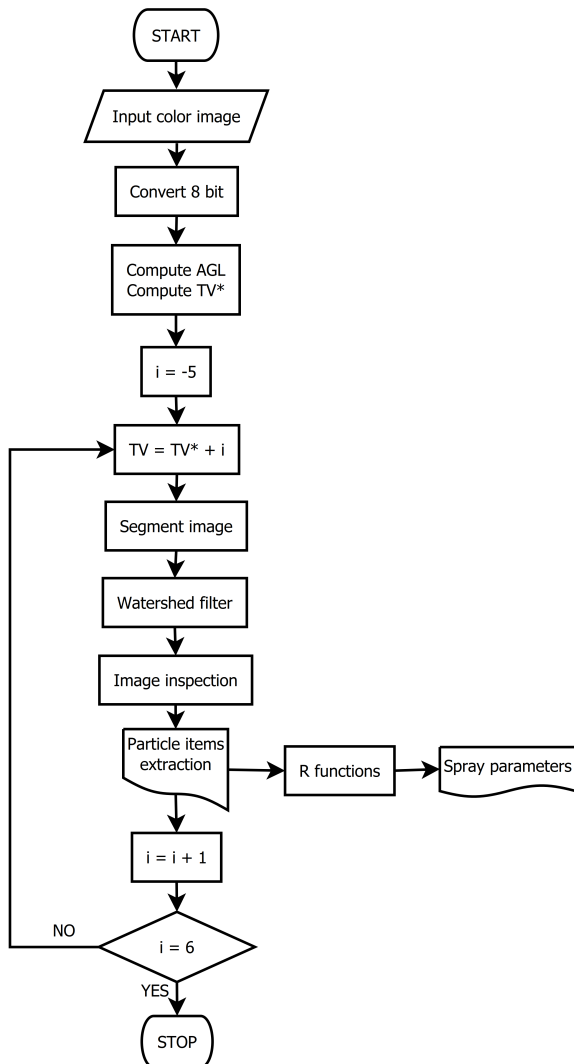


Figure 3.3: Flow chart of the image analysis procedure. Each image was segmented 11 times with 11 different threshold values (TV), computed in function of the average gray level (AGL) of the image and the threshold value TV^* predicted by Equation 3.8.

3.3.4 The Spray Parameters Calculation

Starting from the particle area A'_i (pixel), the corresponding particle diameter D'_i (pixel) was computed according to Equation 5.1:

$$D'_i = \sqrt{\frac{4A'_i}{\pi}} \quad (3.1)$$

Real-world diameter was obtained by applying the measured calibration factor:

$$D_i = C_f D'_i \quad (3.2)$$

Knowing the diameter of each particle (droplet), all the parameters usually adopted to describe a spray were computed.

$$\text{Arithmetic mean diameter: } D_{10} = \frac{\sum_{i=1}^N D_i}{N} \quad (3.3)$$

$$\text{Surface mean diameter: } D_{20} = \sqrt{\frac{\sum_{i=1}^N D_i^2}{N}} \quad (3.4)$$

$$\text{Volume mean diameter: } D_{30} = \sqrt[3]{\frac{\sum_{i=1}^N D_i^3}{N}} \quad (3.5)$$

$$\text{Sauter mean diameter (SMD) : } D_{32} = \frac{D_{30}^3}{D_{20}^2} \quad (3.6)$$

Volumetric diameter $D_{v\alpha}$: diameter below which smaller droplets constitute the fraction α of the total volume. The most common volumetric diameters are $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$. They represent diameters below which smaller droplets constitute 10 %, 50 %, and 90 % of the total volume, respectively.

$$\text{Relative Span Factor (RSF): } RSF = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \quad (3.7)$$

Number Median Diameter (NMD): diameter corresponding to the 50th percentile of droplet diameter distribution (50 % of droplet diameter is below NMD and 50 % is above NMD).

The particles of the three Petri dishes were unified for each repetition in such a way to compute the spray parameters on at least 2000 droplets, as recommended by the ISO 5682-1 (ISO 5682-1, 2017). All these quantities were computed by using custom-made R functions. Input data were the excel spreadsheets coming from image analysis with *ImageJ*. Average values were obtained at varying threshold values (TV) for each pressure and they were compared to those obtained when the reference threshold value (TV^r) was used.

3.4 Results

3.4.1 Reference Values

Table 3.1 reports the results of the measurements obtained when the reference threshold values TV^r were used.

Results were coherent with the expectations; in fact, all diameters were affected by pressure: when the spraying pressure increased, droplet size decreased. When the pressure increased from 0.3 MPa to 1.5 MPa, the volumetric diameter $D_{v0.5}$, usually adopted to describe the atomization capability of a nozzle, decreased by 52.0 % (from 864 μm to 415 μm). The Number Median Diameter (NMD) decreased by 9.2 % (from 109 μm to 99 μm), the arithmetic mean diameter D_{10} by 31.8 % (from 195 μm to 133 μm),

Table 3.1: *Spray droplet diameters (μm) and Relative Span Factor (average of three repetitions).*

Pressure (MPa)	D'_{10}	D'_{20}	D'_{30}	D'_{32}	NMD^r	$D'_{v0.1}$	$D'_{v0.5}$	$D'_{v0.9}$	RSF^r
0.3	195	293	391	694	109	441	864	1314	1.01
0.5	175	236	301	490	126	284	624	990	1.13
1.0	151	196	242	368	118	213	456	745	1.17
1.5	133	175	217	335	99	194	415	669	1.15

and the Sauter mean diameter D_{32} by 51.7% (from 694 μm to 335 μm). The Relative Span Factor (RSF) provides a practical mean for comparing various droplet size distributions. This parameter is indicative of the uniformity of the droplet size distribution: the closer this number is to 1, the more uniform the spray will be. In this study, RSF increased from 1.01 to 1.17 when the pressure increased from 0.3 MPa to 1.0 MPa. A further increase in pressure to 1.5 MPa produced a decrease in RSF to 1.15.

The cumulative volumetric curves are shown in Figure 3.4 as a function of the spray pressure. The graph was obtained by considering the average data of the three repetitions for each spraying pressure. All curves are clearly distinct, meaning a significant effect of the spray pressure on volumetric diameters.

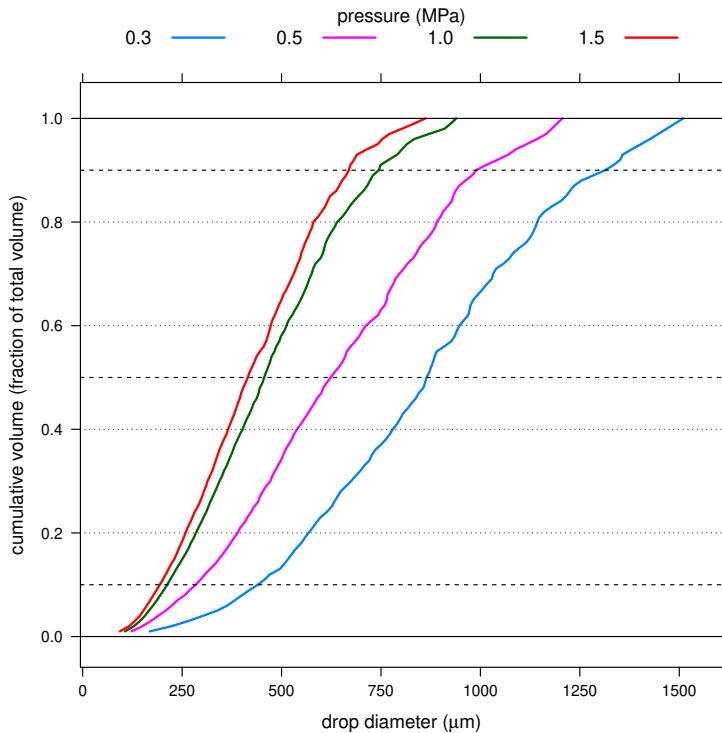


Figure 3.4: Cumulative volume curves as affected by spraying pressure.

3.4.2 Relationship between Threshold Values and Gray Levels

Figure 3.5 shows the relationship between the Average Gray Level (AGL) of an 8-bit image and the reference threshold value (TV^*) used for droplet segmentation, chosen on the basis of the researcher expertise.

The relationship was well described by the linear model:

$$TV^* = 1.0453 \times AGL - 24.4787 \quad (3.8)$$

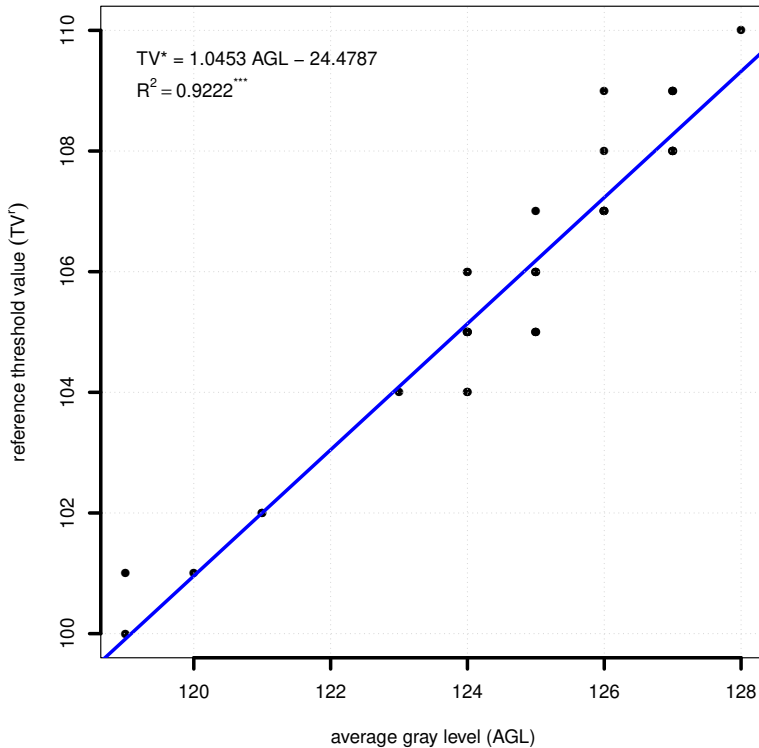


Figure 3.5: Relationship between the Average Gray Level (AGL) of an image and the reference threshold value (TVr) used for segmentation (***: statistically significant at p -level = 0.001).

with residual standard error 0.6994 on 34 df (degrees of freedom), multiple R-squared (R^2) 0.9222, F-statistic 402.8 on 1 and 34 df, and p -value highly significant (p -level < 0.001). Given the high statistical significance of the model, it was used to choose a threshold value operator-independent for subsequent analyses.

3.4.3 Effect of Threshold Value

Figure 3.6 shows the effects of the threshold on volumetric diameters $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$. All data are normalized with respect to the reference values, according to the following equations:

$$D_{v0.1}^n = \frac{D_{v0.1}}{D_{v0.1}^r}; \quad D_{v0.5}^n = \frac{D_{v0.5}}{D_{v0.5}^r}; \quad D_{v0.9}^n = \frac{D_{v0.9}}{D_{v0.9}^r} \quad (3.9)$$

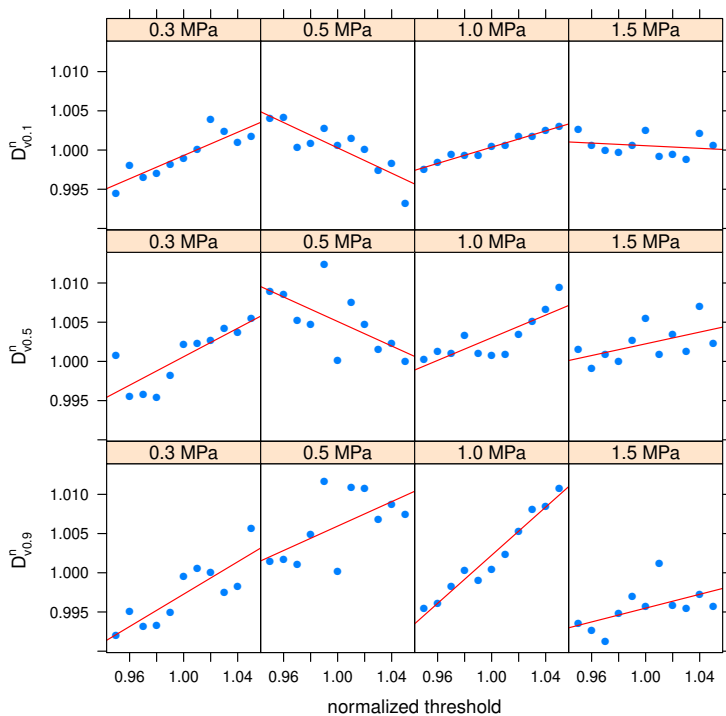


Figure 3.6: Variations in normalized volumetric diameters $D_{v0.1}^n$, $D_{v0.5}^n$, and $D_{v0.9}^n$ with respect to the normalized threshold.

For each sub-plot, threshold values are normalized with respect to the value TV^* predicted by Equation 3.8. Each point represents the average of the three repetitions. All sub-plots show quite evident linear trends, described by the equations summarized in Table 3.2.

Table 3.2: Regression equations between normalized volumetric diameters y and normalized threshold values x ($y = ax + b$).

Diameter	Pressure (MPa)	a	b	R^2	Signif.(1)
$D_{v0.1}^n$	0.3	0.0741	0.9252	0.7595	***
	0.5	-0.0808	1.0811	0.7226	***
	1.0	0.0519	0.9485	0.9697	***
	1.5	-0.0084	1.0089	0.0426	ns
$D_{v0.5}^n$	0.3	0.0908	0.9098	0.6603	**
	0.5	-0.0781	1.0832	0.4242	*
	1.0	0.0722	0.9308	0.6228	**
	1.5	0.0373	0.9649	0.2844	ns
$D_{v0.9}^n$	0.3	0.1032	0.8941	0.7006	**
	0.5	0.0779	0.9281	0.3590	ns
	1.0	0.1534	0.8488	0.9483	***
	1.5	0.0440	0.9514	0.2385	ns

(1) ***: significant at p -level = 0.001; **: significant at p -level = 0.01; *: significant at p -level = 0.05; ns: not significant.

The majority of the relationships (8 out of 12) were statistically significant, meaning that a significant effect of the threshold on the computation of the volumetric diameters. This result confirms the importance of the choice of the threshold value during the image segmentation process. However, according to the regression lines, absolute variations in volumetric diameters

ranged from about 99.5 % to about 101.0 % of reference values. Considering the reference values reported in Table 3.1, when the threshold value ranged from 95 % to 105 % of TV^* , variations in volumetric diameters predicted by regression lines were those reported in Table 3.3.

Table 3.3: Variations in volumetric diameters (range, μm) as predicted by regression lines reported in Table 3.2.

Pressure (MPa)	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$
0.3	439–442	861–869	1303–1317
0.5	286–283	629–624	992–999
1.0	212–213	456–459	741–752
1.5	194–194	415–417	665–668

As general trend, the max-min difference increased when the fraction α of the total volume in $D_{v\alpha}$ increased and decreased when the pressure increased. Differences in $D_{v0.1}$ ranged from 0 μm to 3 μm , in $D_{v0.5}$ ranged from 2 μm to 8 μm , and in $D_{v0.9}$ ranged from 3 μm to 14 μm . The highest difference was 14 μm and regarded $D_{v0.9}$ at 0.3 MPa. Considering the overall accuracy of the measuring system adopted in this study, these differences may be accepted and considered as measuring errors.

A more comprehensive assessment was based on the comparison between reference volumetric diameters and volumetric diameters computed at varying the threshold value. The comparison was carried out for all volumetric diameters ranging from $D_{v0.01}$ to $D_{v1.00}$ with a step of 0.01 and the deviations ($D_{v\alpha}^r - D_{v\alpha}$) for each threshold value, with $\alpha = 0.01-1.00$, are reported in Figure 3.7 for each spraying pressure.

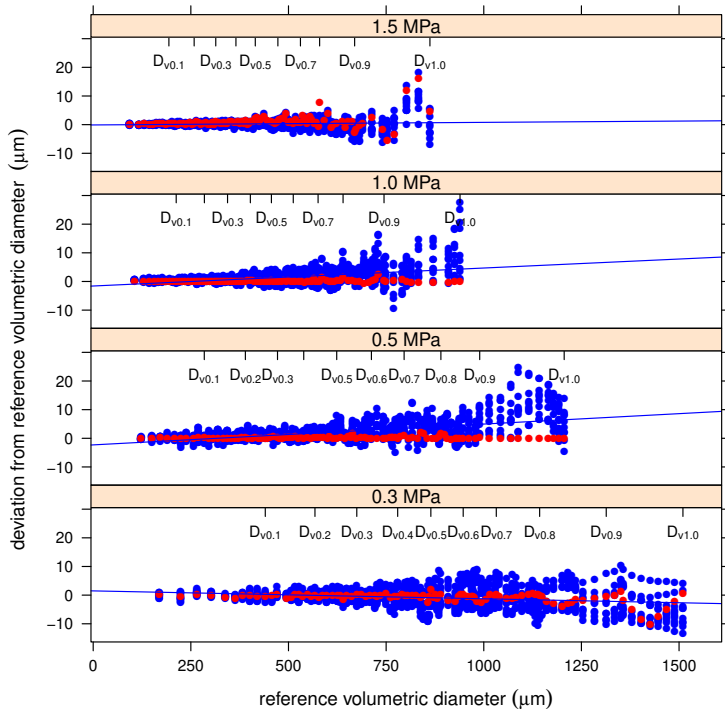


Figure 3.7: Deviations from reference volumetric diameters at varying of pressure (red points denote TV^* threshold).

The plot shows that deviations were almost centered across $0 \mu\text{m}$; however, when the volumetric diameter increased, the range of deviations among the 11 threshold values also increased. As an example, at 0.3 MPa , the range of deviations increased from $4.3 \mu\text{m}$ ($D_{v0.01}$) to $17.8 \mu\text{m}$ ($D_{v0.09}$), at 0.5 MPa increased from $3.1 \mu\text{m}$ ($D_{v0.01}$) to $11.2 \mu\text{m}$ ($D_{v0.09}$), at 1.0 MPa increased from $1.2 \mu\text{m}$ ($D_{v0.01}$) to $11.5 \mu\text{m}$ ($D_{v0.09}$), and at 1.5 MPa increased from $0.7 \mu\text{m}$ ($D_{v0.01}$) to $6.6 \mu\text{m}$ ($D_{v0.09}$). These results confirm that the uncertainty in the measurement of volumetric diameters, in

absolute terms, is affected by the choice of the threshold used for image segmentation and the effects are more pronounced at lower pressures (higher droplet diameters).

On the other hand, considering the results obtained when the image binarization was carried out with the threshold values TV^* predicted by the linear model described by Equation 3.8, the deviations from reference values were much smaller, ranging from $-2.8 \mu\text{m}$ ($D_{v0.9}$ at 1.5 MPa) to $2.3 \mu\text{m}$ ($D_{v0.5}$ at 1.5 MPa). This implies that segmenting the images using a threshold value based on the gray level may reduce deviations from reference values and make the entire process less subjective.

The results obtained considering the arithmetic mean diameter D_{10} , the surface mean diameter D_{20} , the volume mean diameter D_{30} , and the Sauter mean diameter D_{32} are shown in Figure 3.8. The linear trends in sub-plots were described by the equations summarized in Table 3.4.

