Progress in Agricultural Engineering Sciences 20 (2024) 1, 1–36
DOI: 10.1556/446.2024.00118

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Spray drift reduction management in agriculture: A review

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REVIEW PAPER

Received: May 27, 2024 • **Accepted:** July 30, 2024

ABSTRACT

The spray is the primary method to apply pesticides to the crops. To provide enough coverage and deposition on target surfaces, the drop size produced during spray application must be precisely calibrated; nevertheless, it must not be too tiny to cause the undesirable phenomena known as “spray drift”. Spray drift is the movement of droplets in the atmosphere during or after spraying. The negative effect of spray drift can harm human health, livestock, and adjacent crops or can cause environmental pollution. To address this problem, a lot of work has been done. Previous studies on spray drift reduction approaches including factors promoting drift, drift measuring technologies, drift prediction models, and drift reduction technologies, were reviewed in this paper. Based on the literature review, future research and developments are projected. This review may provide guidance and reference to researchers for further development and improvement in drift reduction technologies.

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KEYWORDS

spray drift, pesticides, drift prediction models, drift reduction technologies

INTRODUCTION

In modern agriculture, pesticides play an important role to protect and improve the quality and quantity of the produce. The spray is the primary method to apply pesticides to the crops. Field sprayers are often used to apply sprays to field crops. To provide enough coverage and deposition on target surfaces, the drop size produced during spray application must be precisely calibrated; nevertheless, it must not be too tiny to cause the undesirable phenomena known as “spray drift”. Spray drift is the movement of droplets in the atmosphere during or after spraying (USEPA, 2021). The movement of pesticides is of two types: primary movement and secondary movement. Primary movement occurs during pesticide spraying (Jones et al., 2019). Many factors that affect primary movement can be controlled by applicators, including adjuvants, nozzle type, and operating settings (Bish and Bradley 2017). Secondary movement takes place after pesticide spraying (Jones et al., 2019). Secondary movement-related factors can be more difficult to characterize and are harder to manage. One sort of secondary movement is vapor drift, which results from the volatilization of agricultural pesticides. Wind erosion is another factor that promotes secondary movement which occurs when a pesticide is applied and then carried back into the air with soil particles to which it is attached by the wind (Clay et al., 2001). The spray application method, size of soil particulates, and herbicide absorption rates all have an impact on secondary movement resulting from wind erosion. Furthermore, due to air retention, pesticide particles are easily available for secondary movement when sprayed in stable atmospheric conditions (Bish et al., 2019). The negative effect of spray drift can harm human health, livestock, and adjacent crops or can cause environmental pollution (Hilz and Vermeer, 2013). Spray drift often consists of solid dry particles, liquid droplets, or vapor (gas). Small solid particles left behind by spray during the volatile’s quick evaporation typically result in dry particles (Al Heidary et al., 2014). The amount of drift is influenced by a variety of variables such as environmental factors, droplet characteristics, method and equipment, and operator skills (Rojo-Baio et al., 2019). Knowing the factors that affect spray droplets in the atmosphere is essential to comprehending the drift phenomenon. The forces acting on the droplets are caused by the fluid particle displacement and the velocity difference between the fluid and particle. Analyzing the forces that impact droplets during the deposition process is challenging due to a multitude of variables. To understand the action characteristics of the primary forces, evaporation is ignored, and a droplet is assumed to be a sphere-shaped particle. Except for buoyancy and drag forces, all other forces were ignored. The droplet dynamic model in a fluid medium, according to Newton’s equation (Baetens et al., 2007), is as follows:

$$\mathrm{m_d}\frac{\mathrm{dv_{di}}}{\mathrm{dt}} = \frac{1}{8}\pi\rho \mathrm{d}^2 \mathrm{c_d}\left|\mathrm{V_f} - \mathrm{V_{di}}\right|\left(\mathrm{V_f} - \mathrm{V_{di}}\right) + \frac{1}{6}\pi \mathrm{d}^3(\rho_\mathrm{d} - \rho)\mathrm{g}$$

where, $\mathrm{m_d}$ = Droplet mass in kg; d = Droplet diameter in m; Suffix i = Identifies the direction; $\mathrm{V_f}$ = Fluid velocity in m $\mathrm{s^{-1}}$; $\mathrm{V_{di}}$ = Discrete droplet velocity in m $\mathrm{s^{-1}}$; $\mathrm{C_d}$ = Drag coefficient;

ρ_d = Discrete droplet density in kg m^{-3}; ρ = Air density in kg m^{-3}; g = Acceleration of gravity in m s^{-2} and t = Time in second.

Studies now underway focus on the effects of airborne spray on resident exposure (Butler Ellis and Miller, 2010). In the EU report, three categories of mitigating strategies are suggested including drift-reducing methods, buffer zones, and windbreaks (FOCUS, 2007). In the literature, many spray drift reduction techniques are studied by researchers to minimize drift losses. Thus, this paper's goal is to discuss how various spray drift reduction strategies contribute to lowering drift.

FACTORS PROMOTING SPRAY DRIFT

By understanding the mechanisms behind the factors that influence drift, we can reduce drift and increase the efficiency with which pesticides are used. In this section, several factors that influence the drift are discussed such as nozzle type, droplet size, operating parameters, physical properties of liquid, and atmospheric factors.

Nozzle and droplet size

The nozzle is an important component that produces spray sheets for plant protection. The type of nozzle used has a considerable impact on droplet size. According to research by Nuyttens et al. (2006a,b), droplet size and velocity are strongly influenced by pressure. By regulating spray parameters including droplet size, the nozzle influences drift and droplet deposition in the plant canopy throughout the spraying process (Dorr et al., 2013). Minimizing drift with acceptable coverage is often possible with correct nozzle selection. Spray drift can also be avoided by utilizing low-pressure units because droplet size and pressure have a strong link (Makhnenko et al., 2021). There are several different droplet sizes of nozzles available for use in the agriculture sector. The most common nozzles are the flat-fan and hollow cone nozzles, which create a flat and conical spray, respectively. Typically, flat-fan nozzles function between 200 and 400 kPa and are frequently employed for ground application of broad-acre row crops. In orchards, hollow-cone nozzles are typically utilized and have a pressure range of 300–700 kPa. Spray angle is another factor affecting spray drift. The droplet size may be lowered by adjusting the nozzle angle (Makhnenko et al., 2021). According to Makhnenko et al. (2021), when operated at equal pressures, nozzles with narrower spray angles produce larger droplets than nozzles with broader spray angles. Miller et al. (2008) studied the droplet size at various spray angles and found that the drift can be decreased by using a nozzle with a fan angle of less than 110°.

Studies have revealed that of the influencing factors, droplet size has the greatest impact on spray drift (Makhnenko et al., 2021). The benefits and drawbacks of various droplet sizes are given in Table 1. Eight droplet size categories are given in Table 2 (ASABE S-572, 2009). Liu et al. (2005) state that when air resistance exists, the tiny droplet's falling velocity drops and it is unable to apply sufficient downward force to reach the target point. They observed that smaller droplets are more susceptible to variations in relative humidity and temperature. Moreover, evaporation, which causes droplet size to decrease, can cause fine droplets to float with the wind. According to Wolf (2013), larger droplets (>200 μm) had higher drift resistance and faster falling speeds than smaller ones because they did not evaporate as quickly. According to Wang et al. (2017), droplets of 101.74 μm size had a higher probability of drifting at the same wind

Table 1. Categories of droplet size (own compilation, based on Makhnenko et al., 2021)

Droplet size (μm)	Advantages	Disadvantages
600	- Slow evaporation rate - Minimum drift - Deep penetration - Low drying rate	- Minimum coverage - High bouncing effect - Low pesticide efficiency
350	- Medium coverage - Moderate evaporation - Deep penetration - Favourable drying rate - High pesticide efficiency	- Some droplet bounce
200	- Maximum coverage - Low bouncing effect - High pesticide efficiency	- Fast evaporation - Fast drying rate - Higher drift
100	- Excellent coverage - Low bouncing effect	- Quick evaporation - Quick drying rate - Rapid drift - Poor penetration

Table 2. Droplet size classification (own compilation)

Droplet class	Droplet size (μm)
Extremely fine	<60
Very fine	61–105
Fine	106–235
Medium	236–340
Coarse	341–403
Very coarse	404–502
Extremely coarse	503–665
Ultra-coarse	>665

speed and bigger drift volumes and lengths than droplets of 164 and 228.1 μm size. According to research by Ru et al. (2014), droplets with sizes of 60 and 150 μm may drift a maximum of 30.25 and 10.76 m, respectively, in the direction of the wind. The scientists also discovered that the drift of large droplets was around one-third less than that of tiny droplets. The British Crop Protection reference nozzles catagories are given in Table 3.

