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Spray droplet deposition, collection, and analysis techniques: A review

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Abstract
Spraying is one of the critical operations in agriculture. The importance of the use of chemical pesticides was well recognized in agriculture. Consumption of pesticides was increasing year by year, on the other hand, wastage of chemical pesticides also alarming. Droplet size and droplet densities are critical parameters to identify the effectiveness of sprayer. The smaller droplets were prone to drift and not retained on the plant, whereas larger droplets also not adhere to the plant canopy, hence it is important to consider droplet size as a critical parameter while evaluating the performance of any sprayer. In the scientific community, there are different techniques to analyze the deposition of spray with tracers. Different types of droplet collectors such as natural collectors, artificial collectors, Water Sensitive Papers (WSP) and polyethylene collectors were used by different researchers. Researchers intending to use these new results need to understand with clarity what exactly the measurements provide and how reliably they can provide them. This article intends, therefore, to bring some order to the discussion of techniques used for spray droplet analysis. Most of the techniques are certain to evolve and improve further, but this article can provide a snapshot in time and help create a context for understanding.

Keywords: Spray deposition, droplet analysis, droplet collectors, tracers, image J, drop leaf, deposit scan, laser diffraction (LD), microscopy, laser sheet drop sizing (LSD), particle image analysis (PDIA), digital image analysis (DIA)

1. Introduction

Food grain production in India in the year 2018-19 was 283.37 MT which was 5.4 times more than the food grain production in the year 1951-52, which was 52 MT only. The role played by plant protection practices are well recognized to meet the domestic requirement of food grains and also generating exportable surpluses. Agriculture in developing countries suffers most because of the high incidence of various pests. In India, estimated annual production losses due to pests are as high as US$ 42.66 million (Subash *et al.*, 2017) [50]. Insecticides and fungicides are commonly used for pest control in agriculture. Both totals as well as per hectare consumption of pesticides in India show a significant increase after the year 2009-10. In the year 2014-15, pesticide consumption was 0.29 kg/ha (Gross Cropped Area), where as in 2009-10 pesticide consumption was 0.18 kg/ha (GCA) (Subash *et al.*, 2017) [50].

Pesticides will remain a tool for modern agriculture, so it is important to design strategies that will reduce pesticide impact (Ekstrom and Ekbom, 2011) [17], this can be achieved by the improved application of the selected product for maximum dose transfer to the biological target (Dent, 2012) [15]. The application of pesticides in recommended doses not only reduces the input cost of chemicals but also reduces the ill effects due to excess application of pesticides on crop and environment. Nevertheless, reduction of chemical wastage would reduce the amount of chemical used, thereby reducing the cost of production (Loghavi and Mackvandi, 2008) [32]. Recommended dose of chemical application is critical in spraying activity; under-application results in lack of effectiveness, whereas over-application results in yield reduction, soil and environmental pollution (Gopalapillai *et al.*, 1999) [23].

Now a days different types of sprayers are available in the market with varied specifications. Sprayers like manually operated, power-operated, battery-operated, and tractor-drawn sprayers are available. Farmers can select sprayer based on the requirement from different manufacturers. For evaluating the performance of any sprayer, measurement of certain parameters like uniformity coefficient, droplet size, droplet density, and chemical deposition are important. The size of the spray droplet and deposition of the droplet are critical for effective spraying activity.

Droplet category and application of spraying activity decided by the size of the droplet (Table 1).

Table 1: Droplet category based on droplet size

Application	Droplet category	VMD range (μm)
Fungicide		
Foliar protective or curative	Medium	226-325
Insecticide		
Foliar contact or stomach poison	Medium	226-325
Foliar systemic	Coarse	326-400
Soil-applied systemic	Coarse Very Coarse Extremely Coarse	326-400 401-500 > 500
Herbicide		
Foliar/post-emergent contact	Medium	226-325
Foliar/post-emergent systemic	Coarse	326-400
Soil-applied/pre-emergent systemic	Coarse Very Coarse Extremely Coarse	326-400 401-500 > 500

(**Source:** ASABE Standard 572).

The smaller droplets prone to drift and not retained on the plant, whereas larger droplets also not adhere to the plant canopy due to more runoff (Cox *et al*., 2000) [13], hence it is important to consider droplet size as critical parameter while evaluating the performance of any sprayer. The size of the droplet >150 µm is desirable to reduce the risk of drift in spraying activity (Forster *et al*., 2012) [19]. For effective control of fungal spores on a banana leaf, the mean density of 30 drops $cm^{-2}$and VMD of 300-400 µm was desirable (Washington, 1997) [53]. Patel *et al*., (2016) [44] reported that electrostatic sprayer in the cotton field was efficient at lower values of NMD (24.48 µm) and VMD (45.28 µm) with least uniform coefficient. Insecticides and fungicides require smaller droplets than herbicide applications. Experimental results suggest that for foliar herbicide application droplet range of 100 µm to 400 µm do not significantly differ in weed control unless applications volumes are extremely varied (Hipkins *et al*., 2009) [26]; it is showing that assessment of droplet size and droplet density is critical to characterize the efficiency of any sprayer.

The present article reveals the review of different techniques available in the literature to collect droplets ejected by sprayers, to analyze the droplet size and densities. Next various types of tracer materials and droplet collectors with a brief description, usage and limitations are presented. Finally, the methods to evaluate the pesticide deposit including field experimental procedure are described.

2. Measurement of pesticide deposits

Measurement of pesticide deposits is critical to evaluate the spraying activity, several procedures available in the literature to measure pesticide deposits. All measures in the literature rely either on the use of tracer material or direct use of pesticides. Many researchers preferred to use tracer materials to study pesticide deposition.

2.1. Tracers

Pesticide deposit measurements depend on the use of tracing chemicals or direct use of pesticides. Good tracer must pose some qualities such as (i). Easy to recover from artificial and natural targets. (ii). Recovery of tracer from targets should be high (Allagui *et al*., 2018) [3]. The recovery of tracer is assessed by comparing the amount of measured tracer to the amount of applied tracer; recovery may be affected by background deposits, process of extraction and degradation of dye (Cerqueira *et al*., 2012) [10] Different types of tracers are available in scientific community, such as fluorescent tracers, colorimetric tracers, and metal ion tracers.

2.1.1. Fluorescent tracers

Fluorescent tracers are less harmful, not expensive compared to colorimetric tracers (Palladini *et al*., 2005) [42]. Fluorescent tracers are Eosine, Caacid, Fluorescein, Tinopal, Uvitex, Rhodamine, Brilliant Flavine, Brilliant SulfoFlavine (BSF) and Uranin are analyzed by using spectra fluorometry (Nuyttens *et al*., 2007) [41]. Rhodamine is a low-cost tracer with little influence on the physicochemical characteristics of the spray, the best option to use when filter papers are used as a collector (Bueno *et al*., 2017) [9]. The main limitation with fluorescent tracer was sensibility to the light, hence it is necessary to verify recovery and stability of tracer before conduct experiment.

