Advanced Techniques for Reducing Spray Losses in Agrochemical Application System

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Abstract: Spray losses are the most important problem that faces spray application technology. Lost agrochemicals cause damage the plants near to the field, pollution of ecosystem, reducing spray efficiency and farming cost. Sprays are lost due to spray the wide gaps between plants and also spray drift to non targeted areas with air flow. Reducing of spray losses has increasingly attracted the attention of researchers who are interested in developing spray technologies. Two main techniques are used to reduce spray losses are: Variable Rate Technologies (VRTs) and Drift Reducing Technologies (DRTs). These techniques are unique means in that they reduce spray losses according to requirements of field conditions. VRT is a good tool to spray according to the plant volume using sensor-controlled precision spraying systems. DRT has an important role in reducing the effect of cross wind by increasing of the droplet size using drift reduction nozzles when there is need to spray at high heights above the field. These two techniques offer great research opportunities. This paper presents principles, and potential spraying applications for VRT and DRT. The objectives of this review are to display and discuss the performance of VRT and DRT in reducing spray losses to provide a good background on the challenges and problems that are being faced by these technologies. In addition, perspectives and some appropriate solutions are suggested.
[Hassen NS, Sidik NAC, Sheriff JM. **Advanced Techniques for Reducing Spray Losses in Agrochemical Application System.** *Life Sci J* 2014;11(3):56-66]. (ISSN:1097-8135). http://www.lifesciencesite.com. 9

Keywords: spray losses; ultrasonic sensors; VRT; drift reduction; DRT

1. Introduction

Each year over 2.2 billion kg of pesticide are used worldwide [1]. Many of sprays are lost in the fields because of using conventional spray. Plant protection products (ppp) are dangerous chemical and must be applied with the utmost efficiency and according to the field conditions to prevent environmental pollution and save costs [2]. The ultimate goal of spray application technologies is to put the correct amount of pesticides, on the correct place, at the correct time to reduce of the pest level below the economic threshold to improve agricultural production. In addition, spraying application system is designed to achieve a good spraying distribution and uniformity [3]. Over the last years, the developments in spray technologies have increased and played an important role to maintain biological efficacy of pesticide under acceptable levels of ecotoxicological risk and minimize crop-free buffer zones [2]. The use of new technologies to reduce spray losses had optimized performance of sprayers. There are two main techniques are used to reduce spray losses: Variable Rate spray Technology (VRT) and Drift Reduction Technology (DRT). VRT describes a technique where spray process depends on presence or absence of plant and selectively turn on and off spray nozzles while DRT is used to generate spray quality has ability to resist effects of the cross wind.

Recently, specialists and researchers in this area have taken notice of these techniques for their ability to reduce spray losses for high percentages. However, these techniques face challenges as the result to combinations of crops, operation variables, application methods and environmental conditions and their interactions. Hence, spray loss reducing technologies have not been well examined and evaluated under combinations of harsh conditions and still under very limited field tests. In addition, it is necessary the balance between percentage of spray loss reduction and requirements of optimum spraying. The use of these techniques should be not affect optimum spray parameters (density, coverage and deposition). VRT is an attractive mean in which can be used to spray tree liners and row crop fields. It could spray according to the plant volume. Our emphasis will focus on real-time sensor based VR technology and analyzing the ability of ultrasonic sensors in determining plant structure. In addition, evaluation of the efficiency of targeted spraying in reducing spray losses in comparison with the conventional spraying and evaluation of effect large savings in sprayed application volume rates on optimum spray parameters. One outstanding feature of DRTs is its ability to control spray drift by governing droplet sizes. Our emphasis will focus on drift reduction nozzle technology. The objectives of this review are to display and discuss previous theoretical and experimental results of the performance VRTs and DRTs in reducing spray losses to provide a good background on the challenges and problems that are being faced by spray losses reducing technologies. In addition, perspectives and some appropriate solutions are suggested.