Operating parameters

The operating characteristics of spraying systems have been proven in numerous studies to significantly affect spray drift. Depending on how it is used, a given nozzle can produce varied droplet size distributions. It has been studied that increasing the spray pressure causes the number of small droplets to increase (Kooij et al., 2018). As driving speed increases, the droplets drift also increases (Miller et al., 2011). Tang et al. (2016) observed that in aerial spraying as forward speed rises from 120 to 305 km h^{-1}, the droplet size reduces (by around 70%). Khan et al. (2022) and Ghafoor et al. (2022) report that when the sprayer's forward speed

Table 3. British Crop Protection Council (BCPC) reference nozzles (own compilation)

Classification category threshold	Color	Spray angle (°)	Nominal flow rate (L min^{-1})	Reference flow rate (L min^{-1})	Reference operating pressure kPa
Very fine/Fine	Red/Orange	110	0.38	0.48	450
Fine/Medium	Orange/Yellow	110	1.14	1.18	300
Medium/Coarse	Yellow/Blue	110	2.27	1.93	200
Coarse/Very coarse	Blue/Green	80	3.03	2.88	250
Very coarse/Extremely coarse	Green/White	65	3.78	3.22	200

was raised from 4 to 8 km h^{-1} while keeping the pressure constant, the droplet size decreased. According to Huang et al. (2017) and Khan et al. (2022), droplet drift rises with spray height. According to Ranta et al. (2021), when spray pressure increases, droplet size decreases.

Physical properties of liquid

The liquid properties, such as its viscosity, surface tension, and inhomogeneities, all affect spray drift (Hilz et al., 2013). Dombrowski and Fraser (1954) found that the size of the droplets rises along with viscosity. Mun et al. (1999) claim that this is only consistently true for specific kinds of nozzles. They studied the four types of nozzles. They found that in the case of two nozzles (full-cone TG-SS and hollow-cone D3-25), as viscosity increases, the fine droplets decrease, and droplet size increases. There was no discernible change in droplet size or fine droplet percentage using the flat-fan nozzle (XR8002VS). The scientists found the most striking results in the case of the hollow-cone (TXVS-12), where the viscosity increased and the mean droplet size and fine droplet percentage decreased. According to more recent research by Kooij et al. (2018), the median droplet size remained unchanged and viscosity had little effect on the flat-fan nozzles. Drift and droplet size are also influenced by the liquid surface tension. The nozzle type is mostly responsible for how surface tension affects droplet size. The dynamic surface tension is reduced in hollow cones and flat-fan nozzles, and the reduced surface tension is responsible for producing finer droplets (Hewitt, 2008). Yang and Bain (2009) discovered that the liquid sheet length rises upon breakage as surface tension falls. According to Kooij et al. (2018), when surface tensions fall, so does droplet size.

Another element influencing spray drift is inhomogeneities in spray liquid, such as crystalline active ingredients or droplets of oil emulsion. Droplet size rises with oil emulsion. Mineral oils, vegetable oil emulsions, water-insoluble surfactants, and organosilicons have all been the subject of research on this topic (Miller and Tuck, 2005; Hilz et al., 2012). Cryer and Altieri (2017) suggested that the interaction between the oil droplets and liquid sheets affects the atomization process by drawing an analogy between spray sheet breakage and foam destabilization. According to Stainier et al. (2006), inhomogeneities cause the droplet size to increase. The same tendency was documented by Vernay et al. (2016). According to Dexter (2001), the range of emulsion concentration is $2\times10^{-3} - 5\times10^{-2}$% w/w for coarse spray. It has been noted that, up to a certain point, the average droplet size increases with increasing emulsion concentration before beginning to decline. The crystalline active ingredients in several pesticide formulations are in the micron range. These solid particles are uniformly dispersed throughout the liquid by dispersing chemicals. Researchers find that the size of the droplets increases when solid particles are added to liquid (Qin et al., 2010; Hilz and Vermeer, 2012).

Atmospheric factors

Atmospheric factors are the most significant factors in this study that cannot be overlooked. Wind, temperature, humidity, and air stability, boundary layer are the primary determinants of spray deposition and drift. The wind is produced by mechanical or thermal turbulence. The friction between the ground and the air caused by terraces, structures, trees, uneven terrain, etc. causes mechanical turbulence. Radiative heating causes thermal turbulence, which is caused by the vertical mixing of cool and warm air masses, to occur most days (Monteith and Unsworth 2013). Midday temperature turbulence thickens the surface boundary layer, increasing the likelihood of dispersed and diluted pesticide droplets. Research indicates a linear link between wind speed and spray drift (Thistle et al., 2005). At longer distances, more drift is produced by faster wind speeds (Nuyttens et al., 2005). To continue spraying, wind speeds should not exceed 16 km h^{-1}, according to Sumner (1997). The highest allowable wind speed for spraying, as stated by da Cunha et al. (2016), is 12 km h^{-1}. Maciel et al. (2018) also suggested that the wind speed range for spraying operations should be between 2 and 12.8 km h^{-1}. It should be noted that varying wind directions and speeds have also been linked to unequal spray distribution across the sprayer's left and right sides (Al-Jumaili and Salyani, 2014). Wang et al. (2016) found that when the wind speed exceeded 4 km h^{-1}, the drift rapidly increased. According to Wang et al. (2017), wind speeds varied from 2.74 to 19.8 km h^{-1}, while the cumulative droplet drift rate ranged from 14.3% to 75.8%. Zhang et al. (2015) found that when crosswind speed increased, there were significant changes in both the maximum drift distance and the droplet deposition site. Droplets stay in the air and reach atmospheric altitudes that support droplet mobility even in the absence of wind (Fritz 2006). In comparison to physical drift, research from California found that when winds were lighter to non-existent, aerially applied chemicals travelled farther off-target in greater quantities (Bird et al., 1996). According to Bish et al. (2019), during the growing season for crops, dicamba harm claims were most common in areas and geographies with lower wind speeds.

Other important parameters are temperature and humidity. Droplet evaporation speeds up during the spray deposition process in high-temperature, low-humidity environments. In high-temperature conditions, the volatilization of pesticide products may also increase, which makes the droplets smaller and more prone to drift (Chen et al., 2021). The ISO 22866 standard (ISO 22866:2005) specifies that temperatures between 5 and 35 °C are appropriate for outdoor measurements of spray drift. Spraying should be evaded when the temperature is over 30 °C and the relative humidity is less than 55%, according to Da Cunha et al. (2016). Generally, spraying environments are best when the relative humidity is around 70%; when it is less than 50%, however, additional care is needed (Sumner, 1997). Spraying at low wind speeds, low temperatures, low turbulence, low solar exposure periods, and high relative humidity may often greatly minimize spray drift (Carlsen et al., 2006). According to Luo et al. (1994a,b), a 1,070 μm droplet evaporated in 540 s at a temperature of 25 °C and 60% relative humidity. Furthermore, they found that at 10 °C and 60% relative humidity, a 910 μm droplet evaporated in 780 s. An 85 μm droplet at 10 °C temperature and 60% relative humidity would constrict to half its initial size in 107 s, according to Picot et al. (1981). Miller and Tuck (2005) reported that the large temperature difference (ΔT) between spraying liquid (T_{liq}) and surrounding air (T_{air}) affect the droplet size, where $\Delta T = T_{liq} - T_{air}$. According to the authors, the droplet size decreases when $\Delta T < -5°C$ at fixed T_{liq} and $-20 < \Delta T < 20$, but no change was found when $\Delta T > -5°C$.

Another key element is atmospheric stability, which refers to how much an air mass rises or falls due to buoyancy produced by variations in the intensity, velocity, and temperature of the surrounding air. Droplets will either stay suspended in the air or disperse to the top layer in a stable atmospheric environment rather than depositing into the cooler bottom air. However, several droplets may drift and move if the stable state is broken (Miller and Ellis, 2000). Numerous studies indicate that increased atmospheric stability will enhance the potential for drift. Miller and Stoughton (2000) determined that a stable air environment is important in far-field droplet drift and deposition. According to Miller et al. (2000), droplet deposition was less common in unstable than in stable environments. According to Fritz et al. (2006), smaller droplets are more susceptible to the effects of a stable atmospheric condition, and their suspension times are longer than those of larger droplets. Bish et al. (2019) discovered that as the air became steadier, the average amount of pesticides identified increased. The authors found that the bigger the temperature difference ($\Delta T = T_{air}\ at\ 305\ cm - T_{air}\ at\ 46\ cm$), the more stable the air. Additionally, the authors found that during the first eight hours following treatment, the detectable pesticide increased by1.67 $\mu g\ m^{-3}$ for every one-degree variation in temperature. Miller et al. (2000) reported similar findings, finding that lower amounts of the pesticide (malathion) were gathered in unstable conditions than in stable ones. The stability of the atmosphere may be influenced by the surrounding bodies of water, terrain, wind, and ground cover Bish et al. (2019). The list of major variables influencing spray droplet size is given in Table 4.

SPRAY DRIFT MEASUREMENT TECHNIQUES

Numerous offline and online techniques are available for measuring drift. Droplet drift may be monitored in the lab and the field. Tracers and in situ collectors are often used to measure field spray drift (Garcera et al., 2017). The results of these sophisticated, labour-intensive, and time-consuming investigations are affected by climatic variables (Torrent et al., 2017). Different spray drift measurement techniques such as field measurement, laser diffraction, phase doppler particle analyzer, high-speed imaging, LiDAR point clouds, machine learning, light detection and ranging, open-path Fourier transform infrared spectroscopy, and drift test bench are discussed in this section.