Except for the Sauter Mean Diameter, in almost all other cases the trend was downward (coefficient $a < 0$), meaning a reduction in mean diameters when the threshold value increased. However, in most cases (10 out of 16), the regression lines were not statistically significant. Considering the reference values reported in Table 3.1, deviations predicted by the regression lines were almost always lower than $2 \mu\text{m}$. This result implies that choosing the threshold value in an interval of ± 5 points across TV^* , the effect on these diameters is negligible from the practical point of view.

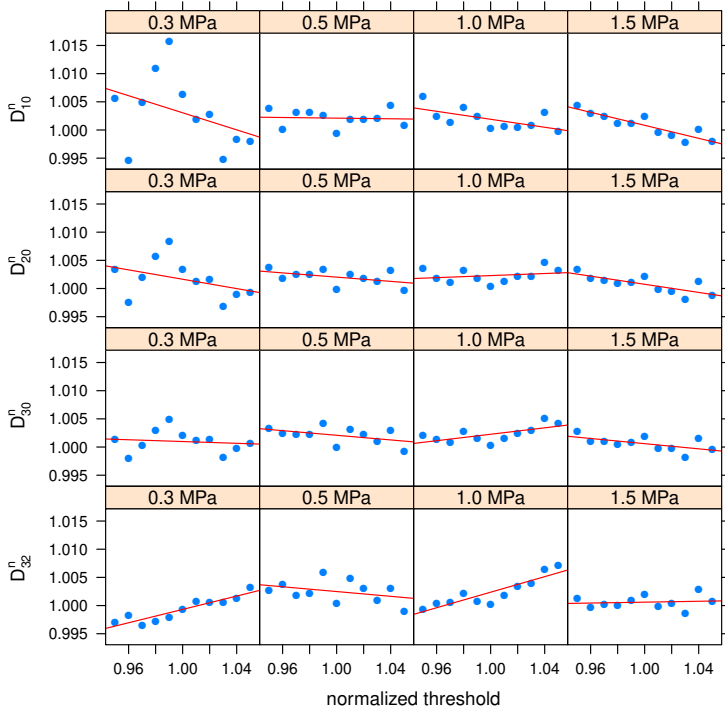


Figure 3.8: Variations in normalized arithmetic, surface, volume, and Sauter mean diameters with respect to the normalized threshold.

Finally, the results of the Number Median Diameter were similar: even if the regression lines describing the trends in NMD were statistically significant, variations in diameter values were always lower than $2 \mu\text{m}$.

Table 3.4: Regression equations between normalized mean diameters y and normalized threshold values x ($y = ax + b$).

Diameter	Pressure (MPa)	a	b	R^2	Signif.(1)
D_{10}^n	0.3	-0.0758	1.0788	0.1462	ns
	0.5	-0.0029	1.0050	0.0039	ns
	1	-0.0354	1.0373	0.3888	*
	1.5	-0.0578	1.0586	0.7960	***
D_{20}^n	0.3	-0.0415	1.0432	0.1580	ns
	0.5	-0.0188	1.0208	0.2121	ns
	1	0.0092	0.9931	0.0611	ns
	1.5	-0.0361	1.0369	0.5890	**
D_{30}^n	0.3	-0.0079	1.0089	0.0169	ns
	0.5	-0.0206	1.0227	0.2164	ns
	1	0.0286	0.9737	0.4375	*
	1.5	-0.0230	1.0236	0.3509	ns
D_{32}^n	0.3	0.0592	0.9401	0.8535	***
	0.5	-0.0212	1.0237	0.1242	ns
	1	0.0690	0.9334	0.8092	***
	1.5	0.0040	0.9967	0.0130	ns

(1)***: significant at p -level = 0.001; **: significant at p -level = 0.01; *: significant at p -level = 0.05; ns: not significant.

3.5 Discussion

Spray droplet size measurement is a very complex task that has been addressed in many ways over the years. All methods, both intrusive and non-intrusive, based upon the image analysis have to face and solve the problem of separating the objects of interest (the droplets) from the background by choosing an appropriate threshold value based on both image attributes and the operator experience. This approach leads to a lack of uniformity and the

reproducibility of the results is still uncertain, which is why different automatic thresholding algorithms have been developed (Glasbey, 1993; Huang and Wang, 1995; Otsu, 1979; Ridler and Calvard, 1978). In this study, a preliminary analysis carried out by using the most common automatic segmentation algorithms such as *isoData*, *mean*, and *Otsu* available as plugins in *ImageJ*, produced unsatisfactory results for the present application, so a global thresholding based on the average gray level of the image was exploited.

Several studies on spray image analysis have concerned the use of WSPs, despite their limitations when used to characterize spray droplet distribution and deposition in field application, especially when high volume rates are applied (Salyani et al., 2013). Measurements are affected by the threshold value used for image processing. Salyani and Fox (1999) applied a manual procedure to fit the threshold intensity for each sample. Panneton (2012) proposed a methodology similar to that investigated in the present study: for each card, a range of threshold values was applied, and the corresponding coverage was computed. The range of threshold values was chosen using a trial-and-error process and the “optimum threshold level” was determined from visual observation. Sánchez-Hermosilla and Medina (2004), working on samples with different coverage levels, established relationships between threshold and statistical image histogram parameters such as mean, mode, and median of gray levels. The best correlation was found with the mean gray level and resulted in a linear equation similar to Equation 3.8, but with different coefficients due to the different features of the images. Considering the “true” covered surface that was obtained by digitizing the images with CAD software, the mean relative error was 5.15% in the

coverage measurement. Finally, Xu et al. (2019) tested on WSP seven grayscale parameters and five threshold selection methods and concluded that the luminosity grayscale parameter and the max-min threshold selection method (based on the average of minimum and maximum grayscale to separate foreground and background of images) got the best results. Again, a manual validation was performed in comparison to the computer recognition results.

In general, each measurement technique produces different results. Sijs et al. (2021), comparing the image analysis VisiSizer technique, a stroboscopic imaging method developed in-house, a Phase Doppler Particle Analysis, and Laser Diffraction (Malvern Spraytec), reported that the larger the droplets, the bigger the differences between the results obtained by the different methods. The authors recommend the need for selecting the size measurement technique to fit the physical nature and the expected range of droplet parameters. Nuyttens et al. (2007), analyzing 17 bibliographic references of the results obtained in different laboratories, where different techniques were adopted to test reference nozzles pre-screened for laboratory purposes, reported a wide range of absolute measurements: when median values of $D_{v0.5}$ increased from about 140 μm to about 395 μm , the interquartile range was on average 24 % of the median values. Variations in results were then much higher than those experienced in this study due to the threshold choice, always lower than 1 %, except for $D_{v0.9}$ at 1.0 MPa (1.5 %) and NMD at 0.5 MPa (2.0 %). These results do not intend to be valid for each situation: the regression equation (Equation 3.8) may change if images are acquired with different light conditions, or if a different coloring tracer is used. However, the approach of choosing the threshold value here dis-

cussed remains valid and, after validation, can be implemented within automatic tools for image segmentation. Another limitation of the actual procedure is represented by the inspection of the segmented images to manually remove the unrelated particles introduced from the segmentation process or to separate the particles not separated by the watershed filter. This procedure is tedious, time consuming, and may reintroduce elements of subjectivity. In future developments, we will try to eliminate this step by applying filters on the extracted particles based on their size and their shape descriptors or developing a suitable algorithm capable of minimizing the noise.

3.6 Conclusions

Image analysis is present in several procedures for droplet size measurement, both intrusive and non-intrusive. A common problem to be addressed is the droplet features extraction from the image, which is affected, among other things, by the thresholding algorithm. In this study, images of droplets of an air induction nozzle were acquired by exploiting the Liquid Immersion method. Images were firstly segmented by applying a reference threshold based upon the operator expertise and subsequently, this reference threshold was correlated to the average gray level of the image. Having found that the correlation described by a linear trend was highly significant, each image was reprocessed 11 times using, in addition to the threshold value predicted by the regression (TV^*), five higher and five lower values with a step of one. In relative terms, this consists in varying the threshold value in the range of about $\pm 5\%$ of TV^* . The spray parameters were computed for each threshold value and the results were

compared to the reference ones. Results allowed drawing the following main conclusions:

- Volumetric diameters $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ varied linearly according to the variations in threshold values, and in the majority of cases trends were statistically significant. However, from the practical point of view, variations ranged from about 99.5 % to about 101.0 % of reference values (maximum variation of 14 μm), and then absolute errors, with respect to variations of about $\pm 5\%$ in the threshold value, were lower than 1.0 %.
- Error was affected by droplet size modified by spray liquid pressure: as a general trend, the max-min difference among the 11 threshold values increased when the fraction α of the total volume in $D_{v\alpha}$ increased and decreased when the pressure increased.
- Considering the results obtained when images were binarized using the threshold values TV^* , deviations from reference values ranged in absolute terms from $-2.8\ \mu\text{m}$ ($D_{v0.9}$ at 1.5 MPa) to $2.3\ \mu\text{m}$ ($D_{v0.5}$ at 1.5 MPa), corresponding to variations in relative terms from -0.43% to 0.55% . The practical effect on the three volumetric diameters $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ may therefore be neglected.
- The effects of threshold value on mean diameters, Sauter mean diameter, and number median diameter were similar to those observed for volumetric diameters, i.e., variations well described by linear trends, in six out of 16 statistically significant, but ranging from -0.21% to 0.68% for mean diameters and SMD and from -0.64% to 1.35% for NMD.

All considered, the study confirms the importance of accurately choosing the threshold for image binarization. Using a threshold value based upon the average gray level of the image can allow to develop an automatic tool for image segmentation that will be faster than manual thresholding and operator independent. Moreover, variations in the threshold value in the range of about $\pm 5\%$ have effects on droplet size parameters which can be considered negligible in practice. These results could be useful in developing automatic tools for image analysis without introducing significant errors.

Chapter 4

Comparison between Liquid Immersion, Laser Diffraction, PDPA, and Shadowgraphy in Assessing Droplet Size from Agricultural Nozzles

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4.1 Abstract

Spray droplet diameters play a key role in the field of liquid plant protection product (PPP) application technology. However, the availability of various measurement techniques, each with its unique operating principles for evaluating droplet size spectra, can lead to different interpretations of spray characteristics. Therefore, in this study, four measurement techniques – Liquid Immersion (LI), Laser Diffraction (LD), Phase Doppler Particle Analysis (PDPA), and Shadowgraphy (SG) – were utilized to evaluate the droplet size distribution of agricultural spray nozzles. Additionally, PDPA and SG were used to assess the average velocity of spray droplets. Experiments were conducted in three different laboratories with the main aim of comparing results obtained with various types of equipment utilized under ordinary practical conditions. Spraying tests were carried out using three flat fan nozzles and an air-induction flat fan nozzle. As a general trend, the lowest values for droplet diameters were measured using the Laser Diffraction technique, followed by Shadowgraphy. The PDPA technique provided the highest values for mean diameter (D_{10} , D_{20} , and D_{30}) and the numeric median diameter ($D_{n0.5}$), whereas the Liquid Immersion method yielded the highest values for the Sauter mean diameter (D_{32}) and volumetric diameters ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$). Importantly, all measurement techniques were able to discriminate the four nozzles based on their $D_{v0.5}$ diameter. Average droplet velocities showed a similar pattern across the four nozzles with the PDPA and the SG measurement techniques. The differences in diameter values observed with the four measurement techniques underline the necessity of always including reference nozzles in spray quality assessments to base

classifications on relative rather than absolute values.

4.2 Introduction

With the increasing demand for food production driven by significant population growth over the past decades, the application of Plant Protection Products (PPPs) in agriculture has become essential to enhance productivity and meet the needs of the global population (Tilman and Clark, 2015). While PPP application remains the most common tool for crop protection, in recent years, the European Directive 2009/128/EC (European Union, 2009) has served as a reference point for farmers and bystanders, promoting alternative approaches to PPP use. These approaches include the organic farm and the adoption of Integrated Pest Management (IPM) to sustain crop productivity and profitability (Ryalls et al., 2024).

Liquid PPP application is a complex task that requires consideration of various factors, including the diversity of sprayers and their operating parameters, different spraying methods, types of nozzles and their maintenance status, environmental conditions (such as temperature, relative humidity, and wind speed), and the operator's expertise. All these variables need to be taken into account during phytosanitary treatments as they determine how effectively the canopy crop is covered by the liquid mixture (Derksen et al., 2008).

The droplet size spectrum in spray applications holds significant importance as it directly impacts the effectiveness of applications in terms of target coverage, environmental pollution through evaporation, drift and run-off, and operator safety, encompassing risks of ingestion, inhalation, and dermal expo-

sure (Carvalho, 2017; Damalas and Eleftherohorinos, 2011; Kim et al., 2017; Wong et al., 2018). Consequently, in the field of agricultural spray applications, measuring droplet size distribution has long been recognized as a primary concern. Firstly, droplet size plays a crucial role in enhancing the biological efficacy of a treatment by ensuring optimal spray deposition on the target surface, whether it be a leaf, a fruit, etc. Secondly, droplet size contributes to reducing off-target losses, such as evaporation, drift, and run-off, while also minimizing negative repercussions on operator safety (Lefebvre and McDonell, 2017a).

Recognizing the pivotal role of droplet size spectra in treatment performance, the American Society of Agricultural and Biological Engineers (ASABE) developed the specific standard S572 (ASABE S572, 2020). This standard categorizes spray droplets into eight classes, ranging from extremely fine to ultra-coarse. The boundary between two adjacent classes is determined based on a set of reference nozzle-pressure combinations, following the guidelines outlined in the ISO 25358 standard (ISO 25358, 2018). This approach offers a practical and effective solution for the relative comparison of nozzles operating under identical laboratory conditions but utilizing different measurement techniques and setups (Fritz and Hoffmann, 2016).

This classification is also valuable for farmers in selecting the correct nozzle and working pressure for specific treatments. Thus, PPP applications can be executed carefully, minimizing the risk of productivity loss while mitigating unwanted effects on human health and the environment. Each nozzle, with its unique features, such as type, orifice size, and atomization capabilities, produces droplets within a specific size range. Thus, selecting the optimal nozzle-pressure combination is crucial to achieving the

highest treatment efficiency in terms of deposition on crop surfaces. Notably, nozzles that produce finer droplets are essential for achieving uniform coverage across the target plant surface, as these fine droplets can easily penetrate the inner parts of the canopy. Conversely, nozzles that generate coarser droplets are typically employed for anti-drift purposes (Chethan et al., 2019; Martins et al., 2021; Nuyttens et al., 2007). Therefore, agricultural nozzles can be regarded as the cornerstone of a spraying system.

The literature encompasses numerous techniques and procedures for measuring the droplet size of sprays as extensively explored by researchers. Leveraging the principles of measurement technology, droplet size can be assessed through either non-intrusive or intrusive methods, both of which significantly influence the results, particularly depending on the type of measurement technique and its settings.

Non-intrusive systems, such as Phase Doppler Particle Analysis (PDPA) (Nuyttens et al., 2006a), Laser Diffraction (LD) (Fritz and Hoffmann, 2016), and Shadowgraphy (SG) (Choo and Kang, 2004; De Cock et al., 2015; Minov et al., 2014; Murphy et al., 2004), while they are known for providing quick droplet size information, are often expensive, complex to operate, and require specialized equipment. On the other hand, intrusive techniques, such as Water Sensitive Papers (WSPs) (Salyani and Fox, 1999) and the Liquid Immersion (LI) method (Eigel and Moore, 1983; Fujimatsu et al., 2014; Hulburt and Hanratty, 2002; Kathiravelu et al., 2016), offer the advantages of simplicity and cost-effectiveness, but they must face challenges such as difficulties in achieving representative samples of droplets.

Over the years, numerous studies have investigated droplet size distribution, aiming to assess its impact using prevalent

measurement techniques. Sijs et al. (2021) conducted research comparing three methods for measuring droplet size: image analysis (using both the commercial VisiSizer and an in-house-developed stroboscopic imaging system), the PDPA technique, and Laser Diffraction (using the Malvern Spraytec). They utilized multiple nozzles and a surfactant-based adjuvant to vary droplet sizes between 10 μm and 2000 μm . The study revealed a direct correlation between droplet size and the degree of variation in results produced by the different methods, with larger droplets exhibiting greater variations in results. The authors concluded by emphasizing how the limitations of each method can influence droplet size measurements and underscored the importance of selecting the appropriate measurement method to match the expected range of droplet parameters.

da Cunha et al. (2019) conducted research to evaluate the droplet spectra produced by a flat fan nozzle under different pressures. They employed two direct methods: a Spraytec real-time analyzer and a Shadow Sizer particle image tool, as well as one indirect method based on Water Sensitive Papers. The use of different measurement techniques resulted in variations in the analyzed spray parameters. Particularly, the direct methods exhibited average differences of approximately 58 % in volume median diameters (VMDs), with the Spraytec device yielding the highest value. The authors also emphasized the need for caution when using WSPs for droplet size calculation due to difficulties in measuring fine droplets, which could potentially interfere with the obtained results.

Given the differences among these methods and measuring protocols, the primary objective of the present study was to compare four droplet size measurement techniques as applied in

three research laboratories under ordinary working conditions. Specifically, the aim was to evaluate two techniques based on laser principles (Laser Diffraction and Phase Doppler Particle Analysis) and two techniques based on image analysis processing (Liquid Immersion and Shadowgraphy). The focus was on examining how these four measurement techniques quantified the droplet size distribution produced by four agricultural nozzles under identical operating conditions. Many of the studies on this topic often report only the average values of volumetric diameters ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$) as measured with different methods. In this research, a comprehensive statistical analysis of volumetric, mean, Sauter, and numeric median diameters, as well as relative span factors (RSFs), is reported to highlight any differences between the measurement techniques. In addition, by presenting results obtained from various laboratories under practical conditions, the study recognizes the potential challenges in interpreting these results and acknowledges the discrepancies that may arise between measurements obtained using different types of equipment.

4.3 Materials and Methods

4.3.1 Experimental Setup

Four common droplet size measurement techniques were compared in measuring the droplet size distribution of four nozzle-pressure combinations: Liquid Immersion (LI), Laser Diffraction (LD), Phase Doppler Particle Analysis (PDPA), and Shadowgraphy (SG). Depending on their working principles, these techniques can be essentially categorized as laser-based (LD and

PDPA) or image processing (LI and SG) methods.

The measurements were conducted in three different laboratories: the LI method was employed in the Section of Mechanics and Mechanization of the Department of Agriculture, Food and Environment (Di3A) at the University of Catania (Catania, Italy); the LD system was implemented in the Department of Agricultural Engineering of the Federal University of Viçosa (Viçosa, Minas Gerais State, Brazil); and the PDPA and SG techniques were used in ILVO's Spray Tech Lab of the Flanders Research Institute for Agriculture, Fisheries and Food (Merelbeke, Belgium). A general view of the four experimental setups is shown in Figure 4.1.