2.1.2. Colorimetric tracers

Some of the colorimetric tracers are Erythrosine, Tartrazine, Lissamine Green and Orange, and Brilliant Blue (Murray *et al*., 2000) [39]. Adsorption of dye on target surfaces and degradation is a problem in colorimetric tracers. Tartrazine tracers are used in vineyard filed to assess the quality of spray droplet distribution to evaluate developed sprayer (Codis *et al*., 2013) [11]. A mixture of tracer pesticide (Tebuconazole) with a fluorescent dye (Rhodamine), metal ions (cobox) and sodium chloride used to compare spray deposits on different crops (Cerqueria *et al*., 2012).

2.1.3. Metal ion tracers

Metal ions like copper oxychloride, copper hydroxide, metallic salts, metal chelates are used as tracers. Metal ions are light stable, soluble in water and can be measured at very low concentrations. The first metal ion used as tracer was the copper as the analyte for the measurement of deposits fungicides containing metal like copper oxychloride, metallic salts, copper hydroxide was used (Cerqueria *et al*., 2012). The recovery of copper analyzed by Atomic Absorption Spectrometry (AAS) was more than 90% (Braekman *et al*., 2009) [8]. The use of metal ions is complex, very expensive and needs much time for analyzes.

3. Field experimental procedure to measure pesticide deposit

Spray deposition per unit area can be determined easily by observing the weight difference of the collector before and after spraying activity. Nylon screens used for collecting spray solution mixed with royal blue indigo dye at a rate of 5g per liter in water. Nylon screens were weighed with an accurate weighing scale (least count 0.001g) before and after spraying activity. The amount of spray deposit per unit area was determined by taking the difference between the weights of nylon screens and dividing it by the total area of the screen. Maximum Spray deposition of 0.816 µl cm^{-2} was observed in the middle of guava orchard in this method (Wandkar *et al*., 2017) [52].

Tartrazine tracer material mixed to chemical at a rate of 1 kg/ha. Spray droplet collectors such as natural collectors or artificial collectors were placed on the plant at different levels of the canopy as shown in Fig 1. Collect all collector samples after spraying and wash with distilled water of 100 ml. Three samples of 5ml were taken and filtered through a 0.22 µm microfilter and optical absorbance was measured in a spectrophotometer at a wavelength of 427 nm (Llop *et al*., 2015 and Stajnko *et al.*, 2012) [31, 49]. A spectrophotometer is an instrument that can measure the absorbance of a sample at a particular wavelength. As per Beer's law absorbance of a solution is directly proportional to the concentration of a solution (Beer., 1852) [7].

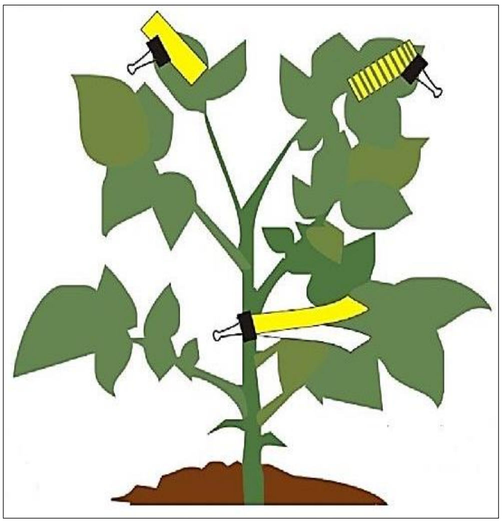


Fig 1: Placement of droplet collectors on plant canopy

Bueno *et al*., (2017) [9] used Rhodamine as a fluorimetric tracer with a concentration of 100 mg l^{-1}. Samples were kept in 100 ml of an aqueous solution containing 0.2% tween 80 and stirred for 15 min at 120 rpm on a shaker table. The solution was transferred to plastic cups after 10 min of rest, fluorimeter used for extracting tracer concentration in ηg ml^{-1}. Brilliant Sulfaflavine (BSF) tracer with concentration of 3 g l^{-1} was used to study the efficiency of handgun broadcast system. Tracer collected on nylon screens were rinsed with 30 ml of purified water. A 4 ml sample rinsate solution placed in a cuvette for determination of peak fluorescent intensity with illuminance spectrometer with wavelength of 460 nm (Derksen *et al*., 2010) [16]. Acid Yellow 7 tracer deposited on monofilament nylon screens of 20 cm × 20 cm size was analyzed by dipping screens into 500 ml bottles and washed by shaker table for 5 min with 50 ml of distilled water. Then 5 samples were drawn and analyzed with fluorescent detector (Fox *et al.*, 2004) [20].

By measuring the absorbance of a solution with a known concentration of a chemical, this can be used as a reference to estimate the concentration of a chemical in an unknown solution by measuring the absorbance of unknown concentrated chemicals. From the absorbance - concentration standard curve, one can determine the concentration of a chemical in a solution by measuring absorbance of unknown concentration solution. For example, the absorbance of unknown concentration solution was 0.7, from the curve one can find the concentration of a particular chemical as 3.5 g l^{-1} (Fig. 2) (Gore, 2000) [24].

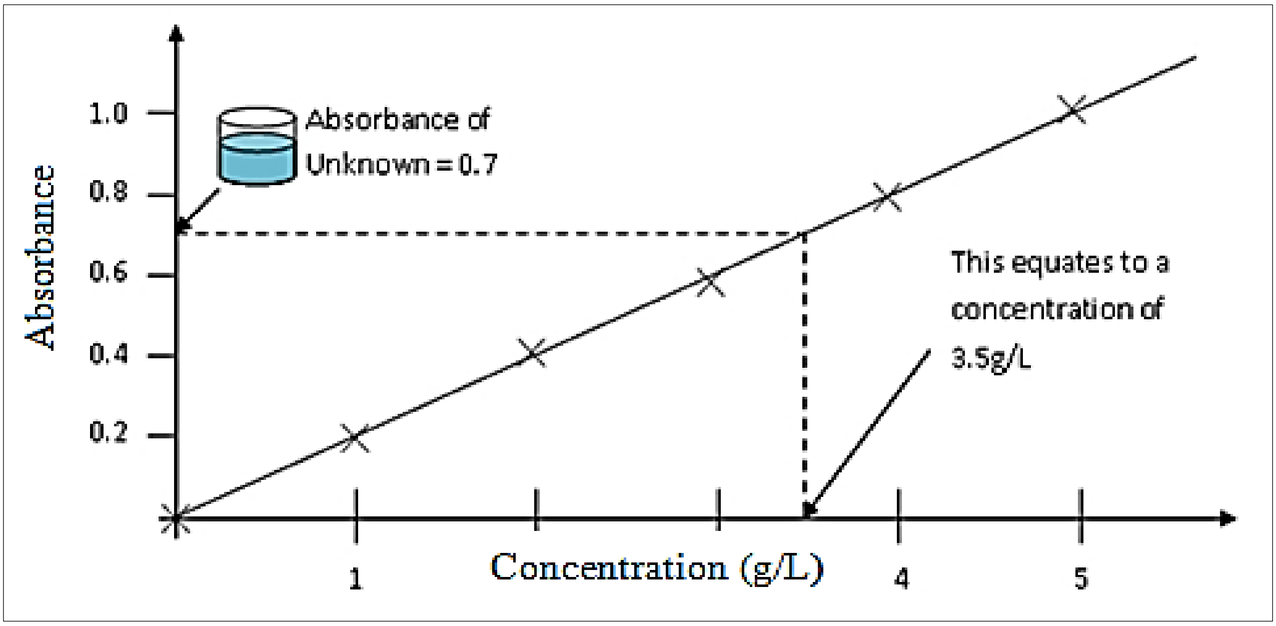


Fig 2: Absorbance - concentration curve

Theoretical deposit of tracer material per unit area was calculated by equation (1) (Pergher and Gubiani, 1995) [45].