Field measurement

The ISO22866:2005 standard is typically utilized for field spray drift measurement. The standard stipulates that the spray track's length must be at least twice as long as the longest downwind sample distance and that the directly sprayed area must be at least 20 m wide upwind of the harvested area's boundary. It must also be symmetrical regarding the sampling array's axis (Fig. 1). The standard stipulates that the following environmental conditions must be met: (a) the percentage of wind data with an outlier of less than 1 m s^{-1} cannot be higher than 10%; (b) the average wind direction towards the spray track must be 90° ± 30°; (c) the percentage of wind direction frequency >45° to the spray track cannot be higher than 30%; and (d) the mean temperature must be between 5 °C and 35 °C.

Table 4. List of the major variables influencing spray droplet size (own compilation)

Factors	References	Effect on droplet size	Typical ranges and products
Nozzle type	Kooij et al. (2018)	Large orifice size nozzle will produce a larger droplet size at a given pressure	Flat-fan, hollow cone Orifice size: 10^{-7}–10^{-6} m^2
Nozzle spray angle	Kruger et al. (2013)	As the spray angle increases, the droplet size decreases	60–130°
Spray pressure	Broniarz-Press et al. (2016)	As spray pressure increases, the droplet size decreases	0.1–0.4 MPa
Traveling speed	Nuyttens et al. (2007), Khan et al. (2022)	Droplet size decreases with an increase in traveling speed	4–25 km h^{-1}
Adjuvants	Lewis et al. (2016)	Adjuvant increases the droplet size	Polyacrylamide or guar gum
Surface tension	Kooij et al. (2018)	Increases in the equilibrium surface tension of the solution lead to an increase in droplet size in surfactant-free fluids with surface tensions between 20 and 72 mN m^{-1} an increase in the solution increases in droplet size. Though, when surfactants are present the results differ	Surfactant-containing products and solvent-based formulations
Hydrophobic particles and oil emulsions	Vernay (2016)	Droplet size increases with increased volume percentage	Crop oils and crop oil concentrates, modified vegetable oil
Atmospheric stability	Hoffmann et al. (2011)	In the field, droplet size usually decreases with increasing wind speed	5–24 km h^{-1}

Using this standard, several investigations have been conducted to assess the spray drift (ISO 22866:2005). Using the ISO22866:2005 standard, Bourodimos et al. (2019) assessed the spray drift of air-assisted sprayers. Grella et al. (2017) used the ISO22866:2005 technique to evaluate the spray drift and ground deposition of air blast sprayers.

Light detecting and ranging (LiDAR) technique

LiDAR system has been used in aerial applications for drift measurement (Hiscox et al., 2006). LiDAR devices enable range-resolved assessments of spray drift in real-time. This method is quick and easy to use; the LiDAR measurement can be completed by a single operator. Previous drift investigations have demonstrated high agreement between collector data and LiDAR measurement (Gregorio et al., 2014). Gregoria et al. (2019) employed a LiDAR system to classify spray nozzles based on possible drift risk. Twenty-three drift potential tests were carried out with the static position sprayer using ten hollow cone nozzles. Between conventional and drift reduction nozzles, the percentages for the reduction in drift potential varied from 88.6% to 93.6%. The scientists found that the LiDAR system could distinguish between drift reduction

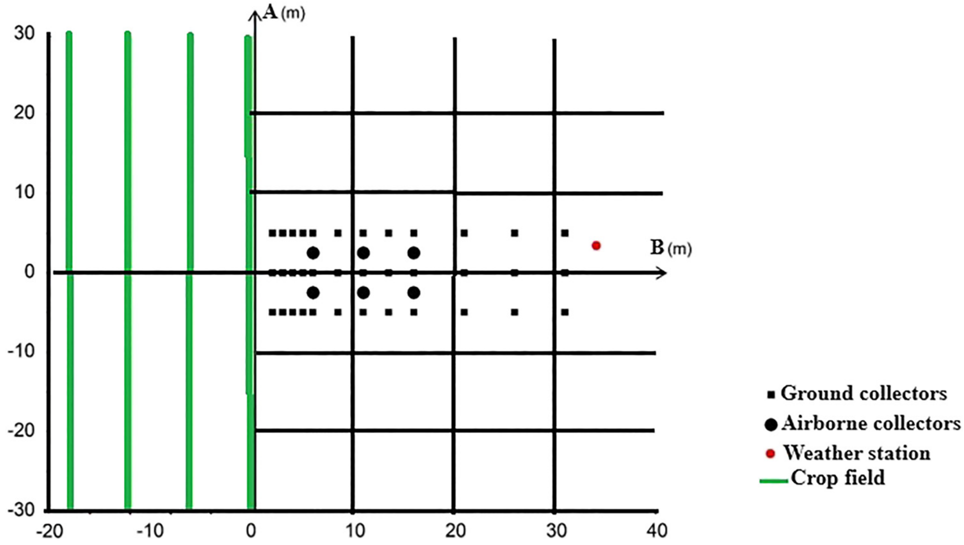

Fig. 1. Layout according to ISO22866:2005 standard (own source)

nozzles and standard nozzles in real application scenarios, resulting in a drift potential decrease of 56.7%. The LiDAR technology, according to the authors, is an advantageous substitute for determining drift potential reduction.

Open path Fourier transform infra-red (OP-FTIR) technique

Spray drift may also be measured using OP-FTIR spectroscopy. In several scientific fields, OP-FTIR is an efficient method for identifying and detecting gases (La Spina et al., 2013). The use of tomography and mathematical inversions to estimate source localization and fluxes is one most promising elements of this technique (Todd et al., 2001). Some studies have examined the potential of OP-FTIR technology for monitoring water droplets and identifying aerosols (Kira et al., 2015, 2016a). According to Kira et al. (2015), passive OP-FTIR can be used to find the spray drift. The possibility of identifying and measuring compounds in both the condensed phase and the gas phase was covered by Kira et al. (2016a). Kira et al. (2016b) recently demonstrated the viability of identifying the organic chemical spectral signature inside droplets in real-time during pesticide spraying. Using an OP-FTIR spectrometer, Kira et al. (2018) studied and compared the spray drift vertical profile produced by several air-assisted sprayers. The authors found that the drift of droplets larger than 5 μm varied significantly amongst sprayers. The authors concluded that spray drift might be greatly (up to 50%) decreased by employing a buffer zone or tree-line barrier. The OP-FTIR system is shown in Fig. 2.

Drift test bench

The spray drift risk associated with field sprayers has been examined using the drift test bench technique (Balsari et al., 2007). The strategy is based on the idea that drift is directly proportional to the amount of initial spray that stays in the environment following pesticide application

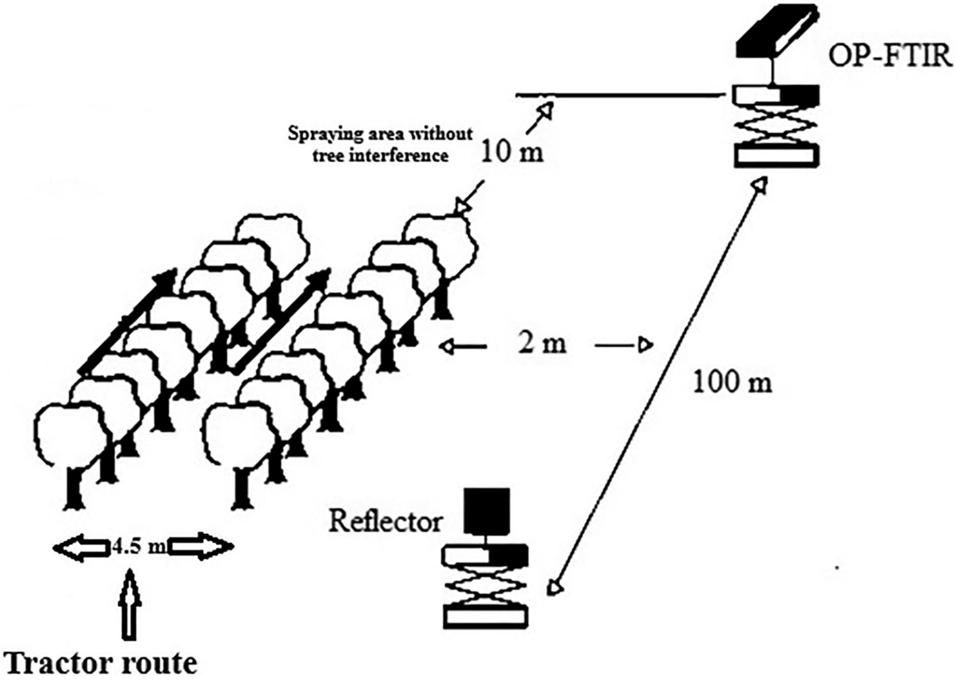

Fig. 2. OP-FTIR system (own source)

and the percentage of droplets that are likely to be taken away from the intended region by air currents (Gil et al., 2014). A standard technique (ISO 22401:2015) was released when the drift test bench was formally accepted as a novel approach for horizontal boom sprayers by the ISO ad hoc research committee (ISO TC23/SC6/WG 16). To gauge the spray drift, Nuyttens et al. (2017) developed a drift test bench. A drift test bench was used to test a total of 16 boom sprayers indoors. Other drift measurement techniques were compared to the test bench's findings (Phase Doppler particle analyzer, wind tunnel, field). Despite significant variances, the scientists found that the drift test bench's results were comparable to those obtained using other drift measurement techniques. Using a drift test bench, Balsari et al. (2017) assessed the viability of categorizing various sprayer settings and enhanced the methodology by drift risk. For this investigation, a crop sprayer mounted on a tractor (Delvano HD3) was used. Three boom heights and three nozzles were assessed. They found that the spray drift is influenced by boom height and nozzle type. Moreover, they effectively divide the various sprayer setups into numerous groups to decrease drift. The authors also spoke about whether it would be feasible to detect agricultural sprayer drift using the ISO 22369-1:2006 test bench techniques. The test bench is shown in Fig. 3.