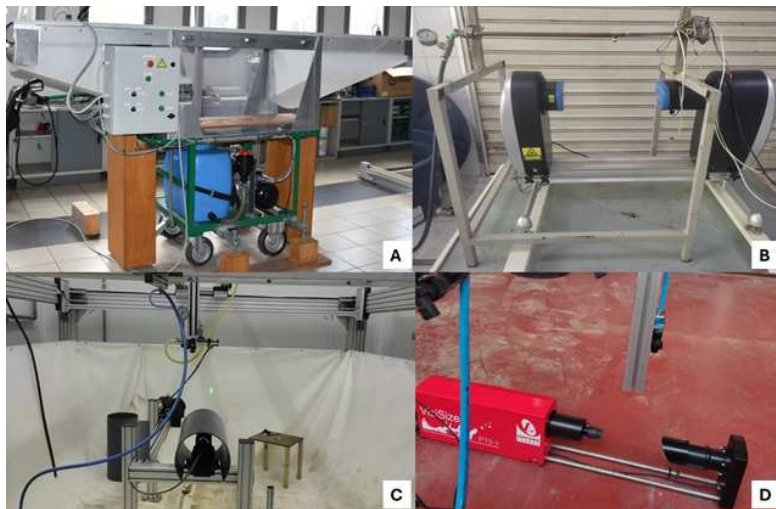


Figure 4.1: *Experimental setup. Test bench for the Liquid Immersion method (A). Laser Diffraction equipment (Spraytec Malvern) (B). Phase Doppler Particle Analyzer (C). Oxford Lasers VisiSize P15 (Shadowgraphy) (D).*

Liquid Immersion Method

The LI method was implemented using a custom-made test bench (Figure 4.1) designed and constructed in the Section of Mechanics and Mechanization of the University of Catania according to the guidelines provided by the ISO 5682-1 standard (ISO 5682-1, 2017). This test bench replicates a spraying system similar to those found in commercial sprayers with hydraulic pulverization systems. During the experiment, the nozzle under test moved at 1.5 m/s while spraying 0.5 m above the target plane. A comprehensive description of the test bench can be found in Longo et al. (2020).

For droplet size measurement, droplets sprayed by the nozzle were captured within three Petri dishes (55 mm in diameter with centers spaced 195 mm apart) containing silicone oil (AR200, Sigma-Aldrich, Milano, Italy). These dishes were placed on a wooden table mechanically insulated from the rest of the equipment to avoid any vibrations. Subsequently, the droplets were photographed in situ using a high-resolution camera with a resolution of 6000 pixels \times 4000 pixels, and the photos were saved as high-quality color JPEG images. Additionally, a calibration factor was calculated by photographing, under the same conditions, a glass disc with a 10 mm \times 10 mm grid pattern with 1 mm steps placed at the three positions of the Petri dishes. This process enabled the measurement, in pixels, of a known distance (10 mm) along two orthogonal directions. Thus, by relating the real length to the pixel length, the calibration factor was derived (4.9 $\mu\text{m}/\text{pixel}$) and applied to determine the real-world droplet size.

The spray droplet images were processed using *ImageJ* analysis software (Abràmoff et al., 2004). Initially, the original-color

JPEG images were converted to 8-bit gray-level images. Subsequently, the images were segmented using the Otsu algorithm (Otsu, 1979). Finally, the segmented images underwent processing with the “fill hole” filter to fill any empty spaces within particles and then the “watershed” filter to separate some touching particles.

For each segmented particle, several shape descriptors were extracted, including area (in square pixels), aspect ratio (the ratio between the maximum and minimum axes of the best-fitting ellipse), and Feret’s diameter ratio (the ratio between the maximum and minimum caliper lengths). Very small particles (up to 4 contiguous pixels) were excluded, as they were considered digital noise. Therefore, considering the calibration factor of $4.9\ \mu\text{m}/\text{pixel}$, the minimum diameter of detectable particles was $12\ \mu\text{m}$. In addition, particles with an aspect ratio or Feret’s ratio greater than 1.50 were also excluded because they strongly deviated from circularity. Spray parameter calculations were based on a sample of approximately 2200–17200 droplets per replication, depending on nozzle type.

Laser Diffraction System

For the LD technique, the Malvern laser particle analysis instrument (Malvern Instruments Ltd., Spraytec, Worcestershire, UK) was utilized, as illustrated in Figure 4.1. A 632.8 nm He-Ne laser with a diameter of 10 mm passed through the sampling zone where the droplets were sprayed. Subsequently, a series of 33 photodiodes, integrated into the lens, detected the resulting light diffracted by the droplets. The collecting lens, attached to the receiver, had a focal length of 750 mm and was capable of counting particles in the range between $2\ \mu\text{m}$ and $2000\ \mu\text{m}$. The distance

between the emitter and the receiver was set to 420 mm.

The system was managed by the Spraytec software. Based on Lorentz-Mie theory, the refractive indices for the material and the medium were provided before starting the spray measurements. Water, with a refractive index of 1.33, was selected as the material of the sprayed droplets, and air, with a refractive index of 1.00, was chosen as the dispersant medium. Additionally, a patented multiple scattering algorithm was enabled to correct for re-scattered light when measuring high-concentration droplet samples.

The spraying system comprised a 150 L plastic tank and a piston pump (Kawashima, model S40L, YungChi Y.C. Industrial Co. Ltd, Changhua Hsien, Taiwan) driven by a 2.2 kW induction motor. Pressure during measurement was monitored by a pressure gauge (Comam Ltd., Belo Horizonte, MG, Brazil). Additionally, adjustment of the required spray pressure was facilitated by a manual pressure-regulating valve. The spraying system also featured a spray boom with the nozzle holder. The spray boom was capable of continuous revolution to ensure the analysis of the entire spray jet. This movement was enabled by an electric motor (Bosch, model CEP, 12 V, Bosh GmbH, Gerlingen-Schillererhöhe, Germany) installed at the right end of the boom and powered by an external 450 W power supply unit.

During the measurements, the nozzle was applied on the spray boom at a distance of 0.5 m from the laser beam: its rotation of 180° on the plane between the two functional modules of the instrument defined the sampling zone as an arc-shaped path intersecting the spray jet. This ensured that all the cross section of the whole spray width was used during the measurement.

Phase Doppler Particle Analysis

The Phase Doppler Particle Analyzer is considered one of the most specialized pieces of equipment for measuring the droplet size and velocity of a spray. The measuring equipment utilized in this study comprised four main components: a climate room, a spray unit, a 3D positioning system, and a PDPA laser system (Figure 4.1). A comprehensive description of the measuring setup can be found in Nuyttens et al. (2006a).

The PDPA laser equipment utilized in this study was the PowerSight one-dimensional system (TSI Incorporated, Shoreview, Minnesota, USA). The system emitted green laser light with a wavelength of 532 nm and comprised an optical transmitter, a receiver unit, an electronic signal processor, and the FlowSizer software for data collection and analysis.

The transmitter and receiver had a focal length of 500 mm. In addition, the optical receiver included three separate photomultiplier tubes (PMTs) to convert the refracted light into electrical signals to be processed by a Real-Time Signal Analyzer (RSA). The light scattering angle of the receiving PMTs was set at 30 degrees (1st-order refraction) with respect to the incident beam. To optimize data quality in spray measurements, two process control parameters were considered. The PMT voltage was set to 580 V—large enough to ensure the detection of signals from smaller droplets within the flow—while the signal-to-noise ratio (SNR) was set to “medium”. The collecting lens ensured a measurable droplet size range between 0.5 μm and 2153 μm .

The settings of the PDPA equipment were selected to ensure that a minimum of 20 000 droplets were captured during the scanning process, thereby providing a reliable information on the droplet size and velocity distribution.

Spray measurements were taken at a fixed point by positioning the nozzle at the center between the two units of the instrument and at a distance of 0.5 m from the laser beam. The distance between the measuring volume and the ground was fixed at 0.8 m.

Shadowgraphy

The Shadowgraphy principle was exploited by using the Oxford VisiSize P15 particle analyzer (Oxford Lasers Ltd., Oxfordshire, UK) (Figure 4.1). Its camera can capture up to 15 000 droplets per second within a field of view (FOV) of $9157 \mu\text{m} \times 6906 \mu\text{m}$. Measurements were conducted over a run-time of 100 s to ensure a sample of approximately 13 000–16 000 droplets per repetition. During the test, the instrument was positioned centrally on the ground under the nozzle at an axial distance of 0.5 m and maintaining a fixed-point position. Any bounce of droplets from the ground was neglected. This measurement point ensured that the sprayed droplets passed transversely through the light source. The VisiSize P15 settings were configured to exclude all droplets with a sphericity below 0.7. Additionally, out-of-focus particles were rejected using a parameter that indicates the degree of focus based on the gray-level intensity at the edge of the droplet. Furthermore, droplets touching the edge of the image were automatically rejected to mitigate the border effect and maintain high measurement accuracy.

4.3.2 Experimental Trials

In this comparative study, four commercial nozzles from two different manufacturers were selected to evaluate droplet spray

characteristics: three stainless-steel flat fan nozzles manufactured by TeeJet Technologies (Spraying Systems Co., Wheaton, IL, USA) and one air-induction flat fan nozzle manufactured by Albuz (Evreux, France). The TeeJet nozzles were the TP 11001-SS, the TP 11003-SS, and the TP 11006-SS, while the Albuz nozzle was the AVI 11003. The TP nozzles were pre-screened by TeeJet to be used as reference nozzles for spray quality classification. When used at the pressures reported in the ISO/FDIS 25358 standard (ISO 25358, 2018), they define the following boundary regions: very fine/fine (VF/F), fine/medium (F/M), and medium/coarse (M/C) (Table 4.1).

Table 4.1: *Nozzles and test conditions used in the experiments.*

Nozzle Type	Manufacturer	Boundary	Nominal Pressure (MPa)	Nominal Flow Rate (L/min)
TP 11001-SS	TeeJet	VF/F	0.45	0.49
TP 11003-SS	TeeJet	F/M	0.3	1.175
TP 11006-SS	TeeJet	M/C	0.2	1.94
AVI 11003	Albuz		0.3	1.2

To ensure consistency and reliability across all measurement techniques, identical nozzles were used in all experimental tests conducted across the three laboratories. Three repetitions were carried out for each nozzle-pressure combination. Spraying stability data during the tests were available for the LI method only. In fact, the test bench management software allowed saving a log file with the main information on the experiment, including pressure, nozzle flow rate, nozzle speed, and position while spraying. During the tests, the average coefficient of variation

values were 0.75 % and 1.69 % for spraying pressure and flow rate, respectively. With the other measurement methods, the spraying pressure was adjusted before starting the measuring session and then was kept constant for the three repetitions. During the experiments, all nozzles were positioned at a height of 0.5 m (axial distance along the z -axis; Figure 4.2) from the sampling area.

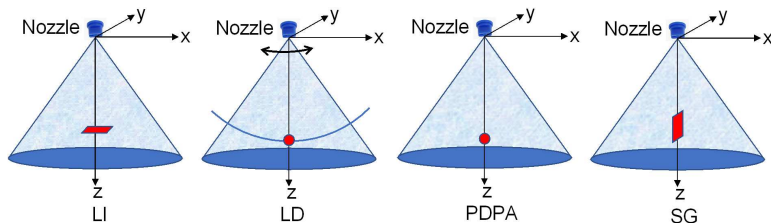


Figure 4.2: Sampling areas (red zones) of the four measurement techniques: Liquid Immersion (LI), Laser Diffraction (LD), Phase Doppler Particle Analysis (PDPA), and Shadowgraphy (SG).

With the LI method, the sampling area was a 6000-pixel \times 4000-pixel rectangle placed on the x - y plane, centered with respect to the z -axis. Considering the scale factor $4.9 \mu\text{m}/\text{pixel}$, the corresponding sampling surface was $29.4 \text{ mm} \times 19.6 \text{ mm}$. During the tests, the nozzle moved at 1.5 m/s along the y -axis while spraying. Sampling was repeated three times in correspondence to the three Petri dishes on the test bench (Figure 4.1). Droplets in the three Petri dishes were merged for each repetition before calculating the spray parameters.

With the Malvern equipment (LD), the sampling area was a fixed point on the z -axis at a distance of 0.5 m from the nozzle. The laser beam was directed along the y -axis. During the tests, the nozzle revolved around the y -axis at 1.1 rad/s . Specifically,

the measurement started with the nozzle in a horizontal position (rotated counterclockwise 90 degrees with respect to Figure 4.2). It then revolved clockwise 180 degrees before returning to the initial position by rotating counterclockwise another 180 degrees. In this way, all the spray jet was inspected by the laser beam during the measurement process. The measurement time lasted from 6 s to 7 s.

With the PDPA system, the sampling area was a fixed point located on the z -axis, 0.5 m distant from the nozzle. The laser beam was directed along the y -axis. With the VisiSize P15 instrument (SG), the sampling area was a 9.16 mm \times 6.91 mm rectangle placed on the y - z plane. The camera was aligned with the y -axis.

Differences in sampling areas and their effects on droplet size measurement were not considered in this study. The main objective of the study was to compare the results as they were obtained under practical conditions in different laboratories.

Simple water was used as the spraying liquid for all measurements, except for the Liquid Immersion method. For this latter, a food dye (*Red Ponceau*; Novema Srl, Turin, Italy) was added at a concentration of 2 g/L. Its red color facilitated the recognition of droplets in the acquired images and their subsequent analysis.

4.3.3 Measurements of Spray Droplet Characteristics

For the droplet spectrum analysis of the four nozzles, the following droplet size characteristics were considered:

- Volumetric diameters ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$): $D_{v0.1}$ and $D_{v0.9}$ represent the diameters at which 10 % and 90 % of the total volume, respectively, is composed of droplets smaller than or equal to these values. $D_{v0.5}$, also known as the

volume median diameter (VMD), is the diameter at which the 50 % of the total volume is composed of droplets with diameters smaller than or equal to this value.

- Relative span factor (RSF): a dimensionless parameter that indicates the degree of uniformity of the droplet size distribution within a spray. It is defined by the following equation:

$$\text{Relative Span Factor (RSF): } RSF = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \quad (4.1)$$

A lower RSF value indicates a more homogeneous droplet size distribution for a spray, with values closer to 0 representing greater uniformity. Conversely, the higher the RSF value, the less uniform the distribution.

- The arithmetic mean diameter (D_{10}) represents the average diameter of all the droplets within a given sample:

$$\text{Arithmetic mean diameter: } D_{10} = \frac{\sum_{i=1}^N D_i}{N} \quad (4.2)$$

- The surface mean diameter (D_{20}) refers to the diameter of a droplet whose surface area, when multiplied by the total number of droplets, equals the overall surface area of the droplet sample:

$$\text{Surface mean diameter: } D_{20} = \sqrt{\frac{\sum_{i=1}^N D_i^2}{N}} \quad (4.3)$$

- The volume mean diameter (D_{30}) refers to the diameter of a droplet whose volume, when multiplied by the total

number of droplets, equals the total volume of the droplet sample:

$$\text{Volume mean diameter: } D_{30} = \sqrt[3]{\frac{\sum_{i=1}^N D_i^3}{N}} \quad (4.4)$$

In these definitions of D_{10} , D_{20} , and D_{30} , D_i denotes the diameter of the i -th droplet, while N denotes the total number of droplets.

- The Sauter mean diameter (D_{32}) or SMD refers to the diameter of a droplet that has the same volume-to-surface area ratio as the total volume of all droplets to the total surface area of all droplets:

$$\text{Sauter mean diameter (SMD) : } D_{32} = \frac{D_{30}^3}{D_{20}^2} \quad (4.5)$$

- The numeric median diameter or NMD represents a diameter at which the 50% of the total number of droplets is lower than this value.

All these characteristics were calculated using the methodologies currently employed in each laboratory: starting from the single droplet diameters and employing custom R functions (R Core Team, 2021) for the LI method (University of Catania, Italy), extracting from VisiSize analysis reports for SG, utilizing appropriate Excel spreadsheets functions operating on single droplet diameters for the PDPA method (ILVO's Spray Tech Lab, Belgium), and relying on the values computed by Spraytec software for the LD method (Federal University of Viçosa, Brazil).

In this comparative study, droplet velocities were also examined using the PDPA system and the VisiSize P15 image analysis

tool. Only average droplet velocity values were considered.

4.3.4 Statistical Data Analysis

Experimental data were analyzed according to the primary objective of the study, which was to elucidate any differences between the measurement techniques. Thus, as a first approach, a two-way analysis of variance (ANOVA) was applied, considering for each nozzle the sum (DS) of all measured diameters (i.e., $DS = D_{v0.1} + D_{v0.5} + D_{v0.9} + D_{10} + D_{20} + D_{30} + D_{32} + D_{n0.5}$) as the dependent variable and the measurement technique and nozzle type as independent variables (Hill and Lewicki, 2007).

Subsequently, for a more in-depth analysis, multivariate analysis of variance (MANOVA) was applied, considering all diameters as dependent variables and the measurement techniques and nozzle type as independent variables. Univariate ANOVAs were conducted when statistically significant differences were detected. Mean separation was obtained by applying Tukey's honestly significant difference (HSD) test for multiple comparisons at a confidence level of 95 % (p -value < 0.05).

Data on average velocity were analyzed using univariate ANOVA, with the measurement technique (only SG and PDPA) and nozzle type as independent variables.

All statistical analyses and data plotting were performed using R version 4.3.0 (R Core Team, 2021) and the "tidyverse" package version 2.0.0 (Wickham et al., 2019).

4.4 Results

4.4.1 Overall Comparison

The univariate ANOVA applied to the sum (DS) of all measured diameters indicated significant differences between both measurement techniques and nozzles (Table 4.2).

Table 4.2: Results of ANOVA based on the sum (μm) of all measured diameters (mean separation between measurement techniques for each nozzle and between nozzles according to Tukey's HSD test at a p -level = 0.05). Means sharing the same uppercase letters in rows and lowercase letters in columns do not differ statistically.

Measurement Technique	TP 11001	TP 11003	TP 11006	AVI 11003	Mean
LD	679 ^c	1044 ^d	1407 ^c	2525 ^a	1414 ^c
LI	732 ^c	1482 ^b	1981 ^a	2685 ^a	1720 ^a
PDPA	954 ^a	1565 ^a	1889 ^a	2259 ^b	1667 ^a
SG	819 ^b	1174 ^c	1606 ^b	2496 ^{ab}	1524 ^b
Mean	796 ^D	1316 ^C	1720 ^B	2491 ^A	1581

Differences between nozzles were expected: TP 11001 exhibited the finest spray, followed by TP 11003, TP 11006, and finally AVI 11003. Across the various nozzles, the closest similarity was found between LI and PDPA, which provided the highest values for the sum of droplet diameters, followed by SG and LD. With the same nozzle, differences among the measurement techniques were most distinctive for the finest spray and decreased towards the coarsest nozzle (AVI 11003).

To gain insight into the droplet size distribution, cumulative volumetric curves for each nozzle and measurement technique were calculated (Figure 4.3). These curves were derived by aver-

aging the results of the three repetitions.