2. Backgrounds and principles

2.1 Variable Rate Spray Technologies (VRTs)

In younger liner groves and row crop fields as shown in Figure 1, a lot of spray is lost around the plants because of using conventional spraying (broadcast spray application over an entire field). However, management of the precision agriculture (PA) encourages reducing pesticides used in the field by using suitable and correct spray applications. To reduce spray losses in these fields, banding spraying application (spraying of chemical materials in parallel bands and area between the bands is left free of chemical) was used instead of broadcast spraying [4]. This type of application is more economical as compared to the broadcast spraying [5] because it is targeting a specific area of the field such as rows or strips. In fact, band spraying is still characterized by considerable inefficiency because an entire band is sprayed regardless of whether there are targets or non-targets presented in the line or band, therefore, spray is lost in the large gaps between trees or plants. Environmental concerns and rising demands for reducing pesticides used in the field increasingly lead to the study of sustainable spraying techniques that could optimize pesticide application by more precise adjustment of spray according to the target characteristics. The continuous growth and change in the size of plant require a continuous adjustment of the applied dose, therefore, several spray systems were developed to control spray process.

Figure 1. Oil palm intercropped with soya bean. This figure is published in colour at (http://www.ecoport.org) (adapted from [6]).

Sensor-controlled precision spraying system for orchard sprayers has been available since 1984 [7]. Recently, VRTs have been widely used for reducing spray losses in banding spray applications. Applicators using VRT are reporting 15 to 50 % savings of agrochemicals in mature groves and >50 % in a new groves [8]. These technique works on the basis of the principle of the variable rate spray application and consists of a detection system and a spraying application system as shown in Figure 2. The detection system is used to detect information on target plant and make spraying decisions while spraying system controls sprayer operation [9].

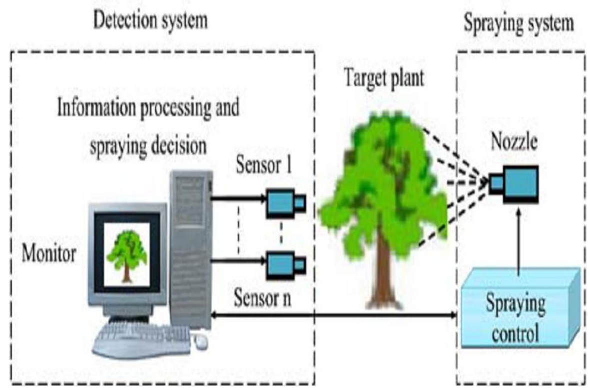

Figure 2. Targeted spraying system based on sensing technology (adapted from [9]).

2.1.1 Sensing System

In the last years, there are a clear growth and advancement in sensing systems used in detecting of the plants. A number of intelligent sensing systems have been developed to detect the plant canopy structure, such as stereoscopy photography, image analysis techniques, analysis of the light spectrum, light detection, ultrasonic sensors and ranging (LIDAR) laser sensors [10]. Measuring of crop dimensions by using of ultrasonic devices is not a new idea. Ultrasonic sensors were originally designed to measure distances in industrial works, where detected objects are rigid, and the reflection surface is perpendicular to the direction of the ultrasonic wave; therefore, some researchers query their usefulness in agriculture [11]. Ultrasonic sensors generate high-frequency sound waves and receive the echo. Determining the distance between the sensor and an object depends on the calculated time interval between signal transmission and echo receipt [12]. Despite of some weaknesses, ultrasound sensors are currently being used for detection and ranging of geometric information of the plant and provide good results about plant structure. There are a lot of advantages of ultrasonic sensors; the most important are their robustness and low price [13].

2.1.2 Sensor/Nozzle Relationships

The use of ultrasonic sensors and control system together with variable rate electro-valves to turn on and off nozzles using the corresponding software for processing unit modified real time of the spray flow rate according to the canopy volume and reduce spray volume [14]. Ultrasonic sensors can also easily determine the presence or not of the crop and to stop spraying between plants or at the end of each crop line by measuring the distance to the crop [15]. Sensors and ultrasonic emitters send ultrasonic waves, when waves are reflected back to sensors by plants, the valves of the nozzles are opened to release spray material. The output of the nozzles depends on the zones of canopy detection by the sensors and can be adjusted to ensure spraying of the plant, sensing spraying system is adjusted to turn on spray nozzles some distance before the detected plant and continue spraying process some "offset" distance after passing the detected plant.