Laser diffraction

Laser diffraction instruments are widely used in agriculture to analyze spray droplets (Sirmour and Verma, 2019; Fritz and Hoffmann, 2016). The most widely used commercial laser

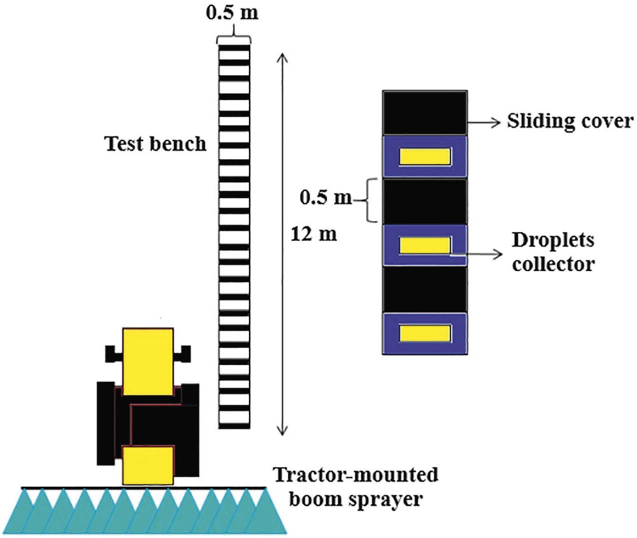

Fig. 3. Spray drift test bench (own source)

diffraction instrument available to researchers today is the Malvern laser (Fig. 4). It is made up of a computer, a receiving system, and a transmitter unit. According to the working principle, droplets interact with a laser beam and scatter the rays, resulting in a diffraction pattern. A multi-element detector collects light that is diffracted by spray droplets when a laser beam passes through a lens's working zone. Both the intensity and angle of scattering are proportional to droplet size. The receiver unit contains semi-circular photodiodes that measure the intensity of scattered light. Curve fitting software is used to transform light intensity into several empirical functions, including the Rosin-Rammler distribution function. The scattering angle is inversely related to droplet size (Merkus, 2009; Pascuzzi et al., 2021; Sijs et al., 2021). This instrument is used by many researchers to measure the droplet size spectra. Tang et al. (2018) examined the droplet size spectra of four air induction nozzles running at three distinct pressures and air velocities using the Malvern laser. They found that whereas DV90 was affected by the quadratic wind speed, DV10 and DV50 droplet sizes decreased almost linearly as the wind speed

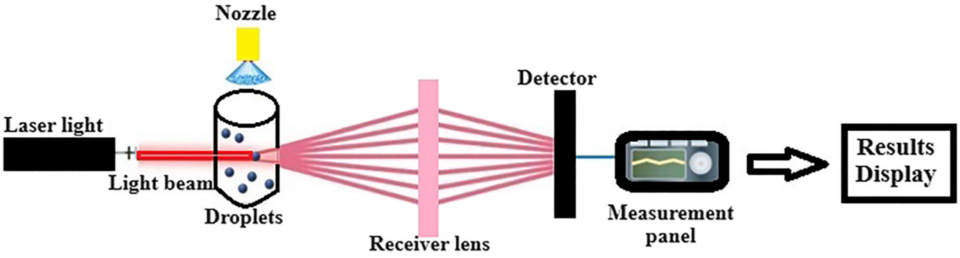

Fig. 4. Laser diffraction working process (Privitera et al., 2023, republished under Creative Commons CC BY – Modified version)

increased. Using the Malvern laser, Gaillard et al. (2022) examined the droplet size distribution of a dilute polyethylene oxide aqueous solution produced by a flat fan nozzle. Grella et al. (2020) measured the droplet size distribution of pneumatic nozzles that were hand- and cannon-type using the Malvern laser instrument.

Phase Doppler Particle Analysis (PDPA)

Another approach that is frequently used to measure droplet size is PDPA. It belongs to the class of flux-sampling devices and is regarded as an effective tool for non-invasive spray research when used in conjunction with the laser diffraction technique. PDPA is a single-droplet technique that is less complex than laser diffraction (Fig. 5). To ascertain the size and velocity of each separately detected drop, it measures and inverts the phase difference of scattered light at different angles (Sijs et al., 2021). Typically, the system consists of a computer, a signal processor, and transmitter and receiver components. The technique involves creating an uninterrupted laser and splitting it into two beams using a beam splitter. Laser beams with the same wavelength collide at “the probe volume,” defining the measurement point as a series of parallel equidistant interference fringes. When a droplet travels over the intersection zone of two beams (sampling area), it creates a diffused light with spatial and temporal modulation. The spatial and temporal frequencies of a droplet are related to its size and speed, respectively. The approach examines individual droplet size and speed simultaneously (Privitera et al., 2023). Nuyttens et al. (2006a,b), utilized an Aerometric PDPA 1D laser to examine 32 nozzle-pressure combinations, yielding 288 measurements. The temperature and humidity of the climate-controlled setting in which the experiment was conducted may be adjusted. The results showed how droplet size and velocity are affected by nozzle design and flow rate. Nevertheless, PDPA and laser diffraction methods are only used to assess the nozzle.

High-speed imaging

High-speed imaging analyzers identify and quantify in-focus droplets in pictures by using a strobe light, a high-speed camera, and image processing software (Fig. 6). A shadow appears on the bright backdrop when the uniform light from the illumination source is reflected off the spray and partially refracted by it. This approach, which is typically used to acquire images in a

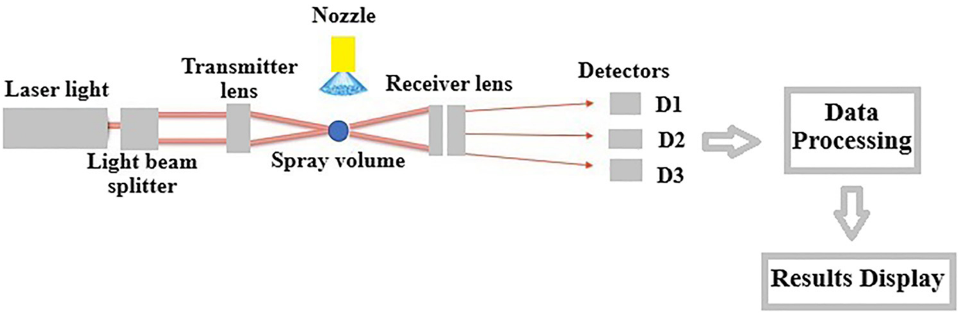

Fig. 5. PDPA working process (Privitera et al., 2023, republished under Creative Commons CC BY – Modified version)

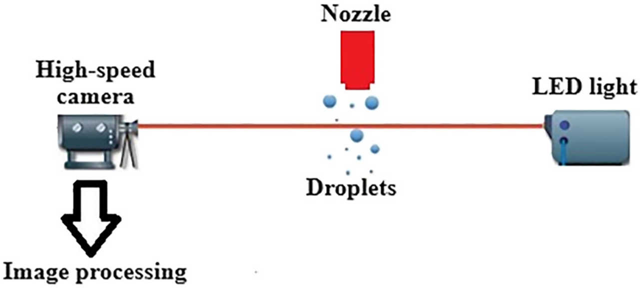

Fig. 6. High-speed imaging working process (Privitera et al., 2023, republished under Creative Commons CC BY – Modified version)

backlit setup, is frequently referred to as the “shadowgraph technique” (Privitera et al., 2023). De Cock et al. (2017) used a fast-imaging approach to assess the drop size distribution of several reference nozzle/pressure combinations as outlined in ISO 25358, for example. The results highlighted the fact that the spray quality categories were clearly defined and demonstrated how the approach may be a viable substitute for the laser-based technology. To better understand drop impact on hot surfaces, French researchers Castanet et al. (2013) carried out an analysis that revealed several benefits coming from the combination of size and observations of velocity. However, this technique has some limitations. Numerous scholars have suggested various adjustments to enhance this constraint. For instance, droplet size and velocity from various spray nozzle types were measured using shadowgraph imaging by Minov et al. (2016). The authors employed a function of the droplet diameter, background, and droplet gray level intensities to limit the error produced by unfocused droplets. The in-focus parameter is the gray level gradient at the droplet edge. Consequently, an in-focus criterion based on the droplet diameter was established to correct the droplet diameter measurement and reject unfocused droplets. US researchers Kumar et al. (2019) developed a novel approach based on digital inline holography (DIH), which allowed them to ensure high-resolution imaging of the sample over an extended depth of field—typically several magnitudes larger than what is achievable with traditional imaging.