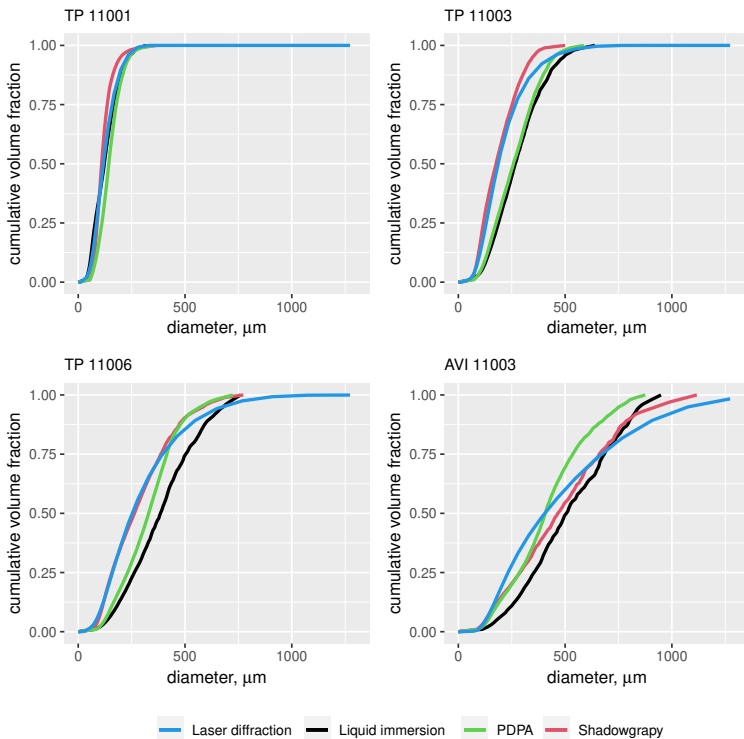


Figure 4.3: *Cumulative volumetric droplet size distribution curves for the four measurement techniques and the four nozzle-pressure combinations.*

Consistent with the results of the univariate ANOVA, the cumulative curves displayed distinct behaviours among the four measurement techniques when applied to the same nozzle. For instance, LD and LI yielded very similar results for the TP 11001 nozzle. Conversely, LI and PDPA showed similar performance for the TP 11003 nozzle, as did LD and SG. Additionally, LD and

SG exhibited similar performances with the TP 11006 nozzle. A lower degree of similarity was observed among the measurement techniques in characterizing the AVI 11003 nozzle.

For a more comprehensive analysis, MANOVA was applied to all considered diameters, and the results are presented in Table 4.3. The analysis revealed that, in most cases, the droplet size distribution parameters produced by the four considered nozzles exhibited significant differences when measured across various measurement techniques. This underscores that, despite identical testing conditions, the outcomes can vary. Consequently, a more specific analysis was conducted, focusing on volumetric and mean diameters.

Table 4.3: Results of MANOVA applied to all the considered diameters.

Source	df	Pillai	Approx F	Num df	Den df	<i>p</i> -Level
MT	3	2.6023	22.0834	24	81	< 0.001
Nozzle	3	2.2492	10.1108	24	81	< 0.001
MT:Nozzle	9	4.9235	5.6902	72	256	< 0.001
Residuals	32					

MT: measurement technique; df: degree of freedom; Num: numerator; Den: denominator

4.4.2 Volumetric Diameters

Figure 4.4 illustrates the effects of the measurement techniques on the volumetric diameters ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$) for the four nozzles considered.

All the measurement techniques correctly separated the four nozzles, classifying TP 11001 as the finest and AVI 11003 as the coarsest, regardless of the volumetric diameters considered.

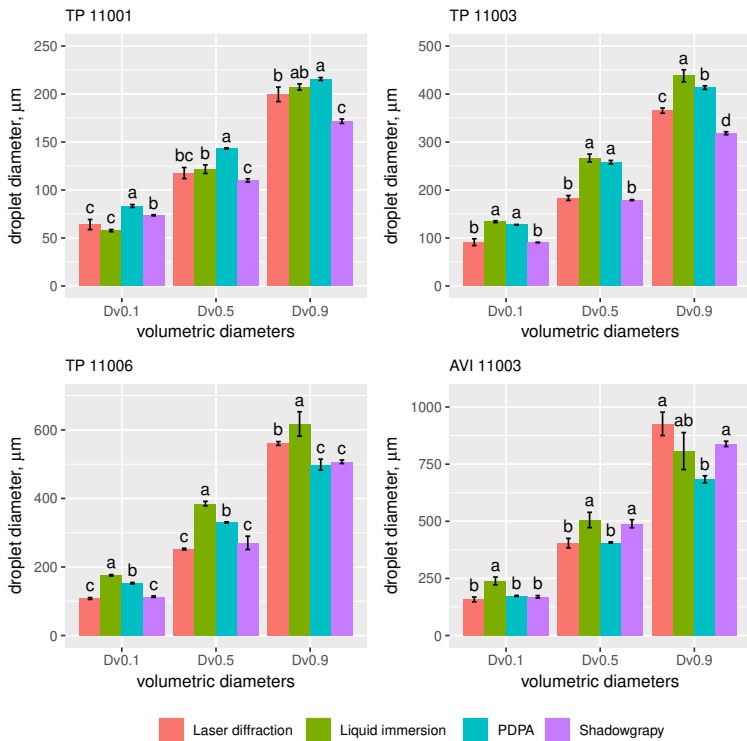


Figure 4.4: Comparison of the four measurement techniques when used for measuring volumetric diameters (mean separation with each volumetric diameter and for each nozzle by Tukey's HSD test at a p -level = 0.05; error bars represent standard deviations). Means sharing the same letters for each volumetric diameter across the four nozzles do not differ statistically.

However, when specific diameters were examined, the four measurement techniques provided statistically different values.

Overall, with the finest spray (TP 11001 nozzle), the PDPA technique provided the highest values of volumetric diameters. For the coarser sprays (all other nozzles), the LI method produced

the highest values for volumetric diameters, though in most cases they were not statistically different from those generated via the PDPA method. In almost all cases, Shadowgraphy provided the lowest values.

Assuming the average from the four measurement techniques as the reference value (\bar{x}) relative deviations (RD_i s) were calculated for each nozzle and volumetric diameter according to the following equation:

$$RD_i = \frac{x_i - \bar{x}}{\bar{x}} \quad (4.6)$$

where x_i is the volumetric diameter obtained with the i -th measurement technique. The mean of the absolute values for RD_i was around 13 %, and mean values decreased as volumetric diameters increased, i.e., from $D_{v0.1}$ (16 %) to $D_{v0.9}$ (8 %). This result implies that the relative differences in volumetric diameters were more pronounced with finer droplets than with coarser ones.

The reproducibility of the results, expressed in terms of the average coefficient of variation (CV) values of the volumetric diameters across the four nozzles, was highest with PDPA (with the lowest average CV of 1.25 %), followed by Shadowgraphy (CV = 2.00 %). Laser Diffraction exhibited the lowest reproducibility with the highest CV (4.23 %).

4.4.3 Relative Span Factors

The homogeneity of droplet size distributions, as indicated by RSFs, was examined to understand the variation in the uniformity of droplet size measured during the spraying process. The mean RSF values are shown in Table 4.4.

Considering the average values across all the spray nozzles, the analysis of variance showed that the four measurement tech-

Table 4.4: Means of relative span factors as determined by the four measurement techniques (mean separation with each nozzle by Tukey's HSD test at a p -level = 0.05). Means sharing the same uppercase letters in rows and lowercase letters in columns do not differ statistically.

Measurement Technique	TP 11001	TP 11003	TP 11006	AVI 11003	Mean
Laser Diffraction	1.16 ^a	1.49 ^a	1.79 ^a	1.90 ^a	1.58 ^a
Liquid Immersion	1.23 ^a	1.14 ^c	1.15 ^c	1.12 ^c	1.16 ^c
PDPA	0.93 ^b	1.11 ^c	1.05 ^c	1.26 ^{bc}	1.09 ^d
Shadowgraphy	0.89 ^b	1.27 ^b	1.46 ^b	1.37 ^b	1.25 ^b
Mean	1.05 ^C	1.25 ^B	1.36 ^A	1.41 ^A	1.27

niques produced statistically different results. More specifically, the PDPA system revealed the most uniform measured droplet size distribution with an RSF value of 1.09, which was significantly lower compared to the other measurement techniques. Conversely, LD showed the most uneven droplet size distribution (RSF = 1.58), with values oscillating between 1.16 for the TP 11001 nozzle and 1.90 for the AVI 11003 nozzle. These results were consistent for each nozzle.

Comparison of the nozzles while keeping the measurement technique unchanged showed a general trend of increasing RSF values from finer (TP 11001) to coarser sprays (AVI 11003).

4.4.4 Characteristic Mean Diameters

The analysis of variance, applied to the characteristic mean diameters (D_{10} , D_{20} , D_{30} , and D_{32}) and the NMD, showed that the measurement techniques produced statistically different results. Comparisons between the measurement techniques with the same nozzle are reported in Figure 4.5.

As a common trend, the LD method yielded lower values

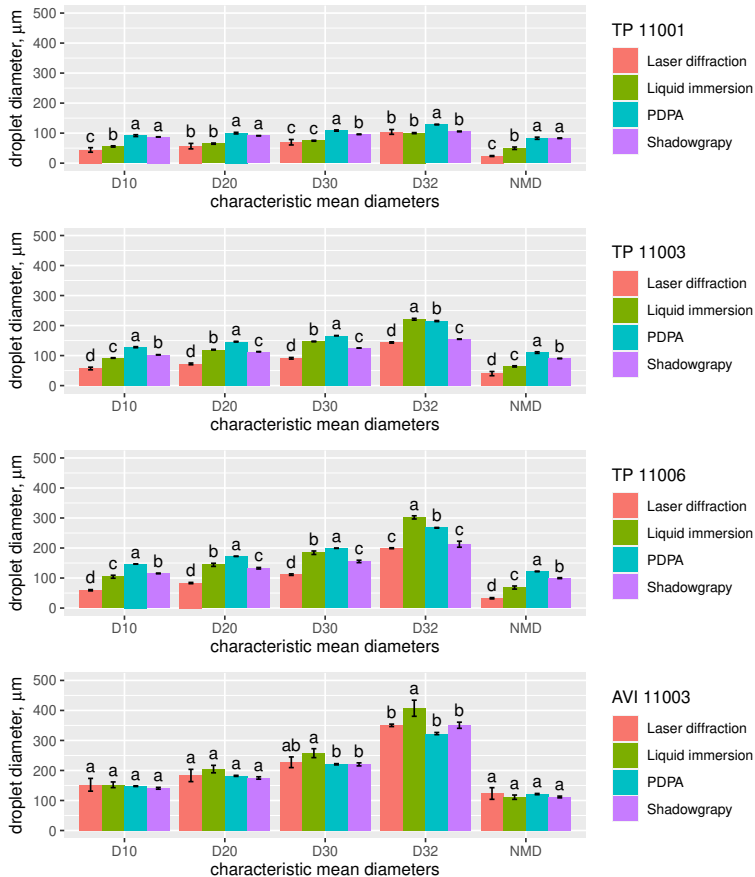


Figure 4.5: Comparison of the four measurement techniques when used for measuring mean characteristic diameters (mean separation with each diameter and for each nozzle by Tukey's HSD test at a p -level = 0.05; error bars represent standard deviations). Means sharing the same letters for each characteristic mean diameter across the four nozzles do not differ statistically.

for all diameters compared to those determined by the other methods when testing the four nozzles. This result confirms the higher sensitivity of the LD technique to smaller droplets

compared to the other techniques.

More specifically, with the TP 11001 nozzle, higher values of diameters were measured with the PDPA technique, which, in most cases, were not statistically different from those obtained via Shadowgraphy. Lower values were measured with Laser Diffraction, which, in some cases (D_{20} and D_{30}), were not statistically different from those obtained via Liquid Immersion. With the TP 11003 and TP 11006 nozzles, all measuring techniques provided results that were statistically different. In all cases, except for the D_{32} diameter, the highest values were provided by the PDPA technique. The differences among the measurement techniques were smaller with only the air-induction nozzle (AVI 11003), which produces extremely coarse sprays at 0.3 MPa, in accordance with the Albus catalog. For this nozzle, a slight predominance of the LI method was noted for the D_{20} , D_{30} , and D_{32} diameters, which were higher compared to those obtained by other measurement techniques.

Nozzle separation based on the mean characteristic diameters was less effective compared to the volumetric diameters. Specifically, as a result of the ANOVA, only the Shadowgraphy technique yielded statistically different values for the four nozzles for all diameters analyzed. In contrast, Laser Diffraction did not distinguish among the reference nozzles for D_{10} , D_{20} , and NMD diameters. Intermediate results were provided by the LI and PDPA techniques.

The greatest deviations from the average values of the four measurement techniques were found in the NMD diameters of the reference nozzles, ranging from -60% (TP 11001) to 51% (TP 11006). Conversely, NMD values were more uniform for the AVI 11003 nozzle, with an average absolute deviation of less than 5% .

Lastly, when analyzing the reproducibility of the results, measured as the average coefficient of variation values of the mean characteristic diameters across the four nozzles, the best performance was achieved with the PDPA and SG techniques (with CVs of 1.33 % and 1.51 %, respectively). Conversely, the worst results were obtained with the LD technique (CV = 7.95 %), while intermediate results were observed with the LI method (CV = 3.89 %).

4.4.5 Droplet Velocity

Figure 4.6 shows a comparison between the measured average droplet velocities using the PDPA and SG measurement techniques.

From the analysis of variance, it emerged that the two measurement systems produced average droplet velocities statistically indistinguishable across all nozzles (p -level = 0.231): 3.48 m/s with the PDPA system and 3.53 m/s with the VisiSize P15 tool. Considering individual nozzles, the two measurement systems produced statistically different results for TP 11001 and TP 11006 only, albeit with opposite trends. Specifically, Shadowgraphy measured higher velocity values for the TP 11001 nozzle, whereas the PDPA technique measured higher values for the TP 11006 nozzle. For the other two nozzles, the two measurement techniques provided similar results: around 4.48 m/s for TP 11003 and around 2.69 m/s for AVI 11003.

Furthermore, the comparison between the nozzles revealed that the reference nozzles exhibited increasing average droplet velocity values from the finest spray (TP 11001: 2.31 m/s) to the coarsest one (TP 11006: 4.54 m/s). In contrast, the air-induction AVI 11003 nozzle, despite producing droplets with a larger di-

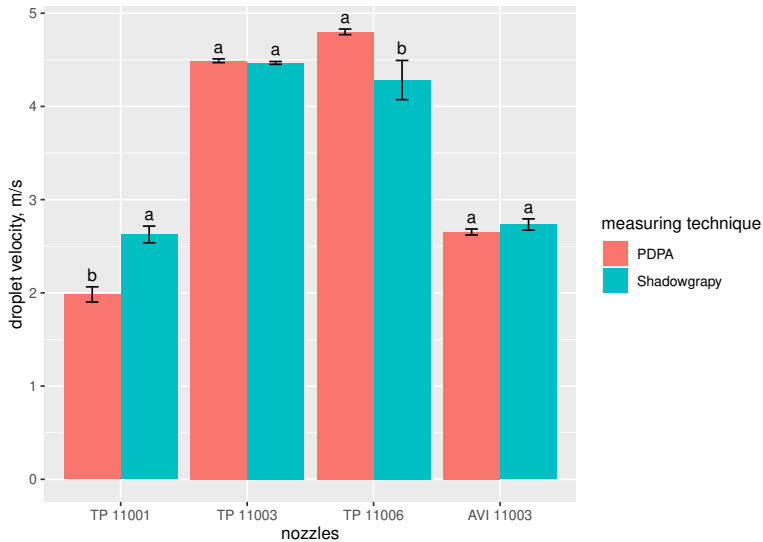


Figure 4.6: Comparison between PDPA and SG when used for measuring average droplet velocity (mean separation with each nozzle by Tukey's HSD test at a p -level = 0.05; error bars represent standard deviations). Means sharing the same letters for each nozzle do not differ statistically.

ameter, showed an average droplet velocity of 2.69 m/s. This reduction in velocity compared to TP 11006 and TP 11003 is likely attributable to the presence of air inclusions within the droplets, which decreased their volumetric mass. Consequently, the combined effect of drag force and gravitational force resulted in a reduction in velocity.

4.5 Discussion

The ranges of values of median volumetric diameters (VMDs) found in this study, considering all the measuring techniques,

were well differentiated across the tested nozzles. For the two laser-based techniques, VMDs ranged from 118 μm (TP 11001) to 404 μm (AVI 11003) for LD and from 143 μm (TP 11001) to 407 μm (AVI 11003) for PDPA. Concerning the image processing techniques, the VMD values ranged from 121 μm (TP 11001) to 506 μm (AVI 11003) for LI and from 110 μm (TP 11001) to 489 μm (AVI 11003) for SG.

Over the years, various researchers have tackled the topic of comparing different droplet size measurement methods, and some of their results align with our comparative study. For instance, many of our findings are consistent with the research conducted by De Cock et al. (2016), who investigated the droplet size distribution of six spray quality boundaries defined by the ISO 25358 standard (ISO 25358, 2018). They proposed a High-Speed Imaging device as a versatile and accurate tool for droplet size and velocity measurements, comparing results with the PDPA system. In addition, measurements were taken at a distance of 0.5 m from the nozzle for both techniques, as in our study. The authors obtained results closely aligned with ours, in particular, that the imaging technique yielded lower values for $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ compared to PDPA measurements for the VF/F (TP 11001), F/M (TP 11003), and M/C (TP 11006) sprays.

However, it is important to note that the volumetric diameters obtained with the PDPA system, and the high-speed device were, in most cases, higher than those reported in our present work. For example, the authors found VMD values of 155 μm (TP 11001), 240 μm (TP 11003), and 304 μm (TP 11006) when using the High-Speed Imaging system and 172 μm , 273 μm , and 366 μm when using the PDPA system. Their results indicated that, although the imaging technique provided lower VMD values compared

to PDPA, the differences were generally small (17 μm for the TP 11001 and 33 μm for TP 11003), except for the M/C spray class, where the difference was more pronounced (62 μm).

Similarly, the authors demonstrated that, consistent with our findings, the High-Speed Imaging technique exhibited a wider range of relative span factors (RSFs), with values ranging from 0.94 (TP 11001) to 1.31 (TP 11006). In contrast, the PDPA method yielded nearly constant RSF values, hovering around 1.00 (ranging from 0.94 for TP 11001 to 1.00 for TP 11006). Moreover, De Cock et al. (2016) found good agreement in droplet velocity measurements between both techniques, except for one specific nozzle-pressure combination (TP 11006).

The results of our study were also consistent with those reported by Miller et al. (2008), who conducted a comparative study of a new design for a double imaging instrument (Oxford Lasers VisiSizer) and a Phase Doppler Analyzer (PDA) to test reference flat fan nozzles positioned 0.35 m above the sampling area. The measurements from their investigation were reasonably aligned and showed a satisfactory correlation with those obtained in our research. The VMDs produced by the TP 11001 and TP 11006 nozzles, when measured with the imaging instrument, were found to be lower than those obtained via the PDA. Specifically, the reported values obtained with the two measurement techniques were 152.9 μm and 172.6 μm for TP 11001 and 340.6 μm and 349.8 μm for TP 11006. The only exception was TP 11003, which indicated a value approximately 22 μm greater with VisiSizer imaging (279.9 μm) compared to PDA (257.3 μm).

Additionally, as a general comparative observation, it was revealed that the VMD values obtained in our study were consistently lower than those reported in the Miller et al. (2008) research

across all nozzles. This discrepancy was likely attributable to the change in spray height. However, the TP 11003 nozzle was an exception, as the variation was found to be insignificant when assessed with the Phase Doppler instrument. In fact, the VMD obtained in our study with PDPA was 258 μm and that observed by Miller et al. (2008) was 257.3 μm .