2.1.3 Targeted spraying

Several targeted spraying systems have been used by researchers to detect and spray plants in the field [16, 17]. For herbicides application, map–based sprayers were used for selective application of herbicides. Weed maps includes crop scouting [18] and remote sensing [19-21]. Spatial application error can be happened during scouting and sensing processes, and come from several sources, including weed patch Geo–referencing error in the original map [21], GPS error in sprayer position [22], and delays due to control system response [23, 24]. Hagger et al. [25] developed a selective hand sprayer that used a pair of red and near–infrared (NIR) reflectance sensors for plants detection. The results showed that over 90% of grass patch areas were killed. NIR photodetector sensing system was also developed by Shearer and Jones [26] to detect inter–row weeds. Time–delay relays were used to activate nozzles after sensing weeds. This system reduced a 15% in herbicide quantities with no statistical evidence of differences in weed control between selective and conventional broadcast spraying. According to Blackshaw et al. [27] the use of NIR system showed limitations in detecting small weeds at oblique sunlight angles. Beck and Vyse [28] invented an apparatus for selectively eliminating weeds. In this method, at least two light (radiation) emitters are used to provide selective elimination, monochromatic light beams of different wavelengths. The light beams detect the weeds by focusing at a small surface area on the ground (which may be, desired plants or undesired weeds or bare ground). A detector provides a signal and a controller analyzes this signal, if the plant is a weed, the desired action might be to spray herbicide on the weed. This apparatus significantly reduces the quantities of herbicides in the field and the cost of labor.

In order to overcome error source in determining absolute vehicle position within the field, sprayer–mounted sensors approach was applied for variable–rate herbicide application as shown in Figure 3 [29]. Sensor–based sprayers work according to the presence and absence of weeds and selectively turn on and off nozzles. When the sensors sense weeds, the vehicle must travel the distance between the sensor and the nozzle before opening the nozzle. This distance must be measured accurately, and control system must be precisely determined the exact time to begin spraying to minimize spatial application error [30].

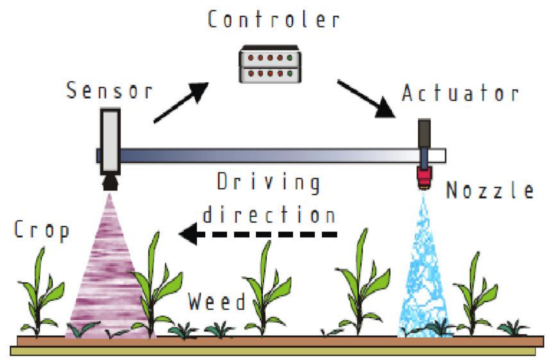

Figure 3. Real-time concept of site-specific weed control (adapted from [29])

Koch and Weisser [31] used different electronic control strategies and obtained no significant differences between a sensor based and a conventional spraying application. Llorens et al. [32] compared ability of ultrasonic and LIDAR sensors with the traditional manual canopy measurement procedure in determining plant characteristics: height, width, and volume or leaf area. The results indicated that an ultrasonic sensor is a good tool to determine the average canopy characteristics, while a LIDAR sensor provides detailed information about the canopy. Ultrasonic and laser sensors, together with an adequate software, seem interesting tools to improve the pesticide application process. Ultrasonic sensors are widely used in VR applications for quantification of plant heights [33, 34]. Tumbo et al [35] used ultrasonic and laser sensors to estimate canopy characteristic (height, width, volume and leaf area) and compared them with manual measurements. The two systems are good and valuable tools for automatic mapping and quantification of canopy volumes in citrus groves.