$$T_d = \frac{Q.T_c}{L.10^4} \quad (1)$$

Where T_d is theoretical deposit per unit leaf area, µg cm^{-2}, Q is application rate, l ha^{-1}, T_c is tracer concentration, g l^{-1}, and L is leaf area index, m^2 ha^{-1}.

Spray deposit per unit area was calculated by equation (2) (Musiu *et al*., 2019) [40].

$$d = \frac{T_{cl}.W}{L_a} \quad (2)$$

Where d is deposit per unit area, µg cm^{-2}, T_{cl} Is tracer concentration, g l^{-1}, W Is the volume of extract used, ml, and L_a Is the total area of the sample (leaf/paper), cm^2.

In experimentation for treatment comparisons, tracer application rates (1) needed to change, atmospheric conditions were not constant; hence it was necessary to normalize data.

Normalized deposit can be calculated with equation 3. (Llop *et al.*, 2015) [31].

$$N_d = \frac{d}{T_d} \qquad (3)$$

Where N_d is normalized deposit.

Analysis of the tracer deposits was performed using the appropriate instruments for the detection of each tracer.

- A UV/Visible, double-beam spectrophotometer (Shimadzu UV-1601 PC, Kyoto, Japan) equipped with a 630-nm wavelength filter was used to quantify the Brilliant Blue tracer.
- A flame photometer (Digimed DM-61, São Paulo, Brazil) was used to quantify the sodium ions.
- A fluorescence spectrometer (PerkinElmer LS-55, Waltham, Mass.) equipped with an exciter filter wavelength of 540 nm and a 585-nm emitter filter was used to quantify the Rhodamine B.
- An atomic absorption spectrophotometer (PerkinElmer 2380, Waltham, Mass.) was used to quantify the copper ions (Cu).
- For the quantification of tebuconazole, an analytical method was developed using a liquid chromatography, equipped with Shimadzu LCMS solution software, and a mass detector LCMS-2010 EV (Cerqueira *et al.*, 2012) [10].

The tracer concentrations obtained using the different measuring techniques for the washing solutions from the natural and artificial targets and initial concentration used in the tracer solution permitted determination of the volume retained on the target. The values of the spray deposits per unit area (ml cm^{-2}) were obtained by the relationship between the volume captured on the target and the target's respective area (Cerqueira *et al.*, 2012) [10].

$$Ci \,.\, Vi = Cf.\, Vf \qquad (4)$$

Where Ci is spray mix initial concentration, mg l^{-1}, Vi is volume extracted from the target, ml, Cf is concentration detected in optical density, mg l^{-1} and Vf is dilution volume of each target sample, mL.

4. Droplet collectors

Droplet collectors are essential to collect spray to analyze the performance of the spraying activity irrespective of type of tracer used. Several types of collectors are available such as natural collectors, artificial collectors, water sensitive papers and polyethylene collectors. Main natural collectors are plant leaves, which can collect chemical deposits. Leaf samples can be washed with distilled water or solvent to extract and quantify the amount of tracer deposited over leaves (Martin, 2014) [35]. Crop vegetation density is an important factor to consider while using natural collectors. Researchers relied on Leaf Area Density (LAD) and Leaf Area Index (LAI) to identify crop density. Artificial collectors are replacement to natural collectors. To get accurate results and to avoid field disturbance artificial collectors are used (Forster *et al.*, 2014) [18]. Artificial collectors were more efficient than natural collectors (Cerqueira *et al.*, 2012) [10]. To collect the spray droplets in the air, polyvinyl chloride (PVC) line of 2 mm diameter was used, efficiency of 80% observed (Gil *et al.*, 2007) [22]. A plastic carpet of 20 cm × 30 cm was used to measure ground deposition of chemical under wheat crop. The efficiency was measured by comparing the amounts collected on the carpets to the amounts measured on the same width on a patternator (Bahrouni *et al.*, 2010) [6]. Water sensitive papers (WSP) are also coming under artificial collectors. WSP can be used to measure droplet spectra and deposition quality of chemical in field spraying experiments, but does not gives an idea about the efficiency of the formulations, retention and coverage properties on crop surface (Halley *et al.*, 2008) [25]. The smaller droplets are easily measured on WSP collector than the larger droplets, higher volume rate (Salyani *et al.*, 2013) [48]. The spray droplet leaves a blue stain on the WSP which coated with a layer of bromoethyl blue during treatment with water content. The WSP does not require a fluorescent dye tracer in the mixture and can be analyzed by software to get droplet data but the WSP spoils easily at high humidity and does not capture very well small droplets <50µm. An artificial superhydrophobic surface composed of complete polytetrafluoro - ethylene (PTFE) coated microscope slide blade to measure spray deposition on wheat and barley leaves (Massinon *et al.*, 2017) [36]. Monofilament nylon screen targets of 3.8 cm × 3.8 cm size with nominal porosity of approximately 56% and fiber frontal area percentage of 44% were used to simulate leaves to collect foliar spray deposition on abaxial surface (Fig. 3) (Derksen *et al.*, 2010) [16].