Another noteworthy aspect concerns the common occurrence of measuring smaller droplet size diameters with the Malvern Spraytec instrument, which was validated in a specific comparison conducted by Dodge et al. (1987). In this study, an Aerometrics Phase Doppler Particle Analyzer and a Malvern Laser Diffraction instrument were used for this purpose. The authors stated that the mean droplet sizes, as measured with the PDPA system at various points in the sample, were generally larger.

In light of the aforementioned results, the differences among the measuring techniques may be primarily explained by the differences in the methodological procedures. Each method comes with drawbacks, limitations, and sources of errors, and the results are affected by various parameters (Privitera et al., 2023).

PDPA systems are point sampling devices and flux-sensitive instruments. This implies that the instruments focus on a portion of the total spray pattern and have to target several test points within the spray in order to obtain a composite sample of the spray flux distribution. Moreover, results are affected by droplet velocity in each class size (Schick, 2008). PDPA systems are complex, requiring precise alignment of lasers and optics, which can be difficult to set up and maintain, but it is crucial for accurate measurements and avoiding the introduction of significant errors. Moreover, in dense sprays, multiple scattering events can occur, complicating the interpretation of the scattered light and

leading to potential measurement errors. In cases of high droplet concentration, overlapping droplets can cause signal interference, making it difficult to accurately measure individual droplet sizes. Finally, as reported in Sijs et al. (2021), non-spherical droplets may be interpreted as slightly smaller droplets, resulting in a finer droplet size spectrum. The same applies to inhomogeneous droplets due to the presence of air bubbles, as in air-induction nozzles.

Laser Diffraction analyzers are spatial sampling devices. Despite being widely used for measuring droplet sizes in various applications, they have several drawbacks and inaccuracies, as reported in Kelly and Etzler (2006). In LD instruments, a curve-fitting program is used to convert the light intensity distribution into any one of several empirical drop-size distribution functions, such as the Rosin-Rammler or the log-normal distributions. Based on Lorenz-Mie theory, LD assumes that all particles are spherical. In reality, droplets can be irregularly shaped, which can lead to inaccurate size measurements. The most serious limitation of this technique is the multiple scattering, which occurs in dense sprays when the light, before reaching the detector, is scattered by multiple drops. This can complicate the interpretation of diffraction patterns and result in errors. The results of the LD technique can be influenced by overestimation of the number of small droplets due to their low velocity and thus higher concentration in sample volumes (Sijs et al., 2021). The accuracy of LD measurements depends on correct knowledge of the refractive indices of droplets. Variations in refractive indices, due to differences in temperature, composition, or phase, can affect results. Moreover, droplets at the edges of the laser beam or inhomogeneities present in the optical system can cause

distortions in diffraction patterns, leading to errors in size determination. Finally, regular calibration and precise alignment of the optical components are required to ensure accurate measurements. Misalignment or poor calibration can lead to significant errors.

Among the drawbacks of the Shadowgraphy technique, Erinin et al. (2023) reported limitations in resolution due to the optical setup, including the camera resolution and the quality of the lenses used. Small droplets (less than 50 μm in radius) might not be accurately resolved. Moreover, real-world sizes are obtained using a calibration target (reticle): any errors in calibration can directly affect the accuracy of droplet size measurements Cerruto et al. (2021a). Erinin et al. (2023) found that holography can measure droplet radii more accurately than Shadowgraphy. Accurate detection of droplet edges is crucial for size measurement. Variations in lighting, droplet transparency, and background noise can complicate edge detection, leading to measurement errors. Factors such as vibration, air currents, and temperature changes can affect the stability of the optical setup and the quality of the images, leading to measurement errors. Shadowgraphy is highly sensitive to the quality and uniformity of illumination. Inconsistent lighting can cause shadows and reflections that distort droplet images. The technique has a limited depth of field, meaning that only droplets within a certain distance range from the camera are in sharp focus. Out-of-focus droplets can be inaccurately sized or missed entirely. Finally, the technique requires advanced image processing algorithms to accurately identify and measure droplets. In dense sprays, droplets can overlap in images, making it difficult to distinguish individual droplets and accurately measure their sizes. This can be computation-

ally intensive and may introduce errors if the algorithms are not robust.

The Liquid Immersion method, in contrast to the other three, is intrusive. In fact, it measures droplets immersed in another liquid rather than “flying” droplets. This represents an important drawback due to droplet evaporation and coalescence. The evaporation effects are very significant in the measurement of fine droplets because, being too small to break the surface tension of the immersion liquid (silicone oil), they evaporate. Moreover, coarse droplets may fragment when they hit the immersion liquid surface. Coalescence phenomena may occur during or after terminal resting inside the emulsion. All these aspects—evaporation, fragmentation, and coalescence—may result in droplet size measurement error (Fujimatsu et al., 2014). However, considering the operating conditions of this study (room temperature, very low time of measurement, and water surface tension higher than silicone oil surface tension), errors due to evaporation, coalescence after resting, and droplet fragmentation can be neglected. Another limitation regards the fraction of the liquid surface area that should be covered by droplets. If too many droplets are collected, the probability of error due to overlap is high, and, consequently, droplet counting is difficult. Moreover, overlap between droplets, despite the use of the “watershed” filter, may explain the greater volumetric and Sauter mean diameters measured with LI respect to the other techniques. Alternatively, if too few droplets are collected, the sample may not be representative of the spray. A further limitation is the sample preparation, which can be complex and time-consuming. It often requires careful handling to ensure that droplets are adequately suspended in the immersion liquid without coalescing or breaking apart. Like other meth-

ods, LI presupposes spherical droplets: this may not always be the case, especially for larger droplets or those containing small air bubbles. Distortions and deformations may also occur due to the properties of the immersion liquid, such as its refractive index, viscosity, and surface tension. Like other image-based measurement techniques (Shadowgraphy), LI requires precise calibration for accurate measurements. Errors in calibration factors ($4.9 \mu\text{m}/\text{pixel}$ for LI and $4.7 \mu\text{m}/\text{pixel}$ for Shadowgraphy in this study) proportionally affect all measured diameters (Cerruto et al., 2021a). A further error source is the thresholding algorithm used to segment droplets with respect to the background. Variations in threshold values affect droplet diameter calculation (Cerruto et al., 2022).

A critical factor that has great influence on the results of nozzle spray droplet measurement is the size and position of the sampling area. In the present study, the sampling area was substantially different in the four measurement techniques: a single point on the nozzle axis with PDPA, an arc-shaped path with LD, a horizontal rectangular surface with LI, and a vertical rectangular surface with SG. Only the axial distance of 0.5 m from the nozzle was kept constant in the four experiments. Since only the droplets within the working area are analyzed, this can lead to variations in results. However, according to the main aims of this study, comparisons were aimed at analyzing the differences that may emerge between the various measuring techniques as applied in the various laboratories when utilizing different equipment. Although real-world agricultural sprays produce polydisperse droplets, a better comparison could be achieved by applying monodisperse sprays, which have a uniform size and could provide a more detailed way of coping with the perfor-

mance of different measurement techniques.

In the context of agricultural spray analysis, the question of which measurement system to use is a constant consideration. Among the techniques available in the literature, the Liquid Immersion method can be considered reliable and a viable alternative for droplet size measurement purposes. Despite its cost-effectiveness and simplicity, it is not widely used for this purpose, and it is often overlooked. This could be attributed to the perception that more technologically advanced and expensive techniques inherently provide more accurate and reliable data. However, findings from this study challenge this perception, showing that the Liquid Immersion method can yield data with a high degree of reproducibility in spray analysis comparable to those obtained with more sophisticated techniques, such as Laser Diffraction or Phase Doppler Particle Analysis technologies. It is also adopted to confirm the adequacy of data obtained by optical methods, such as PDPA systems (Fujimatsu et al., 2014). This highlights that even the simplest methods for droplet sizing deserve more recognition and wider adoption in agricultural spray analysis.

One of the key advantages of the Liquid Immersion method is that it does not require specialized training for its implementation, making it accessible to a wide range of users. This is particularly beneficial in resource-limited contexts where the high cost of advanced systems can be prohibitive. In contrast, Laser Diffraction, Phase Doppler Particle Analysis, and Shadowgraphy, while offering accurate and real-time data, require significant investment in equipment that is not always affordable for users.

The ISO 25358 (ISO 25358, 2018) standard recognizes differ-

ences in spray droplet diameters resulting from various measuring principles and recommends classifying sprays based on a comparison of the spray droplet size spectrum produced by a nozzle or atomizer under specific operating conditions with reference spectra. Both the reference-class spectra and the test droplet size spectra to be classified should be measured using the same device and setup for similar droplet sizes. In our study, the statistical analysis of volume median diameters correctly distinguished the three reference nozzles, irrespective of the measurement technique adopted. Considering the cumulative volume curves, all measurement techniques classified the AVI 11003 in the coarse region. Therefore, the cumulative curves obtained in this study with each measurement technique and for the reference nozzles should be considered reference spectra for classification purposes.

4.6 Conclusions

The droplet size distributions of three reference spray nozzles and one air-induction nozzle were measured in three different laboratories applying four different measurement techniques under identical operating conditions. The techniques used were the Liquid Immersion method, the Laser Diffraction system, Phase Doppler Particle Analysis (PDPA), and the Shadowgraphy principle. This comprehensive study provided essential data for comparing the results of each measurement technique in relation to droplet spray parameters. The results of the study allowed the following main conclusions to be drawn:

- The various techniques employed in different laboratories under ordinary working conditions for measuring droplet

size yielded disparate results. These differences can be attributed to various causes, including the limitations and advantages of each type of measuring equipment, operational procedures, measuring protocols, and experimental errors. Probably the most important source of variation in the results was the choice of the sampling region. In this study, it was chosen according to the usual practices in each laboratory, but the axial distance of 0.5 m from the nozzle was kept constant. This diversity in results highlights the complexity of accurately determining droplet size and emphasizes the need for careful consideration when selecting an appropriate measurement technique.

- As a general trend, the Laser Diffraction technique provided the lowest droplet diameter values, followed by Shadowgraphy. The PDPA technique provided the highest values for mean and numeric median diameters, whereas the Liquid Immersion method yielded the highest values for Sauter and volumetric diameters.
- Despite differences in absolute VMD values, each measurement technique correctly separated the three reference nozzles and classified the AVI 11003 nozzle in the coarse region. On this basis, the use of reference nozzles is essential for comparing droplet size distributions obtained via different measurement techniques. These nozzles produce droplets that serve as a common benchmark, and, therefore, they should always be included when performing droplet size measurements to enable comparisons between techniques. The absence of such a reliable reference may lead to incomparable measurements due to differences in

operating principles. Ultimately, the use of this set of certified reference nozzles should be regarded as the primary means to validate data obtained via multiple measurement systems. It will help users to choose the proper nozzle for a specific application.

All things considered, the aforementioned aspects should be carefully taken into account when measuring droplet size distributions using different types of equipment and procedures, as they may modify nozzle spray quality classification and impact final results. Additionally, further research should be conducted to explore the potential sources of variability in greater depth and optimize the selection of measurement techniques for specific applications.

Chapter 5

Preliminary Results on the Correlation Between Drop Size, Foliar Deposition and Surface Coverage to Reduce Plant Protection Product Use

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5.1 Abstract

Drop size spectrum, percentage of covered surface of the target and foliar deposition are the most important factors affecting the results of a plant protection treatment, as well as the environment and operator safety. The main objective of this research was to study the correlation between drop diameters, foliar deposition on orange leaves and surface coverage on Water Sensitive Papers (WSPs) under laboratory conditions. The first results showed that the foliar deposition per unit surface ($\mu\text{L}/\text{cm}^2$) was positively and significantly correlated with the percentage of covered surface and all main characteristic diameters of the spray (volumetric diameters, Sauter mean diameter, and numeric median diameter). It may be estimated from percentage of covered surface on WSP, and spray drop diameters by means of a multiple linear regression (determination coefficient between observed and predicted deposits equal to 0.96), but further experiments are necessary to validate the model in field and to cope with different practical situations in terms of spray quality and covered surface.

5.2 Introduction

Drop size, surface coverage of the target and foliar deposition are the main factors affecting efficacy and efficiency of a plant protection treatment, as well as environment and operator safety during Plant Protection Product (PPP) applications.

Drop size affects environmental pollution due to off-target losses deriving from evaporation, drift and run-off (Garcerá et al., 2017; Sánchez-Hermosilla et al., 2011; Torrent et al., 2017) and operator safety due to its effects on dermal, ingestion and inhala-

tion exposure (Nuyttens et al., 2009; Rincón et al., 2018; Wong et al., 2018).

Surface coverage is essential when contact PPPs are used, which control pests due to direct contact with the outside layer of plants. They require a sufficient coverage of the target, and pests are killed when enough of the surface area is covered with PPP. In (Prokop and Veverka, 2006), the authors report that smaller droplets allow covering larger areas and products containing contact active substances show an increased efficacy with a higher droplet density per unit of leaf area. Droplet density and surface coverage are usually assessed by means of Water Sensitive Papers (WSPs). They are specially coated semi-rigid papers that change color (from yellow to dark blue) when in contact with water-based droplets (Syngenta, 2002). The subsequent analysis of droplet stains by means of image processing software, allows measuring droplet density, drop diameters and surface coverage (Cerruto et al., 2019; Cunha et al., 2012b).

The deposit represents the amount of active ingredient on the target, from which depend on the proper dose and then the efficacy of a treatment; it may be increased by using suitable adjuvants. Deposit assessment is usually performed by adding a tracer to the mixture to be sprayed and then measuring the amount of tracer deposited on the target (Ferguson et al., 2016; Pascuzzi and Cerruto, 2015; Pascuzzi et al., 2017). The procedure is quite complex, so different methods based on image analysis or machine learning are proposed in the literature (Cerruto et al., 2019; Guo et al., 2020; Massinon and Lebeau, 2012).

The main objective of this research was to carry out a preliminary study aiming at correlating the foliar deposition on orange leaves to drop size and surface coverage measured on WSPs un-

der laboratory conditions. The ultimate objective was to develop a model capable of predicting foliar deposition based on surface coverage and spray drop characteristics. The study was carried out considering three stainless steel flat fan nozzles (TP11001-SS, TP11003-SS, and TP11006-SS from TeeJet Technologies) at three different spraying pressures.

5.3 Materials and Methods

5.3.1 Equipment for Data Acquisition

Experimental tests were carried out by using a custom test-bench purposely designed and built to measure the drop size spectrum from hydraulic nozzles by exploiting the Liquid Immersion method (Longo et al., 2020). The test-bench reproduces a standard commercial sprayer and essentially consists of a transportable trolley carrying a 70 L tank, a diaphragm pump driven by an electric motor, a manual pressure regulator, and a spray boom carrying one multiple nozzle holder. The spray boom is applied to a mobile support that moves along two slides placed above and parallel to the plane of the trolley, at a distance of 0.5 m from the targets. The whole system is managed by a custom software user interface that allows controlling the spray boom movement, starting and stopping spraying, registering pressure and nozzle flow rate. According to the procedure described in the ISO 5682-1 standard (ISO 5682-1, 2017), the test liquid (a mixture of water and food dye Red Poinceau, concentration of 2 g/L) was sprayed above three Petri dishes containing silicone oil (viscosity = 200 mPa s, volumetric mass = 1050 kg/m³). In addition, three WSPs and six orange leaves (three with upper

side surface and three with under side surface exposed) were placed next to the Petri dishes during the spraying tests (Figure 5.1). This arrangement allowed to measure at the same time drop size, superficial coverage on WSP, and foliar deposition on orange leaves.

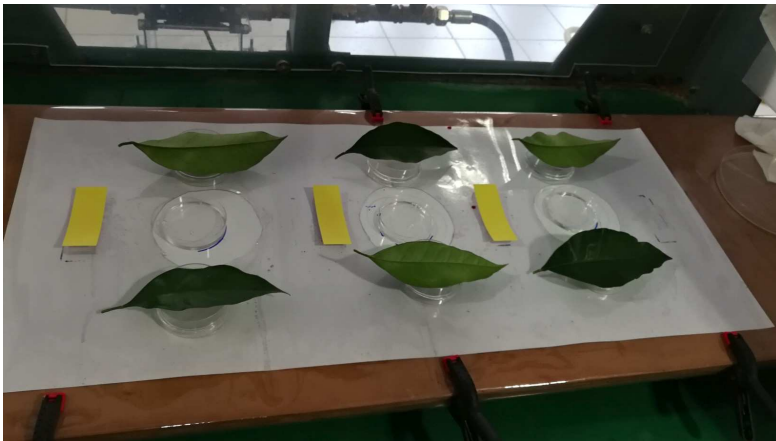


Figure 5.1: Arrangement of Petri dishes, orange leaves, and Water Sensitive Papers for experimental tests.

Before spraying, each leaf was flattened and scanned at 600 dpi and then the image was analyzed with *ImageJ* software (Abràmoff et al., 2004) to measure the leaf surface. The calibration factor was deduced from the scanner resolution: 600 dpi correspond to $42 \mu\text{m}/\text{pixel}$. Measured leaf surfaces ranged from 34.56 cm^2 to 61.46 cm^2 (mean value 45.96 cm^2), with standard deviation and coefficient of variation of 5.69 cm^2 and 12.4 %, respectively.

5.3.2 Spray Drop Size Measurement

Petri dishes with the drops captured inside the oil were photographed in situ by a high resolution DSLR camera (6000 pixel \times 4000 pixel) and the images were saved in high-quality colour JPEG format. Successively, they were analyzed by using the *ImageJ* software (Abràmoff et al., 2004) to extract drop features. In detail, each image, after sporadic preliminary modification to correct any imperfections (presence of little bubbles in the oil), was converted to 8-bit gray levels and then segmented to separate drops from the background. Though many segmentation algorithms exist (Cerruto et al., 2022), in this study the Otsu method was adopted (Otsu, 1979). Segmented images were then processed by applying the “fill holes” filter to fill any holes in objects, and the “watershed” filter to separate or cut apart particles that touched. There were no further manual interventions on the segmented images.

After segmentation, the following geometrical features of the particles were considered: area, aspect ratio (ratio between primary and secondary axis of the best fitting ellipse), Feret’s ratio (ratio between maximum and minimum Feret’s diameters). The Feret’s diameter is a measure of an object size along a specified direction. It can be defined as the distance between the two parallel planes restricting the object perpendicular to that direction. It is therefore also called the caliper diameter, referring to the measurement of the object size with a caliper. Maximum and minimum Feret’s diameters are the maximum and minimum caliper, respectively. In post-processing stage, particles up to 4 contiguous pixels were excluded, considered as digital noise. In addition, particles with aspect ratio or Feret’s ratio greater than 1.50 were also excluded, because deviating excessively from the

circular shape.

Starting from the particle area A'_i (square pixel), the corresponding particle diameter D_i (μm) was computed according to Equation 5.1:

$$D_i = C_f \times \sqrt{\frac{4A'_i}{\pi}} \quad (5.1)$$

where C_f is the calibration factor ($4.90 \mu\text{m}/\text{pixel}$), measured by photographing in the same conditions an object of known size.

Finally, knowing the diameter of each particle (droplet), volumetric diameters $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$, Sauter Mean Diameter (SMD) and Numeric Median Diameter (NMD) were computed. The SMD is the diameter of a drop having the same volume-to-surface area ratio as the entire ensemble of drops. All calculations were carried out by using suitable R functions expressly written (R Core Team, 2021).