LiDAR point clouds

Sets of data points in three dimensions make up a point cloud. A set of Cartesian coordinates (X, Y, Z) correspond to each point position in the 3D geometry that the points represent. Generally, point clouds are generated by RGB-D cameras, 3D LiDAR, 3D scanners, or photogrammetry software, which counts the number of points on an object’s outside surface that it measures. Point clouds are the final product of 3D scanning processes and are used for numerous purposes including rendering, mass customization, and visualization, in addition to creating 3D CAD models for manufactured components, metrology, and quality control. This method uses a LiDAR sensor to acquire point clouds (Seol et al., 2022). Seol et al. (2022) analyzed the spray drift based on 3D deep learning by using a mobile LiDAR system. The authors claim that the obtained results were satisfactory. They expected that this system could measure the spray drift.

Machine learning (ML)

ML approaches are commonly used to quantify and classify spray drop sizes in literature. A piezoelectric sensor was developed by Gargari et al. (2019) to detect vibration signals caused by droplets striking the sensor's active surface. Vibration signal analysis led to the development of a model for classifying spray droplets based on their VMD. In Guo et al. (2020), several ML techniques were covered to create mathematical models that could forecast droplet size (VMD) and deposition for various nozzle types and in the function of sample location coordinates. Pieloth et al. (2023) classified sprays using convolutional neural networks (CNNs) by examining photographs of the spray cones. Less than 1.5% deviated from laser diffraction, according to the scientists' study. Dong et al. (2023) proposed using an artificial neural network model on electrohydrodynamic atomization systems to accurately and successfully correlate the relationship between the process variables and droplet diameter, resulting in determination coefficients that are almost unity.

SPRAY DRIFT PREDICTION MODELS

The most popular prediction model is the computational fluid dynamics (CFD) model, which makes use of the Navier-Stokes equations to solve complicated turbulence and airflow patterns. When examining large-scale 3D flows incorporating wind conditions, the kind of airflow turbulence created by sprayer fans, canopy disturbance, and operational parameters, CFD models are very helpful (Endlew et al., 2010). Sprayer airflow patterns are fundamentally three-dimensional, depending on plant structure, wind, and spraying clouds. In-depth research has been done to learn more about the intricate airflow pattern and droplet drift process, but because of variations in plant structure and environmental conditions, these studies are usually costly and challenging to carry out (Endalew et al., 2010). In recent works, complicated 3D airflow patterns are examined, and numerical solutions are produced by resolving physical conservation equations for mass, momentum, and energy (Hong et al., 2018a,b). Due to the difficulty of modeling complex plant structures and climatic conditions, finding a practical solution for the drift is problematic. Nonetheless, CFD may be a helpful technique to estimate the spray drift under optimal air conditions when comparing different sprayer designs and operating settings (Bartzanas et al., 2013). The most popular method for modeling spray drift is the Eulerian-Lagrangian approach, which provides a two-part solution (Salcedo et al., 2017). In the first section, the Navier-Stokes equation is solved for the air continuous phase. In the second section, the Lagrangian particle tracking equation is solved for the discrete phase. The interaction between the discrete and continuous phases can be achieved by transferring energy, mass, and momentum. The following is the equation for Lagrangian particle motion:

$$\frac{du_p}{dt} = f_D\left(u_p - u_\infty\right) + g\frac{\rho_p - \rho_\infty}{\rho_p}$$

where u_p = Velocity of particle in m s^{-1}; t = Time in second; f_D = Drag force factor in 1/s; u_∞ = Continuous phase velocity in m s^{-1}; g = Acceleration of gravity in m s^{-2}; ρ_p = Density of particle in kg m^{-3}; and ρ_∞ = Continuous phase density in kg m^{-3}. The left-hand side term identified the particle's velocity change over time, and the right-hand side terms calculated the drag (first term) and buoyancy (second term) forces that every particle is subject to.

The literature provides clear explanations of how energy, mass, and momentum interchange between continuous and discrete phases, primarily air and droplets (Delele et al., 2007). Convective and latent heat transfers lead droplets to constantly swap mass as they evaporate. Computer simulations include the concurrent variations in droplet sizes brought on by evaporation during conveyance (Hong et al., 2018a,b). The size of the initial droplets to be released from the sprayer's nozzle can be ascertained using the direct measurement or atomization model. The liquid sheet atomization model, which was developed, is employed in most investigations (Endalew et al., 2010). The atomization model uses the following input parameters: nozzle size, spray pressure, flow rate, spray angle, ligament constant, and sheet constant to anticipate the droplet size spectrum at the nozzle's exit (Delele et al., 2007). Some studies used size analyzers to determine the droplet size spectrum (Baetens et al., 2007). Most investigations fitted the resulting size distribution to or compared it with a Rosin-Rammler size distribution. In earlier computational fluid dynamics models, the impact of plants and trees was not considered, but in more recent studies, their effects were incorporated into the models (Endalew et al., 2010). Additionally, a porous media with spherical or cuboidal shapes was used to mimic plants (Mercer, 2009). In recent experiments, a tree (made of porous media) was modelled with different porosities, such as leaves with higher porosity and trunks and branches with extremely low porosities (Hong et al., 2018a,b). All the research reviewed in this paper used simple geometries rather than the geometrical features of tractors and boom sprayers in their computational fluid dynamics models. Two techniques were employed to substitute for the actual movement of the sprayers or tractors in situations when they were moving during the liquid application: moving coordinate system (Baetens et al., 2007) and pulse function (Hong et al., 2018a,b). Most computational fluid dynamics have restricted the computational domain to the border of the protected field or the last row of trees on the protected side to reduce computational costs. According to recent research, the drag effects of plant canopies cause the wind at the computational domain inlet to vary its vertical velocity distribution, which is why the wind profile at inlet limits should deviate from normal atmospheric wind profiles. The canopy wind profile is the name given to this. It was obtained using a steady-state simulation series until the measurement and the simulated wind profile fit (Duga et al., 2017; Hong et al., 2018a,b).

SPRAY DRIFT REDUCTION TECHNIQUES

Drift reducing nozzles

The drift-minimizing nozzle is a crucial component in achieving a good spray effect during the spray application. It immediately affects the spray quality and regulates the whole plant protection spray application system's dependability and effectiveness. To control drift and droplet deposition in the plant canopy during spraying, the nozzle measures the droplet size spectrum distribution (Chen et al., 2021). The drift reduction nozzle currently uses jet technology to create a two-phase flow inside the nozzle that is subsequently atomized into droplets. The liquid's flow velocity greatly rises when it passes through the inner core nozzle contraction part. Following the liquid's release from the compression portion, the rapidly traveling liquid removes the surrounding air, creating a vacuum region nearby. As the air is supplied into the compression area, it mixes and exchanges energy with the liquid, causing the two-phase flow liquid to travel into the diffusion zone jointly. The nozzle was then used to release the big drops and bubbles.

By decreasing the percentage of small droplets that are susceptible to drift, it can accomplish the goal of lowering pesticide droplet drift (Chen et al., 2021). Different kinds of drift-reducing nozzles have been developed recently by numerous businesses, including Germany's Lechler Inc., the US's Lurmark Inc., and others. The IDKT/IDK/ID jet nozzles stand out among the rest for their reduced droplet drift and more consistent droplet coverage; the drift-reducing impact can reach more than 70% at 35 km h^{-1} and more than 95% at 12–28 km h^{-1} wind speeds. The air-suction drift reduction nozzle and traditional hydraulic nozzles' atomization parameters (droplet velocity, droplet size, etc.) were compared by Dorr et al. (2013). The air-suction drift reduction nozzle, according to the researchers, created droplets with a slower deposition velocity that were hard to deviate from. In Song et al.'s (2011) study on the droplet drift mechanism of a fan-shaped nozzle, the drift zone was the spray fan's sides and end, and the driftable droplets were mostly concentrated in the spray fan center from the nozzle of 300–500 mm. The authors concluded that to reduce spray drift, these aspects should be considered while designing nozzles. In the wind tunnel, Tang et al. (2016) investigated the air-induced nozzle (IDK-120-03) and the conventional fan nozzle (LU-120-03). The air-induced nozzle had greater droplet uniformity and higher droplet size, and the scientists found that it was better suited for aerial spraying over a wide range of wind speeds. Li et al. (2019) studied the twin-fluid nozzle. They found that the twin fluid nozzle realized the ultra-low volume spray and had good atomization performance, obtaining droplets at fog level.