Fig 3: Nylon screen on leaf abaxial surface

5. Droplet VMD and NMD

VMD refers to Volume Mean Diameter, which is the mid-way drop size that is reached when the accumulated volume of smaller drops accounts for 50% of the sprayed liquid leaving the nozzle; half the volume is atomized into droplets smaller and the other half of the volume is larger than the VMD (Prokop and Kejklicek, 2002) [46]. The Number Median Diameter is represented by a droplet with size such that one-half of the total numbers of droplets are smaller than this size and one-half of the droplets are larger. For effective control of insect droplets, VMD should be in the range of 140 to 200 µm and droplet NMD should be in the range of 30-50 droplets cm^{-2} (Matthews, 1975) [37]. The ratio of VMD to NMD is called the homogeneity factor.

$$\text{Homogeneity Factor (HF)} = \frac{VMD}{NMD} \qquad (5)$$

HF is an indication of droplet range. The homogeneity factor of unity represents that droplets have the same size, which can only be generated through a uniform droplet generator. The smaller homogeneity factor, the narrower was the spray spectrum (Ahmad *et al.*, 2016). Homogeneity factor and relative span factor are used for indicating of breadth of the droplet spectra. Relative span factor is defined as $\Delta = D_{0.9} - D_{0.1}/VMD$. It provides a direct indication of the range of droplet sizes relative to volume median diameter (Matthews and Hislop, 1993) [38]. The addition of adjuvants did not increase only values of VMD and NMD but influenced volume of droplets under 75 µm. Bouth Agrovital® (96% pinolene) and Ekol® (90% rapsfluid, 10% polyetoxyl esters) decreased volume of driftable particles and droplet deposit on non-target surfaces. This is important for the restriction of pesticide losses and environmental contamination. Increasing of the VMD and the NMD and decreasing of the relative span factor improve the penetration into bottom parts of the plants and the efficiency (Matthews and Hislop, 1993) [38].

6. Droplet analysis

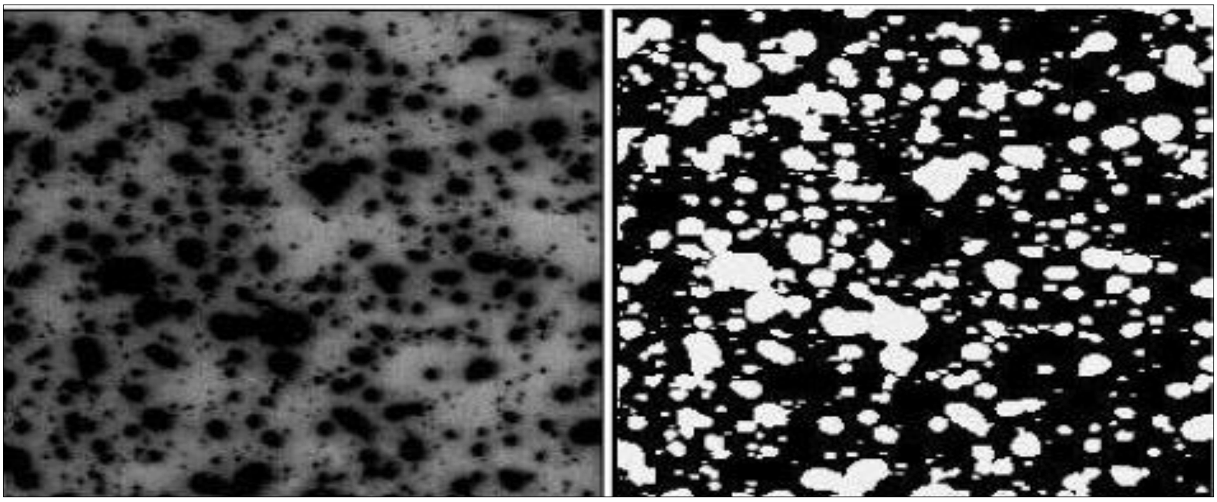
Droplets collected on droplet collectors need to analyze to evaluate the efficiency of spraying activity. WSP after scanning with a digital scanner, color image converted into a gray level image having one variable to analyze: gray intensity (0 to 256). RGB images were split into 3 gray images, one for each primary color. Image J v1.43u software was used to analyze images. By applying the threshold of gray intensity 59, gray image converted to a binary image with two variables, 0 (droplet) and 1(background) (Mangado *et al*., 2013) [34].

Table 2: Classification of coverage per category

Coverage categories	Coverage level (%)	Classification
0	0-5	Insignificant
1	5-20	Under-dosing
2	20-50	Excellent
3	50-80	Excessive
4	80-100	Overdosing

WSPs used to evaluate sonar sensing sprayer in a pomegranate orchard, scanned WSPs were analyzed with Image J software, the average impact of 91 drops cm^{-2} in conventional spraying whereas in sensor-based spraying was 90 drops cm^{-2} (Tewari *et al*., 2018) [51]. Image J software is Java-based image processing software developed by the National Institute of Health and available freely to the public (Collins, 2007) [12].

A portable spray deposition system developed by combining Image J and proprietary custom-developed program, namely “Deposit Scan”; can quantify spray deposit distribution on any type of paper collector. A card produced by Hoechst AG (Frankfurt, Germany), with spots ranging from 50 to 1000µm used as reference card. Deposit Scan can detect droplet diameter up to 17 µm (Zhu *et al*., 2011) [54]. A droplet analyzing system comprises of stereo zoom microscope with CCD camera of radical scientific equipment maker, USB digital scale software installed PC and monitor used to analyze droplets collected on WSPs to evaluate electrostatic sprayer in orchards (Kumar *et al*., 2014 and Patel *et al*., 2016) [29, 44]. A portable image analysis system consists of a camera, lens, and lighting system enclosed in a box. Camera with the digital grayscale with a resolution of 752 × 480 pixels and 8 bites per pixel. 2.4 cm^2 image area covered at a time. The optimum threshold of 10 to 30 gray levels applied to the image for correction (Fig.3), the percentage of area covered on WSP can be estimated with portable image analysis system with an absolute error of 3.5% (Panneton, 2002) [43].



(a) (b)

Fig 4: WSP image, (a) before and (b) after application of a threshold

A Digital Image Analysis (DIA) system comprises a laser, digital camera, and computer. Lab view software used to perform image analysis activity. Command written in the Hyperterminal window program controls the laser beam. The spray droplets were back-lighted with an illumination source and the camera acquires shadow images of drops. Raw images were enhanced by applying filter functions to rectify light drifts (Fig.5) (Lad *et al*., 2011) [30].