5.3.3 Water Sensitive Paper Analysis

After spraying, the Water Sensitive Papers were attached to a sheet of paper and stored to dry naturally. Subsequently, they were scanned at 1200 dpi and saved as colour high-quality JPEG images. The images were analyzed with *ImageJ* by converting them to 8-bit gray levels and then segmenting with the Otsu's method to obtain the percentage of covered surface.

5.3.4 Foliar Deposition Measurement

Spray deposition was measured employing the standard spectrophotometric technique, using the food dye Red Poinceau as tracer. After spraying, each leaf was placed in a numbered plastic bag and then washed with $V_c = 50 \text{ mL}$ of distilled water to

extract the dye. For each plastic bag containing the leaf, about 3 mL of the washing mixture were sampled with a micro pipette and its absorbance Abs was measured by means of a spectrophotometer (Hach DR 3900 model) at 507 nm wavelength. After the absorbance Abs_m of the sprayed mixture was measured, the foliar deposition per unit surface du ($\mu\text{L}/\text{cm}^2$) was calculated as:

$$du = \frac{Abs}{Abs_m} \frac{V_c}{S} \times 1000 \quad (5.2)$$

being S (cm^2) the leaf surface (only one side, because leaves were horizontally exposed to the spray jet).

5.3.5 Experimental Activity

Spraying tests were carried out with three stainless steel flat fan nozzles TP11001, TP11003, and TP11006 from TeeJet (TeeJet Technologies, Illinois, USA) at the nominal pressures of 450 kPa, 300 kPa and 200 kPa, respectively. Effective pressures were deduced from the log files registered by the test-bench during the tests. Nozzle speed while spraying was set to 1.5 m/s. Each nozzle was tested three times, so 9 Petri dishes to measure drop size, 9 WSPs to measure the percentage of covered surface and 18 leaves to measure the foliar deposition were used per each nozzle.

5.4 Results and Discussion

5.4.1 Nozzle Features

Table 5.1 reports the main spray drop diameters measured during the experimental tests. Obtained values agreed with expecta-

tions: in fact, the nozzles under test, when tested at the reference pressures of 450 kPa, 300 kPa and 200 kPa, define the boundary regions Very Fine/Fine, Fine/Medium, and Medium/Coarse, respectively (ISO 25358, 2018). The TP11001 nozzle is classified by the manufacturer as Very Fine for pressures in the range from 350 kPa to 400 kPa kPa, the TP11003 as Fine for pressures in the range from 200 kPa to 400 kPa, and the TP11006 as Medium for pressures in the range from 200 kPa to 400 kPa.

Table 5.1: Average values of the main spray drop diameters.

Nozzle	Pressure kPa	Flow rate L/min	$D_{v0.1}$ μm	$D_{v0.5}$ μm	$D_{v0.9}$ μm	SMD μm	NMD μm
TP11001	473	0.5	59	122	207	101	49
TP11003	274	1.16	134	268	443	221	65
TP11006	193	1.87	175	385	608	302	71

5.4.2 Foliar Deposition

Average foliar deposition is reported in Table 5.2 for each test condition. Differences between the two leaf surfaces were not statistically significant (p -level = 0.226 from analysis of variance), and mean deposits increased from TP11001 to TP11006 nozzle due to the increase in nozzle flow rate. Figure 5.2 (left) shows the trend of foliar deposition vs. nozzle flow rate. When the nozzle flow rate increased from 0.50 L/min to 1.16 L/min (132 %), the corresponding increase in foliar deposition was similar (from 0.66 $\mu\text{L}/\text{cm}^2$ to 1.50 $\mu\text{L}/\text{cm}^2$, 127 %). A further increase in the flow rate up to 1.87 L/min (61 %), produced an increase in foliar deposition by 39 % only (from 1.50 $\mu\text{L}/\text{cm}^2$ to 2.09 $\mu\text{L}/\text{cm}^2$). This

implies that, even if positively correlated, foliar deposition and nozzle flow rate were not linearly related.

Table 5.2: Mean and standard deviation (sd) of foliar deposition ($\mu\text{L}/\text{cm}^2$)

Nozzle	Under side		Upper side		Mean	
	Mean	sd	Mean	sd	Mean	sd
TP11001	0.68	0.09	0.64	0.13	0.66	0.11
TP11003	1.46	0.25	1.54	0.09	1.5	0.18
TP11006	2.01	0.19	2.16	0.24	2.09	0.23

In addition, the foliar deposition normalized to the nozzle flow rate (du_N) had a decreasing trend: when the nozzle flow rate increased from 0.50 L/min to 1.16 L/min to 1.87 L/min, du_N decreased from 1.32 ($\mu\text{L}/\text{cm}^2$)/(L/min) to 1.29 ($\mu\text{L}/\text{cm}^2$)/(L/min) to 1.12 ($\mu\text{L}/\text{cm}^2$)/(L/min).

5.4.3 Covered Surface on Water Sensitive Papers

Mean values of percentage of covered surface on WSPs are reported in Table 5.3. Their increasing trend from 30.11 % to 64.74 % was due to the increase in nozzle flow rate. Conversely, variability, expressed in terms of coefficient of variation, decreased from 14.89 % to 3.22 %. When nozzle flow rate increased from 0.50 L/min to 1.16 L/min (132 %), the corresponding increase in percentage of covered surface was 71 % only. The further increase of 61 % in the flow rate produced an increase of 26 % in percentage of covered surface. This implies that, like foliar deposition, also percentage of covered surface was not linearly related to

nozzle flow rate, mainly due to the overlaps between stains.

Table 5.3: Mean values, standard deviation (sd) and coefficient of variation (CV) of percentage of covered surface on Water Sensitive Papers.

Nozzle	Flow rate, L/min	Mean, %	sd, %	CV, %
TP11001	0.50	30.11	4.48	14.89
TP11003	1.16	51.49	1.75	3.4
TP11006	1.87	64.74	2.09	3.22

The relationship between foliar deposition and percentage of covered surface is shown in Figure 5.2 (right).

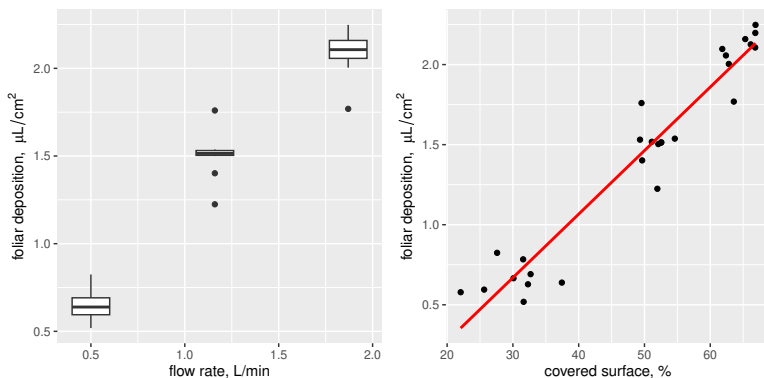


Figure 5.2: Foliar deposition in function of nozzle flow rate (left) and of percentage of covered surface on WSPs (right).

The trend was well described by a first order linear equation:

$$du = 0.040 \times A - 0.521 \quad (5.3)$$

where du ($\mu\text{L}/\text{cm}^2$) is the estimated foliar deposition and A (%) is the measured percentage of covered surface. The regression equation was highly significant (p -level < 0.001), with determination coefficient $R^2 = 0.93$.

5.4.4 Correlation Analysis

Table 5.4 reports the coefficients of correlation between the main quantities involved in the study, where, in addition to the diameters, V (μL) indicates the total volume of droplets captured within the Petri dishes, A (%) the percentage of covered surface on WSPs, and du ($\mu\text{L}/\text{cm}^2$) the foliar deposition per unit surface, averaged between the two leaf surfaces; V_N ($\mu\text{L}/(\text{L}/\text{min})$) and du_N ($\mu\text{L}/\text{cm}^2)/(\text{L}/\text{min})$ represent the total volume and the foliar deposition normalized to the sprayed nozzle flow rate, respectively.

Table 5.4: *Coefficients of correlation between the main quantities involved in the study (significance level: ***: p -level < 0.001 ; **: p -level < 0.01 ; *: p -level < 0.05 ; ns: not significant).*

	V	A	du	V_N	du_N	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	SMD	NMD
V	1	0.93	0.94	0.96	-0.54	0.97	0.98	0.96	0.97	0.76
A	***	1	0.97	0.91	-0.45	0.98	0.97	0.96	0.97	0.72
du	***	***	1	0.91	-0.34	0.97	0.97	0.95	0.97	0.75
V_N	***	***	***	1	-0.50	0.94	0.93	0.93	0.94	0.78
du_N	**	*	ns	**	1	-0.50	-0.53	-0.52	-0.52	-0.31
$D_{v0.1}$	***	***	***	***	**	1	0.99	0.98	1.00	0.75
$D_{v0.5}$	***	***	***	***	**	***	1	0.99	1.00	0.74
$D_{v0.9}$	***	***	***	***	**	***	***	1	0.99	0.77
SMD	***	***	***	***	**	***	***	***	1	0.75
NMD	***	***	***	***	ns	***	***	***	***	1

The majority of coefficients of correlation were statistically significant for p -level < 0.001 ; lower significance was found for

the normalized foliar deposition (du_N) only, which was negatively correlated with all the other quantities.

In practical applications, diameters are known from nozzle features, whereas percentage of covered surface can be easily measured by using Water Sensitive Papers. Thus, the correlations between these variables were explored more in detail and it emerged that the foliar deposition per unit surface was well linearly correlated with all these quantities. Then, a multiple linear regression analysis was applied, considering du as dependent variable and percentage of covered surface and drop diameters as explanatory variables. The resulting model was highly significant, with determination coefficient $R^2 = 0.96$, higher than that obtained considering as explanatory variable the percentage of covered surface only (Eq. 5.2). The coefficients of the model are reported in Table 5.5 and the comparison between observed and predicted values is shown in Figure 5.3.

Table 5.5: *Coefficients of the linear regression between du and explanatory variables*

	Unit	Value
intercept	$\mu\text{L}/\text{cm}^2$	-285.000×10^{-3}
A	%	14.168×10^{-3}
$D_{v0.1}$	μm	3.043×10^{-3}
$D_{v0.5}$	μm	1.393×10^{-3}
$D_{v0.9}$	μm	-0.956×10^{-3}
SMD	μm	2.086×10^{-3}
NMD	μm	3.408×10^{-3}

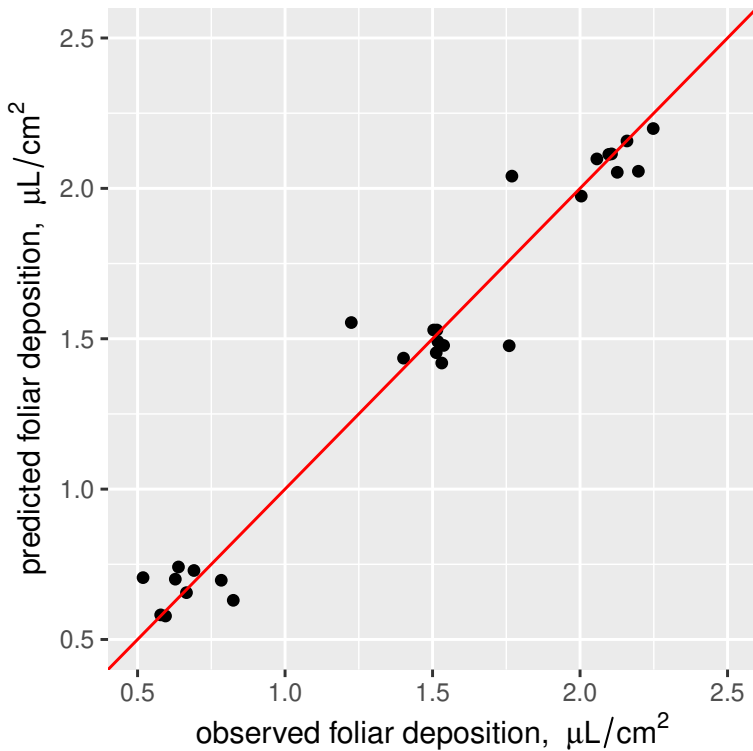


Figure 5.3: Comparison between measured and predicted foliar depositions.

5.5 Conclusions

This research represents a first attempt to correlate the main quantities involved in a plant protection treatment: drop size, measured by exploiting the Liquid Immersion method, superficial coverage of the target, measured by using Water Sensitive Papers, and foliar deposition, measured by applying the spectrophotometric technique. The main results can be so summarized:

- The foliar deposition per unit surface was positively and

highly correlated with percentage of covered surface and all main characteristic diameters of the spray (volumetric diameters, SMD, and NMD). Deposition was also positively correlated with the total volume of droplets collected within Petri dishes (determination coefficient = 0.89).

- A first simple estimate of foliar deposition can be obtained from the percentage of covered surface in the range of approximately (20–80)% by means of a linear equation.
- A more complex, but more precise, estimate of foliar deposition may be obtained by means of a multiple linear regression involving also drop diameters.

The success of a plant protection treatment depends on several factors, one of which is the deposition, i.e., the amount of active substance retained by the target. Generally, measuring the deposition is a complex task that requires the use of tracers. The results of this research are very promising as they allow for the estimation of the deposition from easily measurable quantities (such as the fraction of surface covered on WSPs) or known quantities (like mean drop diameters produced from a given nozzle). However, further studies are necessary to handle different practical situations (such as other spraying pressures with the same nozzle, different nozzles, and varying values of percentage of covered surface) and to validate the models with field tests.

Chapter 6

Use of the Logistic Function to Model Cumulative Volumes of Spray Nozzles

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6.1 Abstract

Modeling spray drop size distribution helps a proper nozzle selection in order to reduce the impact of pesticides on the environment during phytosanitary treatments. In fact, drop size is recognized as the most important factor that affects all the aspects of a pesticide application: biological efficacy, environmental pollution, and operator exposure. This research represents a preliminary study in using the logistic function to fit the cumulative volume curves of a spray. Its S-shaped form may be useful in describing in simple manner the cumulative volume curves and then the pulverization capabilities of a nozzle. Experimental tests were carried out with an Albus (France) orange hollow cone nozzle ATR 80 (European color code) at four pressures: 300 kPa, 500 kPa, 1000 kPa, and 1500 kPa. Drop size was measured by exploiting the Liquid Immersion method in a custom-made test-bench. Preliminary results showed that the proposed model, when used on a validation dataset, fitted the experimental data with high correlation coefficient (on average 0.9992) and low percentage of bias values, tending to improve when the pressure increased (decreasing from 3.69 % to -0.08 % when the pressure increased from 300 kPa to 1500 kPa).

6.2 Introduction

Spray evaluation requires some knowledge of the distribution of droplet size and volume, and the modeling of a spray for Plant Protection Product (PPP) application is very useful for optimizing the effectiveness of a phytosanitary treatment in agriculture (Al Heidary et al., 2014; Cerruto et al., 2019; Chen et al., 2020;

Ferguson et al., 2016). The droplet size spectrum that can be found in a spray depends on liquid properties, nozzle features, atomization process and operating parameters; diameter varies from a non-zero minimum value to a finite maximum value. In fact, as it is well known, within a droplet size spectrum produced by the breakup of a fluid, there is a finite maximum diameter due to the aerodynamic forces, which break the large droplets into smaller ones. On the other side, a non-zero minimum diameter occurs due to the surface cohesive tensions, which increase as the droplet size approaches zero, becoming higher than the available aerodynamic forces (Chryssakis et al., 2011; Lefebvre and McDonell, 2017c).

The scientific literature proposes both analytical and empirical approaches to model droplet size distributions in a spray. Among the analytical approaches there are the maximum entropy (ME) and the discrete probability function (DPF) methods (Babinsky and Sojka, 2002).

According to the ME method, the spray formation is a completely non-deterministic process that can be modelled using the entropy maximization principle (Sellens and Brzustowski, 1985; Xianguo and Tankin, 1987). The most probable droplet size distribution is the one that maximizes an entropic function, such as Shannon or Bayes, within a set of physical constraints (e.g., spray mass conservation, surface energy minimization, etc.). Conversely, the DPF method divides the spray formation process into deterministic and non-deterministic fractions (Sivathanu et al., 1999), inferring that the spray formation is uniquely determined based on a set of initial conditions (physical properties of the fluid and parameters of the atomizer) and of a breakup model of the fluid (Sivathanu and Gore, 1999).

The empirical method is the classic and usually used one. It is based on specially studied theoretical curves that have been originally proposed to describe experimental datasets, and now are considered as “standard” empirical distributions (Rosin-Rammler, Nukiyama-Tanasawa, log-normal, root-normal, log-hyperbolic, gamma, etc.). Each empirical distribution provides a set of parameters, which must be adjusted to “suit” the function to the experimental values (Cerruto et al., 2021b; Panão et al., 2020; Privitera et al., 2023). It has been found that generally the more adjustable parameters are contained in the distribution function, the better is its fitting to the experimental data. This is to be expected, since distributions with a higher number of parameters allow for a huger level of “shape freedom”. These adjustable parameters should be stable, i.e. they should undergo small variations following light variations in the spray inlet conditions. Referring to this, studies have been carried out highlighting that the adjustable parameters stability has been tricky for the Nukiyama-Tanasawa and log-hyperbolic distribution functions, whereas it has been more solid for the log-normal distribution (Paloposki, 1994).

Taking in mind the aforesaid, in the present study the cumulative volume curves were used as starting point and their trends were modeled by using the logistic function. The availability of a mathematical model describing the cumulative curves allows computing and forecasting the volumetric diameters in a given spray. In addition, the effects of the spray pressure were also considered.

6.3 Materials and Methods

6.3.1 Background on the Logistic Function

The logistic function was introduced by Pierre François Verhulst between 1838 and 1847 as a model of population growth. Today it has many fields of application, such as statistics and machine learning (logistic regression), medicine (modeling growth of tumors or widespread of a pandemic) and agriculture (modeling crop response to changes in growth factors). In this study it has been used to model the “growth” of the cumulative volume of agricultural spray nozzles.

A general form for the logistic function can be given as:

$$y = \frac{A_1 - A_2}{1 + e^{k(x-x_0)}} + A_2 \quad (6.1)$$

where $y = A_1$ is the lower asymptote of the curve when $x \rightarrow -\infty$, $y = A_2$ is the upper asymptote when $x \rightarrow +\infty$, and $x = x_0$ is the point where the curve reaches its midpoint ($(A_1 + A_2)/2$).

For the purposes of the present research, Eq. 6.1 was rearranged as:

$$v_c(D) = a \frac{1 + m \cdot e^{-D/D_0}}{1 + n \cdot e^{-D/D_0}} \quad (6.2)$$

which $v_c(D)$ the cumulative volume function, with $a = 1$ (the cumulative volume function tends to 1 when the diameter D increases), and m , n and D_0 parameters to be estimated based upon the measured cumulative volume values.

Figure 6.1 shows the effects of the three parameters on the shape of the curve. The parameters D_0 and n mainly modify the horizontal position of the curves, whereas m acts on the lower asymptote. Ideally, when $D = 0$ the cumulative volume should

be 0 and then $m = -1$, so little variation in m may help fitting better the experimental data at low diameter values.