Spray adjuvant

Spray adjuvants are essential components affecting the quality of spray because they are employed during the spray process to enhance the physicochemical properties of solutions. Adjuvants for spraying can alter the size of droplets by altering the physical characteristics of the liquid. To avoid droplet size decreases during the deposition process, spray adjuvants can significantly reduce droplet evaporation (Hillocks, 2012). Spray adjuvants can cut down on droplet drift by around 50% in the downwind direction, according to Liu et al. (2005). Australia, the United States, and other industrialized nations currently use spray adjuvants that are added to the liquid used for spraying. Dexter et al. (2001) observed that when the adjuvant concentration increased, the fraction of fine or very-fine droplets reduced, and droplet size increased. Wang et al. (2015) investigated and compared the effects of various adjuvant concentrations on a nozzle's drift potential index. The three adjuvants decreased the drift potential index by 98.7%, 58.2%, and 80.1%, in comparison to water, respectively.

Electrostatic spraying technology

Electrostatic spraying is an advanced way to reduce drift (Zhang et al., 2016; Liu et al., 2018). When spraying, high-voltage static electricity creates an electrostatic field between the target crop and the nozzle, which, after atomizing, turns into a spray liquid charge of the same polarity as the nozzle (Fig. 7). The charged droplets adhere to various sections of plants under the influence of electrostatic field forces and other external factors by the electrostatic induction principle, which states that like charges repel one another and opposing charges attract one another (Lan et al., 2018).

This technology can improve the environment around the application area by increasing droplet deposition and spray coverage rate while decreasing spray drift. This technique allows

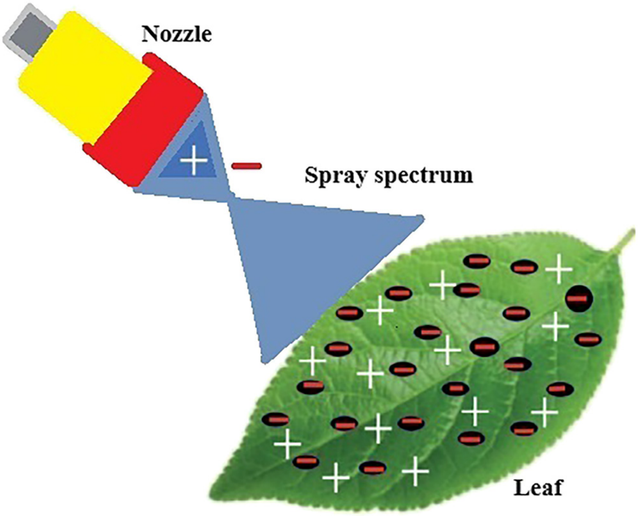

Fig. 7. Electrostatic sprayer and electrostatic spraying process (Ahmad et al., 2021, republished under Creative Commons CC BY 4.0 – Modified version)

droplets to attach not only to the front, but also to the back, middle, and bottom of plant leaves. Patel (2016) asserts that electrostatic spraying systems reduce drift, risks to human health, and environmental issues. According to Patel et al. (2016), electrostatic spraying technology has advanced spraying equipment by increasing droplet retention and deposition on plant leaves.

Variable-rate real-time spraying technology

One method for achieving precise spraying is variable-rate real-time spraying technology, which can decrease spray drift and improve spray application precision. With this technology, crops can be sprayed for a variety of reasons by combining information about target crops, including crop row spacing, plant density, field pests, disease region, and other application factors (Chen et al., 2021). Real-time technology-based variable rate systems have been developing more quickly over the past few decades because of major investments (Hongbin et al., 2018). Variable-rate spraying technology's key features are: 1) Increase the application rate; 2) Saving pesticide; 3) Real-time; 4) Cost-saving; 5) Greater compatibility (Abbas et al., 2020). In variable-rate spraying technology, sensors are utilized for data collection and processing, as well as for the identification of target plants and their geometrical structural properties (Abbas et al., 2020). Analog electrical impulses are converted into measured physical dimensions using the sensors. This section covers the variable-rate spraying technique as well as the additional sensors used in it, including machine vision, LiDAR, ultrasonic, and infrared. Table 5 summarizes the sensors' key features.

Infrared sensors

In spraying systems, infrared sensors are utilized for autonomous spray control and target recognition. This technique is used in orchard sprayers. In comparison to ultrasonic sensors,

Table 5. Properties of different sensors (own compilation, based on Petrovic et al., 2018; Azfar et al., 2018)

Sensor	Properties
Infrared	Operation range: <2 m to >50 m, angle measuring range: <10°, power to resolve angles, ability to operate in rainfall, fog, and snow with limitations, and can work at night
Ultrasonic	Operation range: <2 m, angle measuring range: <10° with limitation, power to resolve angles with limitations, ability to determine the direct velocity with limitations, and ability to operate in rainfall with limitations, ability to operate in fog, snow, and dust
LiDAR	Operation range: <2 m with limitations to >50 m, angle measuring range: <10°, power to resolve angles, and ability to operate in rainfall, fog, snow, and dust with limitations
Machine-vision	Operation range: <2 m to >50 m with limitations, angle measuring range: <10°, power to resolve angles, ability to determine the direct velocity with limitations, and ability to operate in rainfall, fog, snow, and dust with limitations

infrared sensors have faster response times and lower pricing. Indoors, the infrared sensors performed better than the outside. Regardless of how brilliant or dark the colored item is, the type of object to be sensed determines the infrared sensor. Industrialized countries such as Europe, America, and Russia are adopting infrared imaging technology to produce autonomous sprayers (Feng et al., 2013). An automated, electrostatic, infrared target-detecting orchard sprayer was invented by He et al. (2011). The sensors detect variations in the several fruit trees by striking the lower, middle, and top parts of the canopy. The novel target detection sprayer can boost utilization (by over 55%), retain more than 50–75% of pesticides, improve sensor efficiency, and lessen contamination from pesticide application, according to the scientists. The infrared target recognition method, however, is unable to recognize typical data, such as the size and precise dimensions of the object, and the computation and quality analysis cannot be carried out due to this sensor's limitations. Additionally, the target detection mechanism is susceptible to light from the outside (Downery et al., 2011). As a result, modern agriculture is unable to keep up with the demands of technology as it develops (Abbas et al., 2020). The air-assisted sprayer equipped with the infrared sensor is shown in Fig. 8.

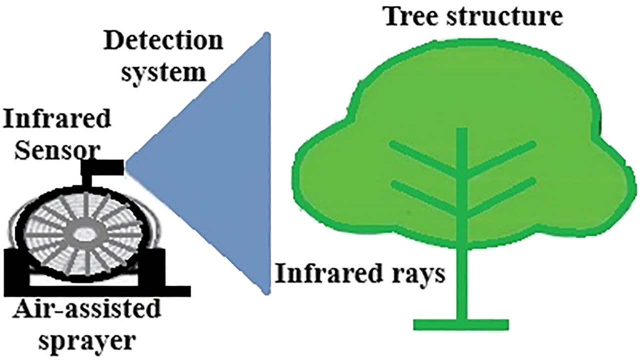

Fig. 8. Infrared sensor-based sprayer and spraying process (Ahmad et al., 2021, republished under Creative Commons CC BY 4.0 – Modified version)

Ultrasonic sensors

The spraying system using ultrasonic sensors is not widely used. This approach might be used for orchard-based management. This technology is adaptable to different agrochemical applications on farms. There was no spraying when there were no plants, full spraying when the canopy thickness exceeded a specified threshold, and semi-spraying when there were tiny-sized plants (Fig. 9) (Escola et al., 2013). To design the variable-rate spraying system with ultrasonic sensors, numerous studies have been done. According to Llorens et al. (2010), using a variable rate application instead of a traditional spray treatment on vine varieties at various crop growth phases resulted in a 58% reduction in application volume and comparable or higher leaf deposition.

Numerous experiments have been done to automatically determine the canopy size (Palleja et al., 2015). Three solenoid valves and ultrasonic sensors were added to an air-assisted multi-nozzle sprayer by Gil et al. (2007). The flow rate was dynamically adjusted based on crop width. Three portions of the crop canopy, each with a solenoid-valve operated nozzle and an ultrasonic sensor, were covered. The authors found that while leaf deposition, uniformity of distribution, and penetration into the inner sections of the crop remained identical, there was a 58% liquid savings compared to the traditional constant application rate.