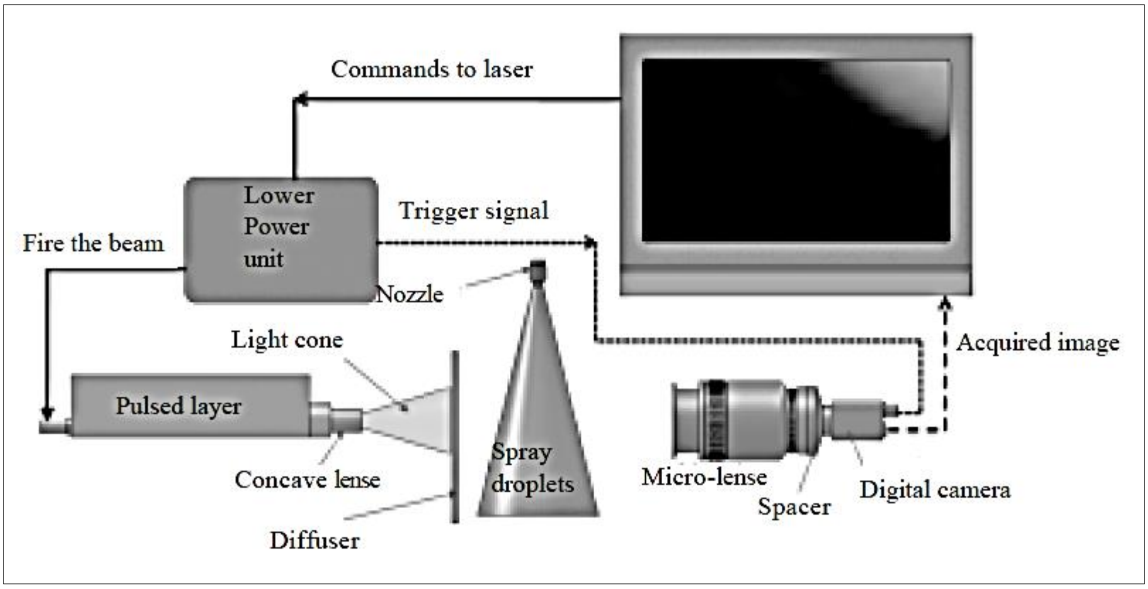


Fig 5: Digital image analysis system using laser beam

Droplet size can be calculated with the following equation (Lad *et al.*, 2011) [30].

$$D_p = 2\sqrt{\frac{A_p}{\pi}} \quad (6)$$

Where D_p is an equivalent diameter of a drop, and A_p is area of the droplet.

Smartphone enabled application called "Drop-leaf" developed by Machado *et al.*, Dropleaf was based on image processing techniques built upon a mobile to calculate droplet coverage density, VMD and diameter relative scan in field instantly. Dropleaf eliminates the laborious manual practice of droplet analysis (Fig. 6). Dropleaf performs five steps; (i). Converting a color image to grayscale image. (ii). Binarization by thresholding, (iii). Dilation and erosion in distinct copies of the image, (iv). Complement operation over dilated and eroded images to produce counter marker, (v). Drop identification via marker-controlled watershed. The Hoechst AG (Frankfurt, Germany) card with spots ranging from 50 to 1000µm used for reference. The results obtained through Dropleaf were compared with DepositScan and Stereoscopic microscope results. The stereoscopic microscope had the best performance; Dropleaf exhibits the best results after the microscope by beating the precision of DepositScan for all the drop sizes (Machado *et al.*, 2018) [33].

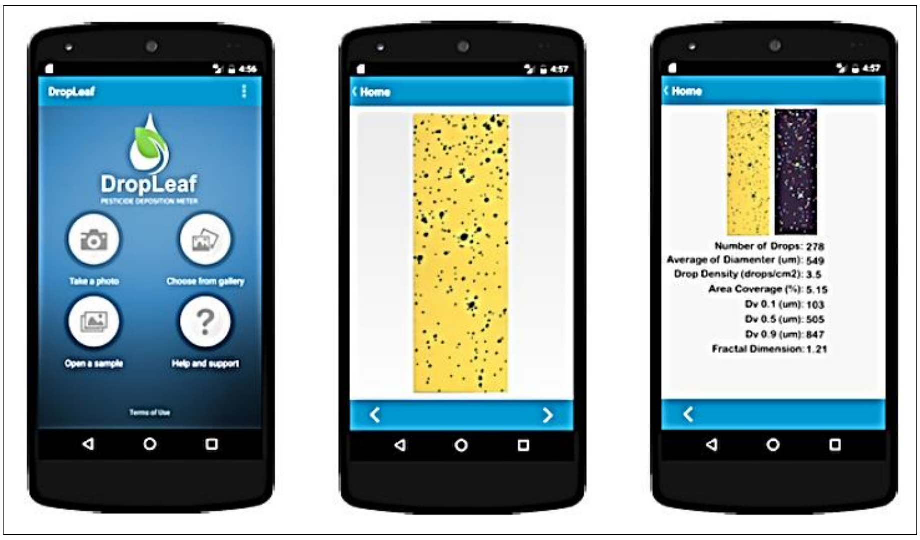


Fig 6: Preview of Dropleaf application

A study was conducted to investigate results obtained by different computer programming tools like CIR, e-Sprinkle, DepositScan and Conta-Gotas. The parameters like VMD, NMD, and droplets per target area were considered. For comparison of results, WSP was analyzed manually also. Spread factor considered for adjusting droplet diameter in all the cases, the volume of each droplet was calculated by using equation 7. They reported that there was a great difference between the values measured for the same WSP sample with different computer programs. (Cunha *et al.*, 2013) [14].

$$V_g = \frac{\pi . D_g^3}{6} \quad (7)$$

Where V_g is volume of each droplet in µm³, and D_g is droplet diameter in µm.

Water Sensitive Papers were analyzed with three different image analysis systems like AM1 (modified area meter equipped with RCA 2014X digital camera and monitor), DS2 (flatbed scanner, 30 µm/pixel resolution and DropletScan Software) and PS3 (Photo-smart scanner, 42 µm/pixel resolution and image processing software). Overall, there was a good correlation (R^2: 90.85 - 97.48) among the three imaging systems in measuring percentage area coverage on WSP. There was a weak correlation between droplet size data obtained by DS2 and PS3 image analyzers (Salyani *et al.*, 2013) [48].

Microscopy is an excellent technique as it allows one to directly look at the particles in question. So the shape of the particles can be seen and it can also be used to judge whether good dispersion has been achieved or whether agglomeration is present in the system. The method is relatively cheap and for some microscope systems it is possible to use image analysis to obtain lists of numbers. Electron microscopy has elaborate sample preparation and is slow. With manual microscopy few particles are examined (maybe 2000 in a day with a good operator) and there is rapid operator fatigue (Rawle, 2015) [47].

In Laser Sheet Drop sizing (LSD) technique when a laser light interacts with a spray, a photon may follow several paths before it reaches a Charge-Coupled Device (CCD) camera. In Fig.7; condition A explains a single scattering event. The laser light interacts with a droplet and reaches the CCD camera without interacting with any other droplet. This is the most ideal condition in the LSD measurement for reliable drop sizing. In Condition B, a photon starts traveling from a droplet illuminated with laser light. However, the photon interacts with several other droplets before its detection by the CCD camera sensor. This path causes misinterpretation of a false droplet (a yellow droplet with a dashed line). Condition C shows a path of a photon that interacted with a droplet; however, the photon is not recorded on the camera sensor leading to a loss in the signal. Conditions B and C are considered as multiple scattering, which may lead to error in the drop sizing of the LSD measurements (Fig. 7) (Aniket and Deshmukh, 2020) [4].