Reducing spray losses using targeted spraying should be not affect efficacy of chemicals. In addition, it must guarantee that large savings in sprayed application volume rates will not affect spray depositions. Moltó et al. [36] applied ultrasonic sensors for the detection and ranging of geometric information from tree canopies; the use of ultrasonic sensors allows modification of the spray volume well according to the crop structure. The results showed that the spray volume significantly reduced while maintaining spray parameters (coverage and penetration) similar to conventional application. Gil et al. [14] used a sprayer prototype with ultrasonic sensors to apply a variable dose rate according to the measuring of the crop width variations. From obtained results, there was a significant reduction in the total amount of applied volume 57% less in comparison with a constant volume rate application; this reduction did not affect the results uniformity of liquid distribution, coverage, penetration and capability to reach the inner parts of the crop. Jejčič et al. [37] developed an automatic system (automatic spraying mode AM) for targeting spraying in orchards using an ultrasound processing system at a forward speed of 3 km h^{-1}. This system consists of control unit, ultrasound sensors, RGB camera, and an electric box containing a tachometer unit with display. The automatic system was compared with spraying system without using ultrasound guidance (control spraying mode, CM). Assessment of spray application of AM showed 20.2% saving of spray per nozzle in comparison to the spraying application in CM and the distribution, coverage and deposition were the same in both spraying modes. Llorens et al. [38] achieved a 58% saving in spray application volume with the variable rate method using ultrasonic sensors for measuring variations in canopy dimensions, the results showed obtaining similar or even better leaf deposits in comparison to a conventional spray application (a constant volume rate).

Ultrasonic sensing was tested under effect several factors. The most important are the distance from the sensor to the target and forward speed of the vehicle. If the distance from the sensor to the plant is a short, the returning echo will be strong. A strong echo will increase the accuracy of ultrasonic distance measurements [39] therefore, as the distance increases from sensor to the plant, the returning echo will be weaker; this will lead to greater errors in ultrasonically measured target volumes. Some of researchers examined the sensor performance under effect of forward speeds. Driving speed is always an important factor when using the sprayer in the field [40]. Zaman and Salyani [16] reported that ground speeds (1.6, 3.4, and 4.7 km h^{-1}) have no significant effect on the difference between ultrasonic and manual volumes. Giles et al [41], found that the traveling at speeds of 2– 6 kmh^{-1} had no significant effects on the capability of ultrasonic sensors to detect plant volume. Jeon et al. [42] used ultrasonic sensor travels at average speeds of 0.8–3.0 m s^{-1} and at height 81.9cm above the artificial plant targets to find the root mean square (RMS) error of the sensor measurements. The result showed acceptable performance of sensor for detecting the plant within the speed range. Random distance-detecting errors were observed during the experiments. Relatively large mean RMS error 19.4 cm was observed at the low speed 0.8 m s^{-1} while mean RMS error 10.8 cm was observed at the speed 3.0 ms^{-1}. The lowest mean RMS error 10.1 cm occurred at the 2.0 m s^{-1}. According to Balsari et al. [17], a crop identification system based on ultrasonic sensors was used to detect canopy characteristics in real time, confirmed its suitability, independently of the driving speed.

GopalaPillai et al. [43] reported that at higher speeds of sprayer, it would be desirable to use the higher frequencies controller to reduce the time lag of system. According to Esau, [44], using of ultrasonic sensors with Variable rate controller VRC were fast and accurate enough to open the nozzle valve with a response time of 0.050 ± 0.003 s.

A wind tunnel was used to evaluate the sensor accuracy and measurement stability under windy conditions. The tunnel simulated laminar wind flow at different speeds passing through the line-of-sight of the sensor. The IP67 sensor was mounted perpendicular to the airflow at 73.7cm above the tunnel floor; it measured the distance to the tunnel floor. The range of wind speeds tested was from 1.5 to 7.5 m/s at 1.5 m/s increments. The ultrasonic sensor output data were acquired for 5min at a sampling rate of 10 Hz with 3 replications for each wind speed. The RMS error of the sensor measurements ranged from 1.11 to 1.34cm across all wind speed conditions evaluated. No significant difference between RMS errors within the wind speed range from 1.5 to 7.5 m/s was found ($P > 0.05$). The results indicated that the accuracy and function of the sensor were not influenced by the tested wind speed range. Thus, the measurement stability of the sensor was reasonable under the windy conditions. And LSD value for RMS errors was 0.07cm ($P < 0.05$) [42].

2.2 Drift Reducing Technologies (DRTs)

Drift reduction is the reduction in the airborne portion of the spray in comparison to the reference (ISO standard). DRTs consist of spray nozzles, sprayer modifications, spray delivery assistance, spray property modifiers adjuvant, and /or landscape modifications [45]. Our emphasis will focus on drift reduction nozzles.