LiDAR sensors

The LiDAR is more precise since it has a better resolution than the ultrasonic sensor. However, it performs worse in rain and dust. Gil et al. (2013) explored the use of scanning LiDAR to characterize spray drift. The LiDAR sensor provides a simple and encouraging way to detect possible drift (Fig. 10). Wei and Salyani (2005) researched using a laser scanner to scan the canopy of a citrus plant. The authors use scanning data to determine the canopy's volume, breadth, height, tree border contour, and leaf density. A test target made of plastic was used, and the findings showed 97% accuracy in measuring length. The researchers found a fair connection between visual evaluation and density estimation. Palacin et al. (2007) estimated the tree spray area in real-time by measuring the canopy volume using a laser scanner. They also reported that

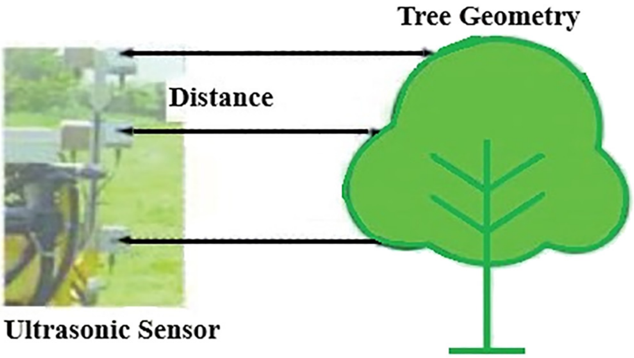

Fig. 9. Ultrasonic sensor-based sprayer and spraying process (Ahmad et al., 2021, republished under Creative Commons CC BY 4.0 – Modified version)

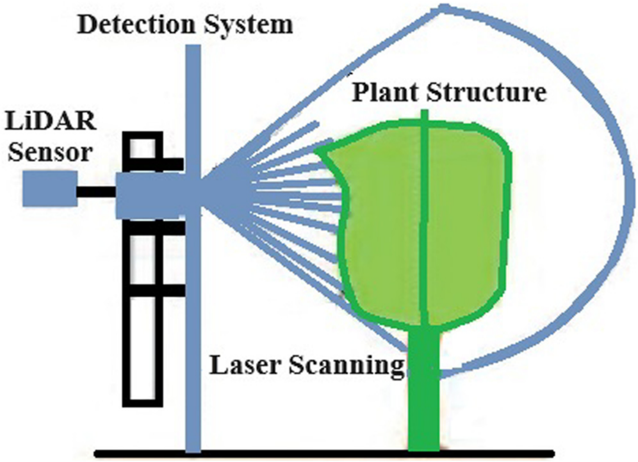

Fig. 10. Laser scanning system (Ahmad et al., 2021, republished under Creative Commons CC BY 4.0 – Modified version)

the size of the tree trunk may have an impact on estimating accuracy and outcomes that are closely tied to tree species. According to Cai et al. (2017), the laser scan system provides accurate canopy volume calculations in real-time, allowing the sprayer to be adjusted at different levels.

Machine vision

Another efficient method for identifying form, size, color, texture, and crop position is machine vision (Fig. 11). It is the computer's vision. The initial stage in machine vision is to take a photo with a CCD camera. The research region was then examined to find various characteristics (Abbas et al., 2020). Oberti et al. (2016) investigated powdery mildew plants, powdery patches

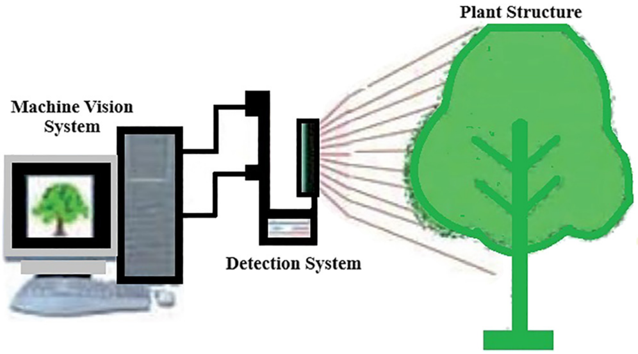

Fig. 11. Machine vision spraying system (Ahmad et al., 2021, republished under Creative Commons CC BY 4.0 – Modified version)

on leaves, and powdery mildew symptoms using a selective spraying robot. The disease spots covered the entire leaf of the plant once they had spread and connected. Consequently, to recognize the symptoms in the multispectral picture, the authors used image processing. Compared to traditional canopy spraying, the spraying robot's ability to recognize and target dangerous areas inside the canopy resulted in a 65%–85% reduction in the amount of pesticide used. To improve the effectiveness of pesticide treatment in orchards, Asaei et al. (2019) developed an orchard sprayer that makes use of machine vision technology and can administer exact pesticide dosages based on a canopy. The authors assessed the sprayer's performance in the olive orchard at four forward speeds in both discrete and continuous scenarios. In comparison to conventional spraying, the authors discovered that variable-rate selective spraying can reduce spraying by 54%.

Robot spraying technology

Accurate target identification and precise spraying are both possible with robotic spraying technology (Vijayakumar et al. 2023). Robotic spraying systems have been successfully designed and developed by several researchers. Lee et al. (1999) designed a robotic tomato plant spraying system. The authors found that the machine had low spraying accuracy (52%). The reason for that was incorrect identification of the target. They also found that they had good spraying accuracy on the circular green targets, with an average inaccuracy of 6.58 mm. Lamm et al. (2002) developed an automated weed management method to discover weeds and identify cotton fields using the robotic platform from Lee et al. (1999). They discovered that 88.8% of weeds were effectively treated and 78.7% of cotton plants were spared. Tian (2002) developed the self-propelled precision sprayer. They found that the spraying accuracy was between 86 and 96% depending upon the sprayer speed. Sogaard and Lund (2007) built an autonomous robot for spraying. The robotic system achieved 99.8% spraying accuracy with a 5 mm by 5 mm spatial resolution. Partel et al. (2019) designed and built the smart sprayer. They found that the spraying accuracy was 91%. The work on variable rate technologies is summarized in Tables 6 and 7. The robotic sprayer is shown in Fig. 12.

Pulse Width Modulated (PWM) controlled spray system

Spray drift problems may be resolved with the PWM solenoid valve system without modifying sprayer settings (Zhu and Ozkan, 2019; Giles, 2020). This system can be utilized to regulate the nozzle flow rates to decrease the usage of pesticides, production costs, and environmental risks (Salcedo et al., 2021). The PWM solenoid valve in the current constant-rate sprayer can be connected, allowing a nozzle to regulate its performance. Spray drift can be decreased with PWM-controlled nozzles because they decouple the pressure from the flow rate. Falchieri (2013) designed a spraying mechanism that emits sporadic spray patterns. Because occasional spray deposition would encourage the diffusion of the active component via leaf cuticles, the product's biological efficacy on foliage may rise with this behavior (Gao et al., 2015). Falchieri and Boselli (2020) claim that a conventional mist-blower retrofitted with this technology reduced the dose per hectare by 40% while still being equally effective against *Plasmopara viticola and Cacopsilla pyri* as a conventional mist-blower without this technology. A 40% decrease in the dose per hectare of herbicide applied during pre-emergence in soybean fields was also observed. A laser-guided sprayer with a PWM valve has been developed and modified recently (Shen et al., 2017).

Table 6. The last decade's work on variable rates technologies

Sensor	Work objective	Reference
Infrared	- Using infrared detection technology, identifying the green targets	Li et al. (2012)
Ultrasonic	- Application of low-volume bait treatment on the exterior of the crop canopy	Chueca et al. (2008)
	- For targeted pesticide application in blueberries, the development of an accurate and efficient variable-rate spraying system	Zaman et al. (2011)
	- For nursery liner applications, attain uniform deposition and coverage using the variable-rate ultrasonic sensor system	Jeon and Zhu (2012)
	- Achieving suitable deposition on the canopy and reduction of pesticides used	Hossein et al. (2013)
	- Development of a model of target-oriented variable-rate spraying for planar orchard	Li et al. (2017)
LiDAR	- Improving the sprayer with a laser scanning sensor for varying canopy volumes and foliage densities	Chen et al. (2012) Sanz et al. (2013)
	- For orchards, study the relationship between leaf area density and tree canopy by LIDAR 3D measurement system	Liu and Zhu (2016)
	- Integrating sensors and algorithms into the sprayer to regulate flow in real-time according to the plant structures	Li et al. (2018)
	- Reduce pesticide usage by using a variable-rate orchard sprayer, based on a laser scanning sensor to match canopy features	
Machine-vision	- Automatic disease detection using a variable-rate sensor-based sprayer	Tackenberg et al. (2016)
	- Precision herbicide application by variable-rate camera sensor sprayer	Dammer (2016)

Two goals were accomplished by pairing this sprayer with a high-speed laser sensor, resulting in a considerable reduction in the amount of pesticide utilized: 1) automatically shut off the nozzle and detect gaps between trees, and 2) analyze the canopy's size and density in real-time, and then adjust the spray volume by the volume of canopy foliage as necessary (Silva et al., 2018). According to earlier research, this approach can greatly save pesticide costs and spray drift compared to a conventional spraying system without sacrificing biological efficacy (Chen et al., 2019, 2020; Boatwright et al., 2020; Manandhar et al., 2020). Salcedo et al. (2021) tested the air-blast sprayer and found that the Manual-PWM and Laser-PWM significantly decreased ground and airborne drift losses by 79%, 84.1, and 85%, 90.3%, respectively, in comparison to Disable-PWM. The authors concluded that the air-blast sprayer fitted with a PWM system would greatly increase the application efficiency while greatly reducing spray drift and pesticide costs.