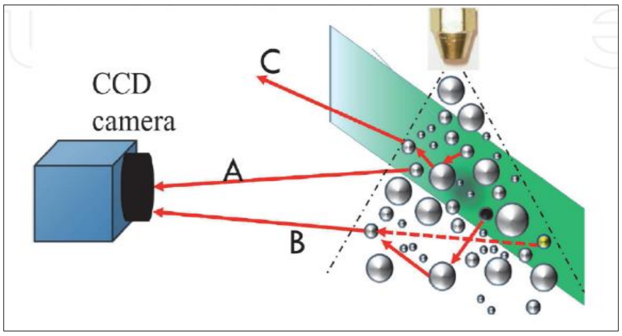


Fig 7: Laser sheet drop sizing
(A) Single scattering event;
(B) Multiple scattering that provides incorrect information about a droplet;
(C) Multiple scattering that results in the loss of the signals

Structured Laser Illumination Planner Imaging (SLIPI) is planar imaging technique in which a sheet of laser light pass through the flow and imaging it, usually at right angles to the plane of laser light. This approach makes it possible to image the drops in a spray (via elastic scattering, usually at a scattering angle of 90°), species (via laser induced fluorescence), temperature (via a fluorescence-based technique), and velocity (particle image velocimetry). For sprays, a specialized planar technique called planar droplet sizing (or laser sheet drop sizing; both names are used), aims to generate a 2-D image of the Sauter mean diameter (SMD) (Fig. 8) (Kristensson *et al.*, 2008) [28].

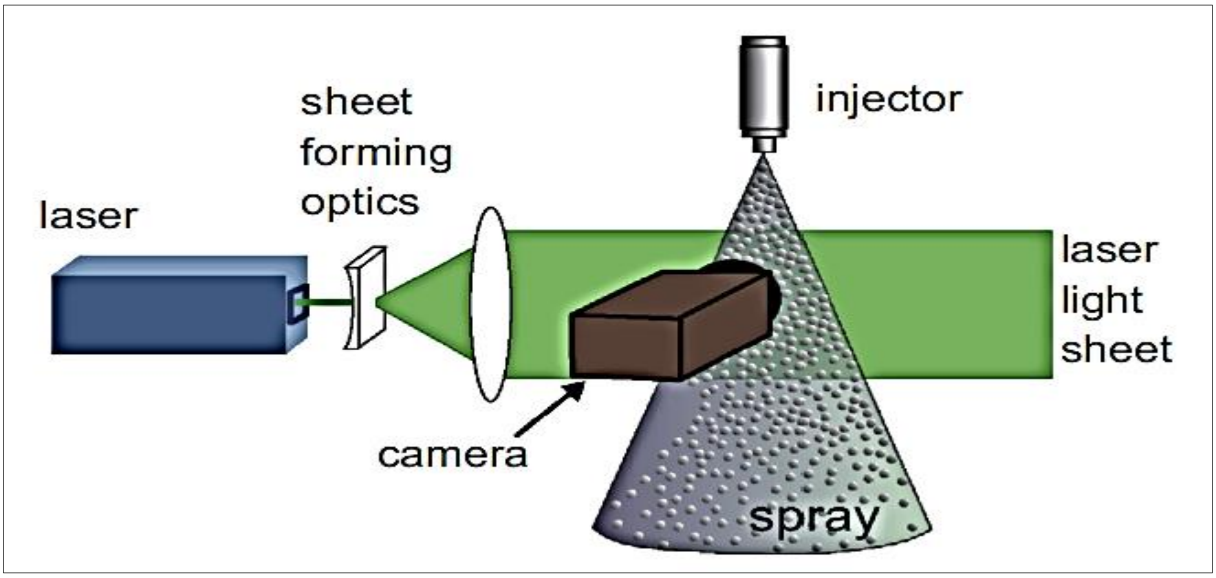


Fig 8: Basic structure of planner imaging in a spray

Particle/droplet Image Analysis (PDIA) spray data obtained via two independent and different optical configurations which employed firstly a diode laser (Oxford Lasers HSI 5000, l ¼ 808 nm) and secondly a Nd:YAG laser (Spectra Physics GCR-150, l ¼ 532 nm). The Nd:YAG laser which offered a very short pulse duration in the range 5-7 ns was expected to allow the PDIA technique to be applied to the sizing of high-speed, small diameter droplets such as those commonly produced by pressure swirl atomizers for instance (Fig. 9) (Kashdan *et al.*, 2007) [27].

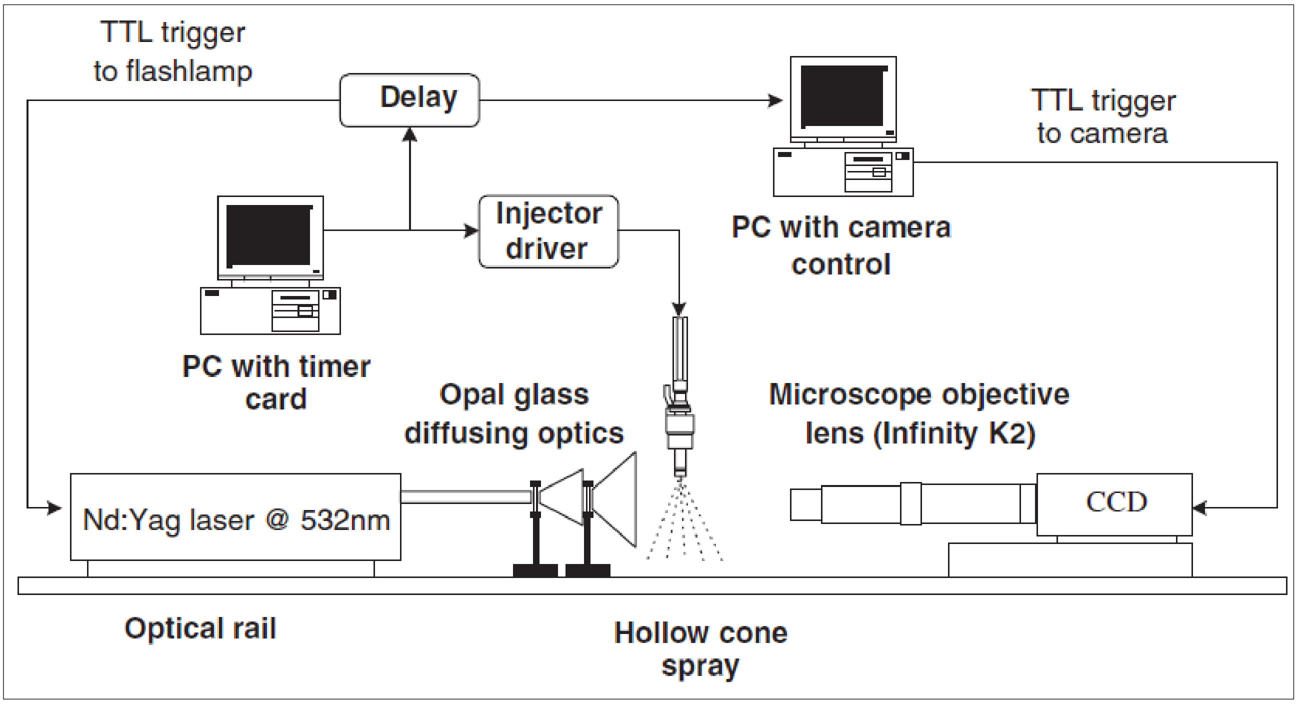


Fig 9: A typical illustration of PDIA method

PDIA technique estimates diameter based on the area of the shadow image it is possible to measure the diameter of non-spherical droplets where the diameter for a droplet of arbitrary shape, D_a is based on the equivalent circular area as given by Equation 8. (Kashdan *et al.*, 2007) [27].

$$D_a = \sqrt{4AC/\pi} \quad (8)$$

Where A is the pixel area, and C is the microns/pixel calibration.