2.2.1 Spray drift

The most complex problem that faces spraying application is spray drift to the non targeted areas. Spray drift has become an important aspect and can be defined as the amount of product that comes directly from the nozzles and is deflected out of the treated area by the action of air flow.

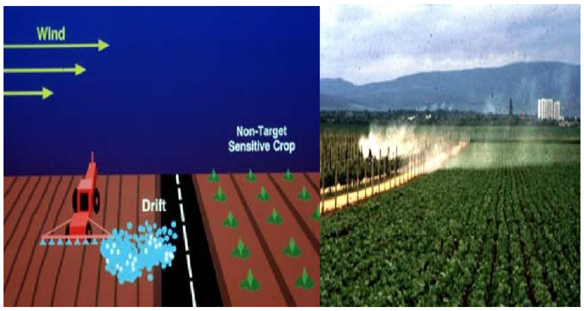

Figure 1. Spray drift to the non targeted areas (adapted from [46]).

Liquid emerges throught the nozzle at high discharge speed in the form of a jet and quikly disintegrates into droplets due to aerodynamic instablities in the break up region which interacts strongly with the atmosphere. The droplets have enough inertia for them to be effective in transferring momentum, matter and heat. The high inertia also causes the ambient air to be dragged into motion, which may either be one of the primary functions of the sprays or may have an important effect on its performance. In the vertical sprays that are high enough above the ground, the inertia of the droplets is determined by their weight (or buoyancy forces) than initial momentum and eventually they can reach their terminal velocity [47]. The spray droplets would induce an average air motion proportional to the relative volume of the droplets and their speed [48].

When a liquid is sprayed into a non–condensing air environment, this leads to an exchange in momentum between the spray droplet and the air. The drops decelerate by aerodynamic drag and the momentum lost by the droplets is acquired by the air. As result to this process, a flow field is created in which air is continually entrained into the spray. Entering of the entrained air in the spray will drag to the eventual contraction of the spray [47]. In agricultural sprays, the nozzles generally are carried behind equipment and move over the plants. The high velocity of the droplets in the spray induces a strong vertical air flow with an initial velocity of about 20 m s−1, which disperses the smallest droplets throughout the jet. The forward speed of an equipment induces a relative cross-wind (typically forward speed in the range of 3 to 5 m s−1), which together with any natural wind (in practice wind speed has to be less than forward speed) affects the spray in two ways, the first effect, by bending over and distorting the vertical air jet induced by the spray and the second effect is deflecting the larger droplets. The smallest droplets escape from the spray as result to the first effect and therefore not falling directly on the crops, commonly termed `spray drift' [49].

2.2.2 Factors affect spray drift

Several factors affect spray drift and more detailed understanding of these factors is necessary to improve performance of spray system in reducing spray losses. The major factors affecting spray drift are droplet size, release height, driving speed and cross wind speed.

1) Droplet size

An Environmental Protection Agency (EPA) has determined that the most influential factor affecting the magnitude of spray drift is droplet size [50]. Practical trails of pesticide applications have shown that small-to-medium sized droplets are desirable to achieve better penetration within the canopy and better coverage but large droplets are good for drift reduction and attaining a balance between the two is essential. Spray drift can be reduced by controlling spray droplet sizes. Generally, droplet size should be an effective spray but no finer than necessary [51].

In order to understand the drift of spray droplets, it is necessary to analyze the forces affect droplets in air. For simplicity, the individual droplets are assumed to be spherical [47] and behave like solid particles [52]. There are three external forces affect an individual droplet in the air: a drag force due to relative motion between the droplet and the air, a buoyancy force due to the air displaced by the droplet, and a weight force due to gravity. The buoyancy force is negligible and can be ignored because the droplet is much heavier than air it displaces, and, these forces sum according to Newton's second law to give the following differential equation for the velocity [52].