Tree injection system

Trunk injection is a way of administering plant protection chemicals that is different from foliar sprays or soil drenches. Compared to conventional techniques, trunk injection offers several benefits, including as improved product delivery efficiency, reduced danger of worker exposure, reduced risk to the environment, reduced harm to non-target species, and the capacity to be utilized in populated regions when other methods are not accessible (Sanchez and Fernandez, 2000; Wise et al., 2014). Trunk injection techniques have been used for a long time in a variety of

Table 7. Advantages and disadvantages of different sensors

Sensor	Advantages	Disadvantages
Infrared	▪ Humidity and temperature have little effect on target identification ▪ Low power requirements ▪ Low cost ▪ Night and daytime reliable	▪ Deficient spatial resolution for use in agriculture ▪ Limited range ▪ Can't detect canopy characteristics information ▪ Light intensity affects detection ability
Ultrasonic	▪ Low cost ▪ Easy to use ▪ Easy interaction with microcontrollers ▪ It is independent of the object's hue	▪ Affected by weather ▪ Limited range ▪ Susceptible to background noise
LIDAR	▪ Fast working ▪ Suitable for usage in all kinds of lighting ▪ Higher accuracy ▪ The accurate description of the tree structure	▪ High cost ▪ Affected by adverse weather conditions ▪ Poor performance in edge detection
Machine-vision	▪ Provide a precise three-dimensional model of the plant canopies ▪ Provide high-precision tree structure information ▪ Provide a large amount of information ▪ Robust enough for open agriculture	▪ High cost ▪ Susceptible to direct sunlight ▪ Need recording procedures and suitable calibration ▪ Extensive computational requirement

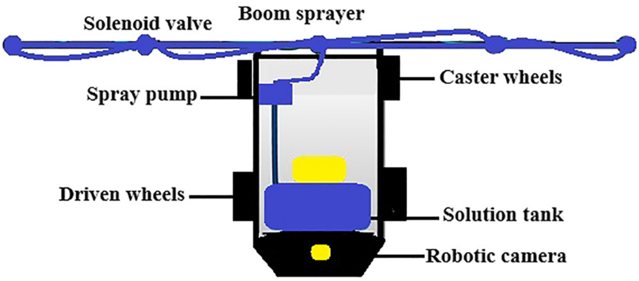

Fig. 12. Robotic sprayer (own source)

crop and non-crop species, but they haven't been perfected for use in commercial crop production. Roach (1939) conducted the first known experiments with trunk injections in the 15th century. He injected arsenic and other toxic chemicals into apple trees through boreholes to render the fruit toxicity. The rise of Dutch elm disease (DED) in the 1960s sparked modern research on injecting liquid materials for plant protection, including several ways (Perry et al., 1991). During the 1970s–1990s, researchers investigated the effectiveness of various substances and performed mechanism-based research on pressured injection systems (Filer, 1973), water and dye flow patterns (Holmes, 1982; Kozlowski and Winget, 1963; Sachs et al., 1977), and varied wood properties (Sinclair and Larsen, 1980; Chaney, 1985). Recent mechanism-based investigations have focused on wounding and degradation (Doccola et al., 2011; Acimovic et al., 2016), water and compound mobility (Tattar and Tattar, 1999; Ford et al., 2007), and safer injection approaches (Shang et al., 2011; Montecchio, 2013). Injection port damage and wound closure in apple plants were examined by Acimovic et al. (2016). In apples and grapes, Dalakouras et al. (2018) looked at the mobility of hairpin and short interfering RNAs. While Kuroda et al. (2018, 2021) examined the radial migration of minerals injected into the trunk, Killiny et al. (2019) assessed antibiotic absorption and translocation after stem infusion. Berger and Laurent (2019) focus on contemporary injectable methods, aspects affecting their effectiveness, and hazards.

FUTURE RESEARCH AND DEVELOPMENTS

Spray drift measurement techniques

The challenges in forecasting the future of spray drift measurement techniques are the increased development of new techniques and rapid advancement in current work. The discussion in this paper explains some recent drift measurement techniques such as the LiDAR technique, OP-FTIR technique, and drift test bench. Future research on the LiDAR technique must make progress in robust model generation by taking the primary influencing factors into account to calculate the dimensions of buffer zones in 3D crops. To obtain more precise findings, a further test will need to be carried out under various weather conditions, scenarios (plots and crops), and configurations (operation parameters, nozzles, air support, and sprayers). A precise and real-time tool for monitoring droplet size would be necessary for the OP-FTIR approach. The OP-FTIR technique also requires extra retroreflectors and an automatic positioner for quick estimates of both vertical and horizontal profiles. Further development of the method for calculating the drift potential value is needed for drift test bench procedures to make it easier to compare the potential drift results for sprayers operating at various forward speeds. Regarding other approaches, several factors, like sampling method, sample size, location, drop saturation, and evaporation, can contribute to inaccuracy in any approach. Even while instrument designers work hard to reduce these mistakes, it is crucial to understand that there is some degree of uncertainty in every measurement method. It is vital to take into account these possible sources of inaccuracy and how they may affect the outcomes to precisely measure the extent of declines. Novel techniques grounded on artificial intelligence and machine learning techniques might significantly influence precision spraying. By using sensors and other tools built into robots and drones, artificial intelligence applications in agriculture can save pesticide and herbicide usage while increasing crop quality and output.

Spray drift prediction models

The CFD emerged as a viable method for studying turbulent airflows and their interactions with airborne droplets. The CFD model continued to use the older theories, such as canopy airflows, entrained air currents, and turbulent air jets, for several significant elements, such as droplet retention and the release of droplets by plant canopy. The CFD simulation is unable to determine the range of droplet sizes because of insufficient computing power. Therefore, more research is strongly advised to integrate the current information with cutting-edge methods for the prediction of spray drift. Some future work recommendation is discussed as follows:

1. Using fluid-mechanical computer simulations to assess the environmental risk and minimize it for users and regulatory authorities (Alix et al., 2015).
2. The computer simulation can include the spray cloud pattern, sprayer travel conditions, and sprayer physical characteristics to describe real-time droplet trajectories.
3. Using advanced computational systems to import real-time local weather data as initial input and 3D crop images as boundary conditions into the simulation models.
4. The promotion of sophisticated technology will aid in the validation of spray drift models. Because field experiments were challenging, the majority of models were validated using data collected in constrained operational circumstances.

Spray drift reduction technologies

The discussion in this paper serves as an illustration of the various spray drift reduction technologies. To encourage the safe and efficient use of pesticides, research is still being done to improve current technologies and create new ones. For an agrochemical application to be efficient, adjuvants with significant drift reduction and evaporation avoidance are required. In developed countries such as America, Australia, and Europe, a great deal of research has been conducted on the influence of adjuvant formulation on spray drift; yet, the very efficient adjuvants are still not suitable for use with unmanned aerial vehicles (ultra-low or low application). Therefore, it is necessary to research how various solvents, dispersants, and emulsifiers affect the physiochemical properties of maize, wheat, and rice during aerial spraying. Further study is required to create a classification system based on the formulation type’s drift-reducing characteristics. Electrostatic and variable-rate spraying is the method to reduce spray drift and improve pesticide utilization rate. These technologies have been effectively applied to ground and manned aerial applications but in the case of unmanned aerial vehicle applications, these technologies are in preliminary stages. These technologies are currently limited to unmanned aerial vehicle applications. Still, there are many issues in these technologies that need to be addressed. In future research, the progress and advancement of sensors contributed to geometry. For increased production, quality, and optimization, the tree plant classification will allow much-needed improvement. Sensors such as laser and vision are still being tested. Millions of hectares are impacted by variable-rate spraying, which directly affects the environment and civilization. Consequently, more study in that area is required. Variable-rate spraying systems undoubtedly can lessen spray drift, but to realize their full potential, certain technological advancements are still needed. The first step is to increase the speed of computation and improve the research system to develop software. Among them, it is necessary to build a low-cost control system and sensors that help out in large-scale applications.

CONCLUSIONS

This review paper illustrated several approaches to mitigate spray drift. To attain good spraying efficiency, the droplet size spectrum should be consistent and avoid extremes of coarseness and fineness. The negative effect of spray drift can harm human health, livestock, and adjacent crops or can cause environmental pollution. It has been shown that several factors including nozzle type, machine parameters, liquid properties, and atmospheric factors significantly affect the spray drift. Many researchers have already worked on spray drift measuring techniques and prediction models. These measuring techniques are performing well under their boundary conditions. The potentialities of the available drift measuring and prediction techniques should be better exploited. The advancement of new sensors for the geometric characterization of tree crops will optimize the use of variable-rate sprayers in agriculture, leading to increased production and quality through improved training systems. Variable spray improves millions of farmed areas, impacting both society and the environment. Developing accurate, robust, and affordable plantation measurement systems is crucial for promoting sustainable and precision agriculture. Robotic spraying machines are the subject of studies on their design, development, and performance evaluation for crops and orchards. Also, to improve pesticide utilization and sprayer efficiency, researchers are working on simulation modeling. However, to reduce health risks and spray losses during spray application, further studies are still needed.

ACKNOWLEDGMENT

This research was supported by the University of California, Davis, 95616, USA.

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