Laser Diffraction (LD) is more correctly called Low Angle Laser Light Scattering (LALLS). This method has become the preferred standard in many industries for characterization and quality control. The applicable range according to ISO13320 is 0.1 - 3000µm. The method relies on the fact that diffraction angle is inversely proportional to particle size. A laser as a source of coherent intense light of fixed wavelength; He-Ne gas lasers (λ = 0.63µm) are the most common as they offer the best stability and better signal to noise than the higher wavelength laser diodes. A suitable detector; usually this is a slice of photosensitive silicon with a number of discrete detectors. It can be shown that there is an optimum number of detectors (16-32) - increased numbers do not mean increased resolution. For the photon correlation spectroscopy technique (PCS) used in the range 1nm - 1µm approximately, the intensity of light scattered is so low that a photomultiplier tube, together with a signal correlator is needed to make sense of the information. Some means of passing the sample through the laser beam; in practice it is possible to measure aerosol sprays directly by spraying them through the beam. This makes a traditionally difficult measurement extremely simple. A dry powder can be blown through the beam by means of pressure and sucked into a vacuum cleaner to prevent dust being sprayed into the environment. Particles in suspension can be measured by recirculating the sample in front of the laser beam (Alan, 2014) [2]. The laser diffraction droplet sizing method offers a quick and easy method for testing and comparing spray from agricultural spray technologies. However, like any measurement or sampling technique, laser diffraction can potentially bias the absolute droplet size results measured from a given system. Methods such as reference nozzles and curves are a useful tool for comparison of inter-laboratory results (Fritz *et al.*, 2014) [21].

7. Conclusion

The application of chemicals to the crops in the recommended dose is critical. A correct adjustment of sprayer improves efficiency and accuracy of spraying by reducing spray deposits on soil surface and in environment. Measurement of parameters like droplet size, density, chemical deposition is important to evaluate the spraying activity. In the scientific community, there are different techniques to analyze the deposition of spray with tracers. Different types of droplet collectors such as natural collectors, artificial collectors, Water Sensitive Papers (WSP) and polyethylene collectors were discussed in this paper. Droplet analyzing techniques such as image J software, DepositScan, stereo zoom microscopic, portable image scanner, Digital Image Analysis (DIA) and Dropleaf were discussed. Advanced techniques to analyze droplets such as PDIA, SLIPI, LD and LSD were presented. Various experimental procedures and equations to measure spray deposits per unit area also discussed. This review article shows the importance of measurement of VMD, NMD and droplet density. Techniques available in literature to analyze the droplet spectra were gathered and presented in this paper.

8. References

1. Ahmad H, Mohamed H, Sherif AG. Effect of spray application techniques on spray deposits and residues of bifenthrin in peas under field condition. Journal of Pesticide Science 2016;41(2):49-54.
2. Alan R. The Basic Principles of Particle Size Analysis. Surface Coatings International Part A: Coatings Journal 2014;86(2):58-65.
3. Allagui A, Bahrouni H, Youssef Sadik M. Deposition of pesticide to the soil and plant retention during crop