$$m\frac{dv}{dt} = -\frac{\pi}{8}C_D\rho_a d^2|v-u|(v-u) - mgk \tag{1}$$

$$= -\frac{\pi}{8}C_D\rho_a d^2|v-u|(v-u) - \frac{\pi}{6}\rho_w d^3 gk \tag{2}$$

Where m [kg], ρ_w [kg m^{-3}],d[m]and v[m s^{-1}] are the droplet's mass, density, diameter and its velocity relative to the ground, respectively, C_D is the drag coefficient , u is the wind velocity [m s^{-1}], ρ_a is the air density [kg m^{-3}], g is the gravitational acceleration [m s^{-2}] and k is a unit vector pointing vertically upwards. According to Green et al [53], CD is a function to the Reynolds number (Re). Re is given by the following equation:

$$\mathrm{Re} = \frac{\rho_a|v-u|d}{\mu_a} \tag{3}$$

Where, μ_a is the dynamic viscosity of air [kg m^{-1} s^{-1}]. When the droplet is released into air, it accelerates until the drag force balances its weight, after that it continues at a constant terminal velocity v_T. The equation can be expressed as below[52].

$$v_T = u - \frac{4\rho_w g d}{3\rho_a C_D |v_T - u|} k \quad (4)$$

$$v_T = u - Sk \quad (5)$$

Where, S is the downward settling speed. A simple formula for settling speed is presented by Equation (6).

$$S = \sqrt{\frac{4\rho_w g d}{3\rho_a C_D}} \quad (6)$$

Practically, droplets fall downward under effect of gravitational forces while drag forces act to slow the fall rate. As a rule, drops having a sedimentation velocity less than 10% of average wind speed, these drops can be considered drift-prone [54]. Very small droplets less than 150 microns fall so slowly because the upward drag forces is almost equally opposed by gravitational force [55].

2) Spray height

Spray height is the most significant variable in the prediction equation for spray drift [56]. Wind speed is usually greater as nozzle height above the ground increases. A statistical significant difference was noted in the reduction of spray drift for 54% when the boom height is decreased from 70 to 50 cm [57]. According to the results of Nuyttens et al. [58], lowering the spray nozzle height from 50cm to 30cm significantly decreased the amount of spray drift 40.1%. Miller et la. [59] showed that increasing of the nozzle height from 50 to 70 cm increased the airborne spray volume measured at 2.0 m downwind by a factor of approximately four. In aerial application, several sprays were carried out including effect of spray boom height on spray drift, the spraying results indicated that the lower drift had generated at lower release heights [60] and any increasing in the release height affects spray deposition and off-target drifts [61]. In general, nozzle height must be at optimum level according to nozzle characteristics for decreasing spray drift risk [62, 63]. However, the effect of nozzle height on spray drift is very clear and the use of the minimum possible boom height remains an important part of any drift control strategy particularly when fine/medium spray qualities are required for an application [64].

3) Driving speed

During the spraying process, increasing of the driving speed increases spray pressure and air flow around the spray, leads to the smallest droplets escape from the spray and falling far away from the target, resulting in a higher amount of drift [49]. Miller & Smith [65] found that an increase in forward speed from 4 to 8 kmh^{-1}, airborne spray drift increased of 51% and when the speed was further increased to 16 km h^{-1}, airborne spray drift increased 144%. In aerial application, local forward speed plays an important role in controlling the drift potential: the higher the forward speed, the greater the spray drift because the performance of hydraulic nozzles is affected by air shear; as airspeed increases, so does air shear that shatters the large droplets resulting in increasing the percentage of the fine droplets and turbulence [61, 66, 67].

4) Cross wind speed

Spray distribution and drift depend on wind speed during the time of application. In a weak cross-wind, small droplets from the nozzle tend to aggregate towards the spray centerline. While in a strong cross-wind; small droplets cannot resist the strong air flow because of their low inertial energy, making them highly susceptible to the drift [49]. In the field, weather conditions are different from one place to another, change from time to time and it is not easy to control them during testing operation, therefore, some spraying applications were carried out at wind speed varied from 0.3 to 1.8 ms^{-1}[68]. Bahrouni et al. [69] noted that during the spraying process, important pesticide amounts are transferred to the environment by wind.