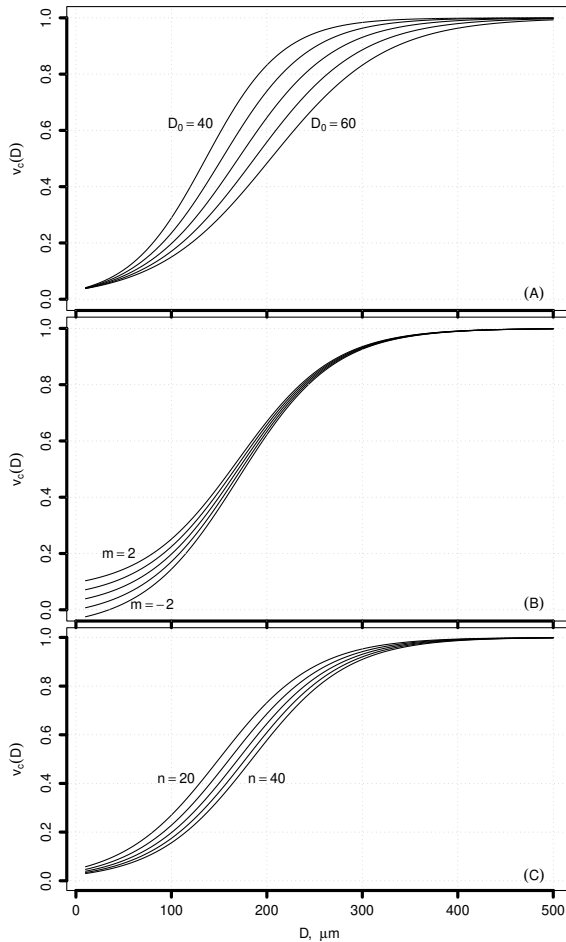


Figure 6.1: Effect of the parameters on the shape of the curve of the logistic model described by Eq. 6.2: (A) D_0 (from 40 to 60 with step = 5, with $m = 0$ and $n = 30$); (B) m (from -2 to 2 with step = 1, with $D_0 = 50$ and $n = 30$); and (C) n (from 20 to 40 with step = 5, with $D_0 = 50$ and $m = 0$).

6.3.2 Experimental Activity

Experimental data on spray distribution of nozzles were obtained by using a custom test-bench designed and built at the Section of Mechanics and Mechanization of the Department of Agriculture, Food and Environment of the University of Catania (Longo et al., 2020) and based on the Liquid Immersion method (Fujimatsu et al., 2014; Kathiravelu et al., 2016).

The test-bench reproduces the hydraulic system installed in a conventional sprayer. In fact, it consists of a 70 L plastic tank, a diaphragm pump (AR30, Annovi & Reverberi, Reggio Emilia, Italy) driven by a 2.2 kW, 230 V AC induction motor with a gearbox, two pressure regulators (the first one for pressure in the range from 0.15 MPa to 0.6 MPa, the second one for pressure up to 3 MPa), a triple nozzle holder on which the nozzles under test are applied. The nozzle holder is installed on a platform that moves along two rails 3 m long, 0.5 m above a mechanically insulated plane, where three Petri dishes containing silicone oil were placed to collect the sprayed droplets. The platform is pulled by two toothed belts, driven in a close-loop form by a 240 W, 24 V V brushed motor (MDC1460 model, Roboteq Inc., Scottsdale, AZ, USA) with a 300 pulse per revolution encoder (ME22 model, INTECNO srl), to control acceleration, speed and position of the nozzle. Actual pressure and water flow rate during the tests are recorded by a piezoresistive pressure sensor (model Series 22 S by Keller Italy Srl, Milan, Italy) installed near the nozzle holder and by a flow meter (Visual Flow model, Arag, Reggio Emilia, Italy) installed after the pressure regulators.

The whole system is managed through a software user interface, implemented in house, that allows to set nozzle speed and sampling frequency, start and stop the spray, monitor water pres-

sure, flow rate, and platform position during the tests. At the end of each test, a log file is provided with the values of timestamp, water pressure, flow rate, platform speed and position.

For the purposes of this research, experimental tests were carried out with an Albus ATR 80 orange nozzle (European color code) at 4 pressures (300 kPa, 500 kPa, 1000 kPa, and 1500 kPa) and with nozzle speed of 1.5 m/s, kept constant in correspondence of the three Petri dishes. To make the separation of drops from the background easier, clean water with the addition of the soluble coloring agent *Red Ponceau* at the concentration of 2 g/L was sprayed. The tests were repeated three times for each pressure and immediately after the end of each repetition the droplets trapped into the silicone oil were photographed in situ using a high-resolution (24 Mpixel) DSLR camera equipped with a macro lens, suitably anchored to the rails in fixed positions with respect to the Petri dishes. The images were saved as high-quality color JPEG files. To have the spatial calibration, in the same positions of the three Petri dishes a 10 mm × 10 mm grid pattern, 1 mm step, engraved on a glass disc, was photographed and the calibration factor was determined (on average 5.3 μm/pixel).

The images were analyzed by means of the software *ImageJ* (Abràmoff et al., 2004), based on the segmentation principle. Each image was converted into 8-bit gray levels and segmented choosing the threshold (TV) in function of its average gray level (AGL) with the relationship reported in Cerruto et al. (2022):

$$TV = 1.0453 \times AGL - 24.4787 \quad (6.3)$$

ImageJ extracted area, axes of the best fitting ellipse, and maximum and minimum caliper (Feret's diameters) of each particle,

discarding those touching the edges of the image. These shape descriptors (best fitting ellipse axes and Feret's diameters) were used to discharge particles strongly deviating from circularity, mainly deriving from the overlapping of stains. In this study particles with ratio between primary and secondary axis of the ellipse and ratio between maximum and minimum Feret's diameter greater than 1.50 were ignored. All particles lower than 5 contiguous pixels were considered as noise and then were also ignored.

All data were saved in excel spreadsheets and then imported into R (R Core Team, 2021) for subsequent analyses (application of the calibration factor and calculation of the volumetric diameters and of the cumulative volume curves) necessary to build the model according to Eq. 6.2.

The entire dataset (i.e. the 3 Petri dishes per repetition, with a total of 3 repetitions) was split into two sub-datasets, one for training the model (training dataset, 67 % of the data, i.e. two repetitions) and the other for validating the model performance (validating dataset, 33 % of the data, i.e. one repetition). The training procedure consisted of determining the model parameters m , n and D_0 values, by minimizing the square error between observed and predicted values along 100 points equally distributed along the logistic function, in the range of measured diameters. Estimation was carried out by using the "nls" (Nonlinear Least Square) function available in the "stats" package of R. The training was performed independently for the two repetitions (considering in each one the three Petri dishes as a whole). The values of the parameters m , n and D_0 in the final model were calculated as the averaged values of the parameter values obtained in each single repetition.

The validation of the model was performed on the third repetition. Specifically, this procedure included the calculation of (i) the Root Mean Square Error (*RMSE*, Eq. 6.4); (ii) the correlation coefficient (*r*) between the observed and the model predicted values; and (iii) the percentage of bias (*PBias*, Eq. 6.5), which is an index that measures the average tendency of the simulated values to be larger or smaller than their observed ones:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (O_i - P_i)^2}{N}} \quad (6.4)$$

$$PBias, \% = \frac{\sum_{i=1}^N (P_i - O_i)}{\sum_{i=1}^N O_i} \times 100 \quad (6.5)$$

with P_i and O_i predicted and observed values, respectively, and N the total number of points. In addition, observed and predicted values of the cumulative volumes were reported graphically to evaluate the performance of the model along all the range of the measured diameters.

6.4 Results and Discussion

6.4.1 Cumulative Volume Curves

Figure 6.2 reports the cumulative volume curves of the ATR80 orange nozzle in function of the working pressure. They were drawn considering all the drops coming from the three repetitions and the three Petri dishes. The results were consistent with the expectation: an increase in the pressure produced an increase in the drop pulverization (reduction in the $D_{v0.5}$ diameter). Volumetric Median Diameters were 172 μm , 148 μm , 137 μm ,

and 135 μm when the pressure was 300 kPa, 500 kPa, 1000 kPa, and 1500 kPa, respectively. The difference between 1000 kPa and 1500 kPa was very low: the two cumulative curves were almost superimposed.

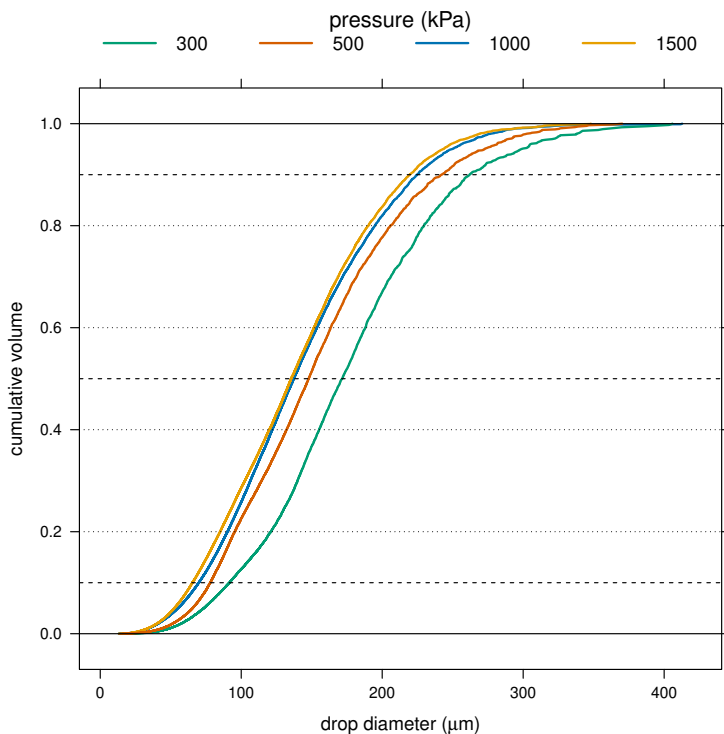


Figure 6.2: *Cumulative volume curves of ATR 80 orange nozzle at different pressures.*

6.4.2 Model Parameter Estimation

Table 6.1 reports the average values of the three parameters in the evaluated pressure range, based upon two repetitions (training dataset). Specifically, m , n and D_0 parameters varied from -2.59 to -1.89 ; from 25.25 to 51.10 and from $39.81 \mu\text{m}$ to $41.76 \mu\text{m}$, respectively. With the exception of the first parameter m , which grew quite linearly with pressure (coefficient of determination $R^2 = 0.977$), the other two parameters did not show clear trends and were almost constant when the pressure was greater than 500 kPa .

Table 6.1: *Model parameter estimation (Eq. 6.2) based on the training dataset.*

Pressure (kPa)	Model parameters		
	m	n	D_0 (μm)
300	-2.59	51.10	41.44
500	-2.40	27.22	41.76
1000	-2.06	28.45	39.81
1500	-1.89	25.25	40.08

This behavior may depend on the characteristics of the nozzle. The manufacturer recommends its use at pressures of about 1000 kPa . However, when used at lower pressures, such as 300 kPa , its performance may degrade. Consequently, the general model described by Eq. 6.2 fits the experimental data less accurately under these conditions. This is primarily reflected in the value of the n parameter, which is 51.10 at 300 kPa , significantly different from the average value of 26.97 obtained at higher pressures (Table 6.1).

The indices of performance of the model are summarized in Table 6.2. They showed very good fitting capabilities of the model for all the pressures: only at 1500 kPa there was a little under-estimation of about -0.42% .

Table 6.2: *Model performance indices (training dataset).*

Pressure (kPa)	Model parameters		
	<i>RMSE</i>	<i>r</i>	<i>PBias (%)</i>
300	0.0009	0.9999	0.15
500	0.0009	0.9997	0.14
1000	0.0010	0.9999	-0.15
1500	0.0026	0.9998	-0.42

6.4.3 Model Validation

When the model was tested on the validation dataset (third repetition), its performances were as summarized in Table 6.3.

Table 6.3: *Model performance indices (validation dataset).*

Pressure (kPa)	Model parameters		
	<i>RMSE</i>	<i>r</i>	<i>PBias (%)</i>
300	0.0206	0.9986	3.69
500	0.0107	0.9990	1.84
1000	0.0022	0.9996	-0.36
1500	0.0005	0.9998	-0.08

All the indices had a trend that tended to improve when

the pressure increased from 300 kPa to 1500 kPa: in fact, the RMSE decreased from 0.0206 to 0.0005, the correlation coefficient increased from 0.9986 to 0.9998, and the PBias decreased from 3.69% to -0.08% .

The comparison between observed and predicted values over all the range of cumulative volume values is shown in Figure 6.3. Results may be very promising, but other experimental tests are necessary, investigating different pressures and working conditions.

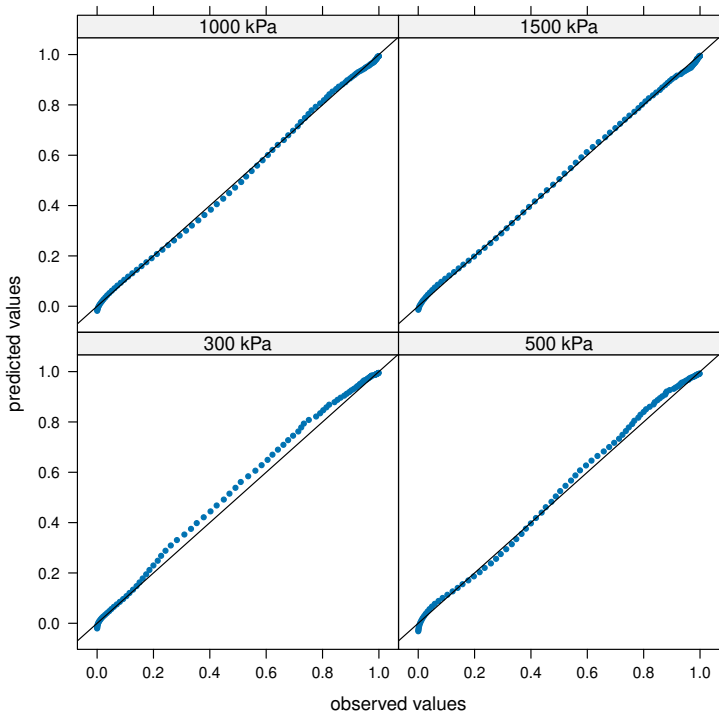


Figure 6.3: Comparison between observed and predicted values on the validation dataset.

6.5 Conclusions

The present study evaluates the use of the logistic function to fit the cumulative volume curves of a spray. The main conclusions that can be driven from the present study are:

- The logistic function accurately describes the relationship between $v_c(D)$ and D .
- Optimized values of m , n and D_0 resulted in low *RMSE* and *PBias* and high r values.
- The model performance improved when the pressure increased, with the major discrepancies occurring at 300 kPa.
- A deeper analysis at a wider pressure range is necessary in order to explore the relationship among the model parameters and application pressure.

Chapter 7

General Conclusions

The herein thesis has contributed to wider scientific insights into the research field concerning the assessment of nozzle spray quality and spray deposition through advanced technologies based on laser-scattering principles and image processing techniques.

As a starting base of the project, much of the Chapter II has been devoted to extensively strength and expand the state of the art of available droplet size measurement techniques for measuring the droplet size distribution in agricultural sprays. Overall, after defining the main spray droplet characteristics useful for the description of the droplet population and focusing on the main droplet size distribution functions, the study paid the attention to comprehensively describe either intrusive (Liquid Immersion and Water Sensitive Papers) and non-intrusive methods (Laser Diffraction, PDPA and Shadowgraphy). They can be essentially categorized as laser-based or image processing methods. For each of them, characteristics, peculiarities and limitations were pointed out. From this review, it emerged that, although there are various techniques capable of measuring droplet size parameters,

practical information on their accuracy and how they compare each other was limited. In view of this, in-depth research was undertaken in Chapter IV.

Remarkable results have been achieved in Chapter III, where one of the most significant limitation common to image analysis techniques, like Liquid Immersion method, was investigated. In fact, this Chapter was intended to evaluate the effects of the image segmentation thresholding on droplet diameter measurement. In detail, we assessed how much variations of about $\pm 5\%$ in the choice of the segmenting influenced the calculation of characteristic diameters. Based on this study, results revealed a valuable possibility of considering the image acquisition system used for this purpose as an automatic tool able to select the threshold value according to the gray level of the image, allowing the segmentation process to be less dependent on the operator expertise. Furthermore, the applied approach may lay the basis for further development and application, by implementing it within tools for image segmentation procedure.

A step forward was achieved with Chapter IV on the basis on what has been highlighted by the literature review (Chapter II). It has been clear how several factors, such as type of measuring technique, their own operating principle and individual setting, can lead to different interpretations in nozzle spray quality classification. For this reason, the ISO 25358 standard recommends classification of spray droplet spectra by relying on reference nozzles to define the boundary regions to increase uniformity in relative measurements and classifications among different measuring systems and laboratories. Hence, this Chapter essentially aimed at comparing the performance of four techniques (Liquid Immersion, Laser Diffraction, PDPA and Shadowgraphy), which

were taken into account by the review, for measuring droplet size and quantifying the droplet size parameters generated by four nozzles under identical operating conditions. Results of the research highlighted that variability in droplet parameters can be associated to the operating principle of each equipment, their individual setup and procedures, and sampling region. In this regard, the necessity of always including reference nozzles for spray quality assessment should be regarded to base classifications of other nozzles in a relative manner, rather than relying on absolute values.

Unlike of the Chapter II, in the Chapter IV we did not include the WSPs as potential tool to evaluate droplet size spectra due to its limitations, such as the spread factor that varies with the different physical properties of the liquid, and the difficulty in detecting fine droplet which may not contain enough water to create a detectable stain, especially in highly humid environment. All this considered, even if using WSPs to characterize droplet size may not be as accurate as other sophisticated techniques, in the long-term future further investigation may be carried out with great caution to the inclusion of WSPs for determining characteristics diameters of spray (Beyaz et al., 2017; da Cunha et al., 2019).

As droplet size, surface coverage of the target and foliar deposition are the main metrics affecting the effectiveness of plant protection treatment, Chapter V focused on conducting a preliminary study aimed at correlating the foliar deposition on orange leaves, droplet size and surface coverage on WSPs under laboratory conditions. With this work, we wanted to improve the understanding of the relationship between these quantities, often involved during plant protection activity. Results prominently

attempted the estimation of deposit from measurable quantities (droplet diameters and fraction of covered surface). Nevertheless, further studies would be needed to include different practical situations, such as other type of nozzles and different spray pressures.

Referring to the first section of the literature review (Chapter II), a wide variety of distribution functions have been proposed to characterize cumulative volumes distribution curves of agricultural spray nozzles, able to fit experimental data with different degrees of accuracy. On this matter, the primary aim of the Chapter VI was to model the cumulative volumetric curves deriving from a hollow cone nozzle by using the logistic function. The work allowed to show that the proposed model fitted the experimental data with high coefficient of correlation and low percentage of bias values, tending to improve when the pressure increased. A further perspective of this study may regard a deeper analysis at wider pressure range applied to several nozzles, in order to explore the relationship among the model parameters and application pressure. This would be useful to provide additional relevance and better understand the applicability of the model for different nozzle pulverization capabilities.

Based on the above, through the different papers that have been published, the achievements of the PhD pathway offer useful and important contribution in the growing scientific knowledge towards the possibility of obtaining a more sustainable perspective within the plant protection control based on PPP application.