spraying: The art state. Journal of Agricultural Science 2018;10(12):104-115.
4. Aniket Kulkarni P, Deshmukh D. Planar Drop-Sizing in Dense Fuel Sprays Using Advanced Laser Diagnostic Techniques 2020. DOI: http://dx.doi.org/10.5772/intechopen.90527
5. ANSI/ASAE S572, Spray Nozzle Classification by Droplet Spectra, USA 2020. http://www.asabe.org
6. Bahrouni H, Sinfort C, Hamza E. An approach for pesticide loss estimation adapted to field crops in Mediterranean conditions. In XVIIth World Congress of the International Commission of Agricultural Engineering (CIGR) 2010, 1.
7. Beer August. Bestimmung der Absorption des rothen Lichts in farbigen Flüssigkeiten, (Determination of the absorption of red light in colored liquids). Annalen der Physik und Chemie 2010;86(1852):78-88.
8. Braekman P, Foqué D, Van Labeke MC, Pieters JG, Nuyttens D. Influence of spray application technique on spray deposition in greenhouse ivy pot plants grown on hanging shelves. Hort Science 2009;44(7):1921-1927.
9. Bueno MR, da Cunha JPA, de Santana DG. Assessment of spray drift from pesticide applications in soybean crops. Biosystems Engineering 2017;154:35-45.
10. Cerqueira DTR, Raetano CG, Henrique M, do Amaral Dal Pogetto F, Prado EP, Christovam RS *et al*. Agricultural Spray Deposit Quantification Methods. American Society of Agricultural and Biological Engineers, Applied Engineering in Agriculture 2012;28(6):825-831. https://doi.org/10.13031/2013.42474
11. Codis S, Bonicel JF, Diouloufet G, Douzals JP, Hébrard O, Montegano P, Vergès A. Eva Spray Viti: a new tool for sprayers agro-environmental performance assessment. In 12th Workshop on spray application techniques in fruit growing (Supro Fruit 2013), Valencia (Spain) 2013.
12. Collins TJ. Image J for microscopy. Biotechniques 2007;43(S1):S25-S30.
13. Cox SJ, Salt DW, Lee BE, Ford MG. A model for the capture of aerially sprayed pesticide by barley. Journal of wind engineering and industrial aerodynamics 2000;87(2-3):217-230.
14. Cunha JPAR, Farnese AC, Olivet JJ. Computer programs for analysis of droplets sprayed on water sensitive papers. Planta Daninha 2013;31(3):715-720.
15. Dent D. Overview of agro-biologicals and alternatives to synthetic pesticides. In The Pesticide Detox. Routledge 2012, 92-104.
16. Derksen RC, Ranger CM, Canas LA, Locke JC, Zhu H, Krause CR. Evaluation of handgun and broadcast systems for spray deposition in greenhouse poinsettia canopies. Transactions of the ASABE 2010;53(1):5-12.
17. Ekström G, Ekbom B. Pest control in agro-ecosystems: an ecological approach. Critical Reviews in Plant Sciences 2011;30(1-2):74-94.
18. Forster WA, Gaskin RE, Strand TM, Manktelow DWL. Effect of target wettability on spray droplet adhesion retention spreading and coverage artificial collectors versus plant surfaces. New Zealand Plant Protection 2014;67:284-291.
19. Forster WA, Mercer GN, Schou WC. Spray droplet impaction models and their use within AGDISP software to predict retention. New Zealand Plant Protection 2012;65:85-92.
20. Fox RD, Derksen RC, Zhu H, Downer RA, Brazee RD. Airborne spray collection efficiency of nylon screen. Applied Engineering in Agriculture 2004;20(2):147.
21. Fritz BK, Hoffmann WC, Bagley WE, Kruger GR, Czaczyk Z, Henry RS. Measuring droplet size of agricultural spray nozzles − measurement distance and airspeed effects. Atomization and sprays 2014;24(9):747-760.
22. Gil Y, Sinfort C, Brunet Y, Polveche V, Bonicelli B. Atmospheric loss of pesticides above an artificial vineyard during air-assisted spraying. Atmospheric Environment 2007;41(14):2945-2957.
23. Gopala Pillai S, Tian L, Zheng J. Evaluation of a flow control system for site-specific herbicide applications. Transactions of the ASAE 1999;42(4):863.
24. Gore MG. (Ed.). Spectrophotometry and spectrofluorimetry: a practical approach. New York: Oxford University Press 2000;2:815.
25. Halley S, Van Ee G, Hofman V, Panigrahi S, Gu H. Fungicide deposition measurement by spray volume, drop size, and sprayer system in cereal grains. Applied Engineering in Agriculture 2008;24(1):15-21.
26. Hipkins P, Grisso R, Wolf R, Reed T. Droplet chart/selection guide. Virginia Cooperative Extension publication 2009, 442-031. Online: http://www.bae.ksu.edu/faculty/wolf/PDF/442-031_DropletChart-SelectionGuide.pdf
27. Kashdan JT, Shrimpton JS, Whybrew A. A digital image analysis technique for quantitative characterisation of high-speed sprays. Optics and Lasers in Engineering 2007;45(1):106-115.
28. Kristensson E, Berrocal E, Richter M, Pettersson SG, Aldén M. High-speed structured planar laser illumination for contrast improvement of two-phase flow images. Optics letters 2008;33(23):2752-2754.
29. Kumar Mishra P, Singh M, Sharma A, Sharma K, Singh B. Studies on effect of electrostatic spraying in orchards. Agricultural Engineering International: CIGR Journal 2014;16(3):60-69.
30. Lad N, Aroussi A, Muhamad Said MF. Droplet size measurement for liquid spray using digital image analysis technique. Journal of Applied Sciences 2011;11(11):1966-1972.
31. Llop J, Gil E, Llorens J, Gallart M, Balsari P. Influence of air-assistance on spray application for tomato plants in greenhouses. Crop Protection 2015;78:293-301.
32. Loghavi M, Mackvandi BB. Development of a target oriented weed control system. Computers and electronics in agriculture 2008;63(2):112-118.
33. Machado BB, Spadon G, Arruda MS, Goncalves WN, Carvalho AC, Rodrigues-Jr JF. A smartphone application to measure the quality of pest control spraying machines via image analysis. In Proceedings of the 33rd Annual ACM Symposium on Applied Computing. ACM 2018, 956-963.
34. Mangado J, Arazuri S, Arnal P, Jarén C, López A. Measuring the accuracy of a pesticide treatment by an image analyzer. Procedia Technology 2013;8:498-502.
35. Martin DE. A fluorescent imaging technique for quantifying spray deposits on plant leaves. Atomization and Sprays 2014;24(4).
36. Massinon M, De Cock N, Forster WA, Nairn JJ, McCue SW, Zabkiewicz JA, Lebeau F. Spray droplet impaction

outcomes for different plant species and spray formulations. Crop protection 2017;99:65-75.
37. Matthews GA. Determination of droplet size. PANS Pest Articles & News Summaries 1975;21(2):213-225.
38. Matthews GA, Hislop EC. Application technology for crop protection. Chemistry and Technology of Agrochemical formulations 1993, 302-336.
39. Murray RA, Cross JV, Ridout MS. The measurement of multiple spray deposits by sequential application of metal chelate tracers. Annals of applied biology 2000;137(3):245-252.
40. Musiu EM, Qi L, Wu Y. Spray deposition and distribution on the targets and losses to the ground as affected by application volume rate, airflow rate and target position. Crop protection 2019;116:170-180.
41. Nuyttens D, Baetens K, De Schampheleire M, Sonck B. Effect of nozzle type, size and pressure on spray droplet characteristics. Biosystems engineering 2007;97(3):333-345.
42. Palladini LA, Raetano CG, Velini ED. Choice of tracers for the evaluation of spray deposits. Scientia Agricola 2005;62(5):440-445.
43. Panneton B. Image analysis of water-sensitive cards for spray coverage experiments. Applied Engineering in Agriculture 2002;18(2):179.
44. Patel B, Singh M, Mishra PK, Manes GS, Mishra A, Sharmaand K. Comparative Evaluation of Electrostatic Sprayer for Cotton Crop. International Journal of Bio-resource and Stress Management 2016;7(5):1049-1053.
45. Pergher G, Gubiani R. The effect of spray application rate and airflow rate on foliar deposition in a hedgerow vineyard. Journal of Agricultural Engineering Research 1995;61(3):205-216.
46. Prokop M, Kejklicek R. Effect of adjuvants on spray droplet size of water. Research in Agricultural Engineering 2002;48:144-148.
47. Rawle AF. Representative sampling-another Cinderella of particle size analysis. Procedia engineering 2015;102:1707-1713.
48. Salyani M, Zhu H, Sweeb R, Pai N. Assessment of spray distribution with water-sensitive paper. Agricultural Engineering International: CIGR Journal 2013;15(2):101-111.
49. Stajnko D, Berk P, Lešnik M, Jejčič V, Lakota M, Štrancar A, Hocevar M *et al*. Programmable ultrasonic sensing system for targeted spraying in orchards. Sensors 2012;12(11):15500-15519.
50. Subash SP, Chand P, Pavithra S, Balaji SJ, Pal S. Pesticide Use in Indian Agriculture: Trends, Market Structure and Policy Issues. Technical Report, ICAR-National Institute of Agricultural Economics and Policy Research, New-Delhi. Policy Brief 2017, 43.
51. Tewari VK, Abhilash Kumar Chandel, Brajesh Nare, Satyaprakash Kumar. Sonar sensing predicted automatic spraying technology for orchards. Current Sciences 2018;115(6):1115-1123.
52. Wandkar SV, Bhatt YC, Jain HK, Dhande KG. Performance evaluation of newly developed variable rate sprayer for spray deposition in guava orchard. International Journal of Plant Protection 2017;10(1):96-102.
53. Washington JR. Relationship between the spray droplet density of two protectant fungicides and the germination of *Mycosphaerella fijiensis* ascospores on banana leaf surfaces. Pesticide Science 1997;50(3):233-239.
54. Zhu H, Salyani M, Fox RD. A portable scanning system for evaluation of spray deposit distribution. Computers and Electronics in Agriculture 2011;76(1):38-43.