Chapter 8

Other Activities

8.1 Effect of Image Binarization on Drop Diameters Measurement

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The manuscript is a shortened version of the Chapter III presented at the International Conference AIIA 2022: Biosystems Engineering Towards the Green Deal. It has been submitted as part of the book series Lecture Notes in Civil Engineering (LNCE), Springer Nature.

Full citation:

Privitera, S., Cerruto, E., Longo, D., Manetto, G. (2023). Effect of

Image Binarization on Drop Diameters Measurement. In: Ferro, V., Giordano, G., Orlando, S., Vallone, M., Cascone, G., Porto, S.M.C. (eds) AIIA 2022: Biosystems Engineering Towards the Green Deal. AIIA 2022. Lecture Notes in Civil Engineering, vol 337. Springer, Cham. https://doi.org/10.1007/978-3-031-30329-6_88.

Abstract

With reference to agricultural nozzles for pesticide applications, droplet size affects biological efficacy of a phytosanitary treatment, environmental pollution, and operator's safety. Measuring droplet size spectrum of nozzles is a very complex task which has been addressed in multiple ways over the years. Measurement methods based upon image analysis have to solve the problem of recognizing the droplets and separating them from the background. This is accomplished by means of "binarization" or "segmentation" of the image, and it requires setting a threshold value to separate specific pixel intensities from each other. In this research the effects of the choice of the threshold value on computed volumetric diameters were analyzed. The study was carried out considering images of droplets of an air induction hollow cone nozzle TVI 8002 at the pressure of 1.0 MPa, obtained by applying the Liquid Immersion method in a custom test bench. A starting threshold value was selected based on the average grey level of the image and then variations of ± 5 units were considered. The results showed that the corresponding variations in volumetric diameters were less than 1%. This means that, once the image acquisition system is established, the binarization process may be made automatic and operator independent, with

variations in results fully compatible with the precision of the whole measurement system.

Keywords: Droplet pulverization, Image analysis, ImageJ, Threshold

8.2 Drop Stain Analysis on Water Sensitive Papers

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The manuscript was presented at the International Conference AIIA 2024: Biosystems engineering promoting resilience to climate change (Padova, Italy – June 17–19, 2024). It is in pending to be published in Springer Nature.

Abstract

Water Sensitive Papers (WSPs) are probably the most widely used artificial targets for assessing spray quality in pesticide applications. However, droplet size and density calculation using WSPs are affected by several factors, being the spread factor and the stains' overlapping degree the most important ones. Thus, WSPs may present very complex patterns when the percentage of

covered surface increases, making difficult the interpretation during the image analysis. Under these circumstances, simulations may help to understand the phenomenon. In this study, WSPs were simulated by varying the percentage of covered surface and recording the number of overlapped stains for each test condition. Simulations were implemented in R software, using the drop size distribution coming from an ATR80 hollow cone nozzle at a pressure of 1.0 MPa. Drop stains were represented as black circles on white background. Simulated images were treated as real images coming from scanned WSPs and then analyzed using the *ImageJ* software. Results coming from image analysis were compared to those used for simulations, allowing to relate droplet density, stain density, degree of overlap between stains and percentage of overlapped stains to the percentage of covered surface measured on the WSP images. These data may help to interpret real WSPs used during phytosanitary treatments and to reduce the use of chemicals in plant protection.

Keywords: Phytosanitary treatment, Spray, Drop size spectrum, Image analysis, ImageJ.

Chapter 9

Annexes: Scientific Curriculum

9.1 Education Background

- 2022–2025: PhD course in Agricultural, Food and Environmental Science, Department of Agriculture, Food and Environment (Di3A), University of Catania, Catania, Italy. Research project: “Nozzle spray quality and spray deposition in agricultural treatments”. Under the supervision of Prof. Giuseppe Ezio Manetto and Prof. Emanuele Cerruto.
- 2018–2020: Master’s Degree in Agricultural Sciences and Technologies (LM-69), University of Catania, Catania, Italy. Thesis title: “Il controllo funzionale delle machine irroratrici in Sicilia”. Final mark: 110/110 (magna cum laude).
- 2015–2018: Bachelor’s Degree in Land Protection and Landscape Planning (L-21), University of Catania, Catania, Italy. Thesis title: “Impianti a solare termico: innovazioni e pro-

spettive". Final mark: 106/110.

- 2015: High School Graduation, Liceo Scientifico "Galileo Ferraris", San Giovanni la Punta (CT), Italy.

9.2 Scientific Identifiers

- SCOPUS ID: 7003949527
- <https://www.scopus.com/authid/detail.uri?authorId=7003949527>
- ORCID ID: 0000-0002-3980-524X
- <https://orcid.org/my-orcid?orcid=0000-0002-3980-524X>
- Web of Science: LDE-9959-2024
- <https://www.webofscience.com/wos/author/record/LDE-9959-2024>
- ResearchGate: <https://www.researchgate.net/profile/Salvatore-Privitera-2>

9.3 Scientific Contributions

9.3.1 Published Articles

- Basílio, S., Furtado Júnior, M.R., de Alvarenga, C.B., Vitória, E.L.d., Vargas, B.C., Privitera, S., Caruso, L., Cerruto, E., Manetto, G. Effect of Adjuvants on Physical-Chemical Properties, Droplet Size, and Drift Reduction Potential. *Agriculture* 2024, 14, 2271.

<https://doi.org/10.3390/agriculture14122271>.

- Privitera, S., Cerruto, E., Manetto, G., Lupica, S., Nuytens, D., Dekeyser, D., Zwertvaegher, I., Furtado Júnior, M.R., Vargas, B.C. Comparison between Liquid Immersion, Laser Diffraction, PDPA, and Shadowgraphy in Assessing Droplet Size from Agricultural Nozzles. *Agriculture* 2024, 14, 1191.

<https://doi.org/10.3390/agriculture14071191>.

- Privitera, S., Manetto, G., Pascuzzi S., Pessina, D., Cerruto, E. Drop Size Measurement Techniques for Agricultural Sprays: A State-of-The-Art Review. *Agronomy* 2023, 13, 678.

<https://doi.org/10.3390/agronomy13030678>.

- Cerruto, E., Manetto, G., Privitera, S., Papa, R., Longo, D. Effect of Image Segmentation Thresholding on Droplet Size Measurement. *Agronomy* 2022, 12, 1677.

<https://doi.org/10.3390/agronomy12071677>.

9.3.2 Conference Proceedings

- Manetto, G., Privitera, S., Avola, M., Lupica, S., Cerruto, E. (2024). Preliminary Results on the Correlation Between Drop Size, Foliar Deposition and Surface Coverage to Reduce Plant Protection Product Use. In: Berruto, R., Biocca, M., Cavallo, E., Cecchini, M., Failla, S., Romano, E. (eds) *Safety, Health and Welfare in Agriculture and Agro-Food Systems*. SHWA 2023. Lecture Notes in Civil Engineering, vol 521. Springer, Cham.

https://doi.org/10.1007/978-3-031-63504-5_50.

- Cerruto, E., Ramírez-Cuesta, J.M., Privitera, S., Pascuzzi, S., Manetto, G. Use of the Logistic Function to Model Cumulative Volumes of Spray Nozzles. 2023 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor), 06-08 November 2023, Pisa, Italy, 2023, pp. 635–639.

<https://doi.org/10.1109/MetroAgriFor58484.2023.10424378>.

- Privitera, S., Cerruto, E., Longo, D., Manetto, G. (2023). Effect of Image Binarization on Drop Diameters Measurement. In: Ferro, V., Giordano, G., Orlando, S., Vallone, M., Cascone, G., Porto, S.M.C. (eds) AIIA 2022: Biosystems Engineering Towards the Green Deal. AIIA 2022. Lecture Notes in Civil Engineering, vol 337. Springer, Cham.

https://doi.org/10.1007/978-3-031-30329-6_88.

- Cerruto, E., Manetto, G., Lupica, S., Privitera, S., Longo, D., Ramírez-Cuesta, J.M. Drop stain analysis on water sensitive papers. In pending to be published in Springer Nature.

9.4 Participation at Research Projects

PRIN 2022 PNRR – Title of the research project: Implementation of a digital tRee to Optimise technical and environmental performances of crop protection equipment (IM GROOT) (<https://sites.google.com/icar.cnr.it/prin2022pnrr/>).

The objective of the project is to develop an innovative and smart tool, a “Digital Tree”, which allows predicting spray behaviour under different operations and field conditions, and consequently improving Plant Protection Products (PPPs) application in olive orchards. To do this, specific sensors will be used for monitoring spray performance, including foliar deposition, losses on the ground and drift.

The overall project has a duration of two years, with research activities organized into seven Work Packages (WPs), each consisting of several tasks (Figure 9.1). My role within the project mainly relates to WP2 activities, which are finalized to the assessment of droplet size distribution, superficial coverage, and foliar deposition at varying of working parameters.

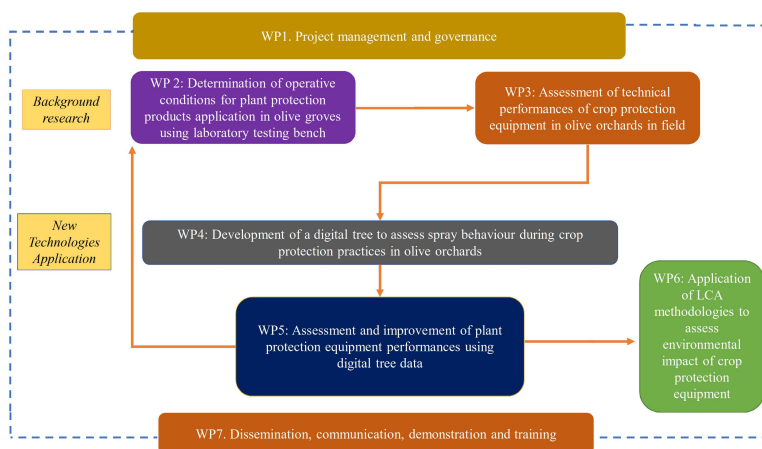


Figure 9.1: Overview of the project structure.

Research Units: University of Catania (UNICT), University of Reggio Calabria (UNIRC), and Institute of high-performance

computing and networking (ICAR-CNR).

Principal Investigators and Members: Emanuele Cerruto (Principal Investigator – UNICT), Giuseppe Manetto (UNICT), Domenico Longo (UNICT), Salvatore Privitera (UNICT), Bruno Bernardi (Associated Investigator – UNIRC), Lorenzo Abenavoli (UNIRC), Souraya Benalia (UNIRC), Matteo Sbaglia (UNIRC), Giovanni Costa (Associated Investigator – ICAR-CNR), Riccardo Ortale (ICAR-CNR), Davide Macri (ICAR-CNR), Agostino Forestiero (ICAR-CNR).

Financial aspects: Requested funds to Ministry of University and Research (MUR) for 299.349 euro.

9.5 Peer Review of Scientific Articles

Reviewer for the Journal of Agricultural Engineering (JAE).

9.6 Visiting Stays in Universities and/or Research Institutes

A nine months' period abroad was spent during the PhD path. In particular, six months were carried out at the Department of Agricultural Engineering of the Federal University of Viçosa (UFV) Viçosa, MG, Brazil, under the supervision of Prof. Marconi Ribeiro Furtado Júnior and three months were conducted at the Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Merelbeke, Belgium, under the supervision of Dott. David Nuyttens. The Brazilian stay was subdivided into two different periods. The first period was carried out from May until July 2023, while the second one was carried out from February until May 2024.

In detail, my research activity conducted during the first training period at UFV was finalized at measuring the droplet size produced by agricultural nozzles at given pressures and spray heights and using pure water as test liquid, through a Laser Diffraction system (Malvern Spraytec). The experimental activity continued during the second period and was focused on the (i) assessment of the effects of two agricultural adjuvants, Squall (anti-drift adjuvant) and Vivolt (wetting agent), on droplet size generated by agricultural nozzles using the Malvern instrument; and the (ii) evaluation of the drift reduction potential of three different solutions, water, water + Vivolt (wetting agent) and water + Aureo (anti-drift adjuvant), by means of wind tunnel.

Starting from September until December 2023, I conducted my second training period abroad at ILVO's research institute where I performed various research activities focused on the: (i) measurement of droplet size and velocity produced by agricultural nozzles at given pressures and fixed spray height and using pure water as test liquid, through the Phase Doppler Particle Analyzer (PDPA); (ii) measurement of droplet size and velocity produced by agricultural nozzles at given pressures and fixed spray height using a image-based processing device (VisiSize P15); (iii) assessment of the effects of two agricultural adjuvants, Squall (anti-drift adjuvant) and Vivolt (wetting agent), on droplet size and velocity generated by agricultural nozzles using the PDPA instrument; (iv) evaluation of the spray pattern distribution of nozzles by using an horizontal test bench, according to the guidelines of ISO 5682-1 standard; (v) assessment of the spray coverage degree (%) and droplet density (droplet/cm²) on Water Sensitive Papers.

Part of the results obtained during these periods at UFV and

ILVO were summarized within the Chapter IV. The additional experimental data collected were preliminarily handled and elaborated and will be object to further analysis for other publications in scientific journals.

9.7 Attendance to Conferences/Workshops/Seminars

- Seminar “Scenari e prospettive del settore agroalimentare siciliano fra investimenti, sostenibilità e innovazione”, organized by Department of Agriculture, Food and Environment (Di3A), University of Catania, in collaboration with the Regional Department of Productive Activities and the Academy of Georgophiles, 10th June 2022.
- Webinar “Verso una distribuzione sostenibile degli agrofarmaci nel vigneto: obiettivi e primi risultati sperimentali nell’ambito del progetto Life PERFECT”, held by Prof. Paolo Marucco, University of Torino, 24th March 2022.
- XII AIIA Conference “Biosystems Engineering Towards the Green Deal”, University of Palermo, Italy, 19th–22th September 2022.
- 4th Joint Meeting of Agriculture-oriented PhD Programs UniCT, UniFG and UniUD, Paluzza (UD), Italy, 3rd–7th October 2022.
- Webinar “L’uso sostenibile dei prodotti fitosanitari”, organized by Giornate Fitopatologiche in collaboration with AIPP (Associazione Italiana per la Protezione delle Piante), 28th November 2022.

- Seminar “AGRITECH project – Kick off meeting”, Department of Agriculture, Food and Environment (Di3A), University of Catania, Catania, Italy, 23rd January 2023.
- Seminar “Energy efficiency of pump system”, held by Prof. Gencho Popov and Prof. Boris Kostov (Faculty of Agriculture and Industry, University of Ruse (Bulgaria), Department of Agriculture, Food and Environment (Di3A), University of Catania, Catania, Italy, 7th February 2023.
- Webinar “Tecnologie smart per una difesa integrata sostenibile delle colture”, organized by the National Centre for Technology in Agriculture AGRITECH within the activities carried out in Spoke 2 (Crop Health: A multidisciplinary system approach to reduce the use of agrochemicals), Department of Agriculture, Food and Environment (Di3A), University of Catania, Catania, Italy, 9th February 2023.
- Webinar “Il bilancio fitosanitario 2022 e 2023 di pomodoro e patata”, organized by AIPP (Associazione Italiana per la Protezione delle Piante) in collaboration with Giornate Fitopatologiche, 12th October 2023.
- Webinar “Il bilancio fitosanitario 2022 e 2023 della vite ad uva da vino e da tavola nel centro-sud”, organized by AIPP (Associazione Italiana per la Protezione delle Piante) in collaboration with Giornate Fitopatologiche, 9th November 2023.
- Webinar “Il bilancio fitosanitario 2022 e 2023 delle Pomacee”, organized by AIPP (Associazione Italiana per la Protezione delle Piante) in collaboration with Giornate Fitopatologiche, 13th November 2023.

- Webinar “Il bilancio fitosanitario 2022 e 2023 della vite nel nord Italia”, organized by AIPP (Associazione Italiana per la Protezione delle Piante) in collaboration with Giornate Fitopatologiche, 23rd November 2023.
- Seminar “L’uso dei droni per l’agricoltura di precisione: dalla pre-pianificazione del volo all’esportazione delle mappe di zonazione”, Department of Agriculture, Food and Environment (Di3A), University of Catania, Catania, Italy, 28th May 2024.
- Webinar “Inquinamento puntiforme e diffuso da prodotti fitosanitari: come prevenirlo e mitigarne il rischio nella pratica di campo”, held by Prof. Paolo Marucco and Prof. Francesco Vidotto, Department of Agricultural, Forest and Food Sciences (DISAFA), University of Torino, Italy, 31st May 2024.
- 6th Joint Meeting of Agriculture-oriented PhD Programs UniCT, UniFG and UniUD, Lesina (FG), Italy, 30th September-4th October 2024.
- Webinar “TA Springer Nature & CARE – CRUI: Research Integrity”, organized by Springer Nature, 8th October 2024.

9.8 Attended Courses and Certificates

- Course “Managing biological data with R” (40 hours), held by Prof. Mario Di Guardo, Department of Agriculture, Food and Environment (Di3A), University of Catania, Catania, Italy, from 22nd February 2022 to 4th March 2022.

- Course “Analisi statistica di base” (40 hours), held by Prof. Corrado Dimauro and Prof. Alberto Cesarani (University of Sassari, Italy), Department of Agriculture, Food and Environment (Di3A), University of Catania, Catania, Italy, from 19th October to 23rd October 2022.
- Course “Agricoltura di precisione 4.0” (4 hours), held by Dott.ssa Federica Ferroni, organized by Agricolus Professional Academy, 9th, 16th, 23rd February and 2nd March 2023.
- English course “Dott 5_Liv. A2+B1” (40 hours), held by Alexander Bolam, from 8th March 2023 to 26th May 2023, organized by CLA (Centro Linguistico d’Ateneo) of the University of Catania. A certificate of achievement, following the final exam, was released on 1st August 2023 (Rep. 1128).
- Course “Writing a scientific review article” (8 hours), held by Prof.ssa Daniela Spina and Prof. Gaetano Chinnici, Department of Agriculture, Food and Environment (Di3A), University of Catania, Italy, 6th and 9th June 2023.
- Course “Scientific publishing in the peer review era” (8 hours), held by Prof. Antonio Biondi and Dott. Michele Ricupero, Department of Agriculture, Food and Environment (Di3A), University of Catania, Italy, 23rd and 27th June 2023.
- Course “CAD and GIS for sustainable agriculture” (15 hours), held by Prof.ssa Claudia Arcidiacono and Dott.ssa Provvidenza D’urso, Department of Agriculture, Food and

Environment (Di3A), University of Catania, Italy, 4th, 5th and 6th July 2023.

- Certificate of achievement TOEPE (Test of English for Post-graduate Education) of the level B2 (CEFR), following the final exam, was released on 14th July 2023, Viçosa, MG, Brazil.
- Course “Multispectral indexes for detecting crop features” (4 hours), held by Prof.ssa Daniela Vanella, Department of Agriculture, Food and Environment (Di3A), University of Catania, Italy, 12th January 2024.
- Course “Hyperspectral and thermal data for precision agriculture applications” (4 hours), held by Prof. Juan Miguel Ramírez-Cuesta, Department of Agriculture, Food and Environment (Di3A), University of Catania, Italy, 19th January 2024.
- Course “Managing biological data with R: applications for plants and fruit tree species” (20 hours), held by Prof. Mario Di Guardo, Department of Agriculture, Food and Environment (Di3A), University of Catania, Italy, from 22nd January to 26th January 2024.

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