3.2 Drift reduction nozzles

The environmental protection agency (EPA) in 2004 recognized a testing program for evaluating of drift reduction technologies DRTs [70]. DRT program is a set of protocols, standard operating procedures, and steps must be maintained throughout the study [71]. There are several metrics can be used in the testing and evaluation of drift reduction technologies to determine whether these technologies reduce drift relative to a reference system. One of the important metrics is reduction in the percentage of fine drops in spray [72]. Spray nozzle is the key factor that controls the spray droplet size. Classification of the nozzles was defined by ASAE [73] using two systems based on the characteristics of the droplet spectrum are: the British Crop Protection Council (BCPC) that placed nozzles into five classes (very fine, fine, medium, coarse, and very coarse) [74], and U.S. classification scheme that placed a nozzle into one of six categories (very fine, fine, medium, coarse, very coarse, or extremely coarse) [75]. Drift reduction technology is classified according to the percentage of drift reduction using two systems [45] are: the Local Environmental Risk Assessment for Pesticide (LERAP) [76] and the International Standards Organization (ISO) systems [77]. In order to reduce spray drift, the most popular approach is through increasing droplet sizes. Several factors govern droplet size; the most important are nozzle type and angle.

Spray nozzle is carefully engineered to achieve a specific performance under certain conditions. Different spray reduction nozzle techniques and procedures were used to determine the effect of the nozzle type on spray droplet size. The previous results showed that there were distinct differences in droplet size between the nozzles tested and the reference nozzle [45]. Nuyttens et al. [78] tested different types of Hardi flat spray nozzles together with the five BCPC reference nozzles by using PDPA, in total, 32 nozzle-pressure combinations. From the results of study, they noticed that the nozzle type and pressure have a significant effect on the droplet size and velocity. According to the [79, 80], there is an inverse relationship between pressure and drop size; larger droplets can be produced by lower pressures and this lead to reduce spray drift. Numerous nozzle designs were developed to work at low pressures for getting certain droplet size. For example, the extended range flat-fan nozzle (XR) was manufactured to operate at low pressures at a range of 100 to 400 kPa to reduce the number of small, driftable spray droplets to control drift and provide uniform spray patterns [81]. Another nozzle type was used for increasing droplet size is pre-orifice nozzle. This nozzle was developed by Delavan-Delta, Inc and also called Drift Guard flat fan nozzle DG, it has ability to produce larger drift-resistant spray droplets due to reduce internal liquid pressure using pre-orifice locates on the side of the nozzle that restrict the flow. This design has been an increased interest nozzle and effectively reduces the volume of driftable droplets found in spray spectrums [81, 82].

Spray nozzle angle is an important variable in determining produced droplet size. The majority of nozzles in agricultural spraying use 80° and 110° angles. There is an inverse relationship between spray nozzle angle and drop size. Increasing of the nozzle angle reduces the drop size [81]. Miller et al. [83] used the double imaging system VisiSizer and Phase Doppler Analyzer PDA to measure the droplet size and velocity distributions for the stainless steel reference nozzles FF120/1.96/2.0 and FF110/1.2/3.0 in a wide range of sprays. The droplet size/velocity measured by the two systems showed that mean liquid velocities for the FF120/1.96/2.0 nozzle were less than the FF110/1.2/3.0 even though the liquid flow rate was higher; this was probably due to a combination of effects relating to the wider spray fan angle and the lower pressure.

Several experiments in wind tunnel were carried out to evaluate performance of the DRTs relying on established professional standards of ASAE [73, 75, 84] and ASTM [85] . Hoffmann et al [45] evaluated drift reduction from three spray nozzle types namely, Hypro ULD 120–04, Teejet AI 11003 VS, and CP11TT 4008 using the USDA-agriculture research service high speed wind tunnel facility evaluations under high speed conditions (45–65 m s^{-1}). The droplet size measured at pressures 207 and 413 kPa and airspeeds 53 and 63 m s^{-1}. The tested nozzles generated spray droplets with volume median diameters 60–80 µm larger than the reference nozzle. The three spray nozzles reduced spray drift by 70–84% in the speed 53 m s^{-1} airstream and from 41 % to 74 % in the speed 63 m s^{-1} airstream as compared to the reference nozzle. Miller et al. [64] used spraying boom consist of two nozzles to measure the effect of spray fan nozzle angles on reducing spray drift, this boom mounted on a controlled transporter mechanism in the main wind tunnel section. The boom was moving at speed of 10.0 km h^{-1} (2.78 m s^{-1}) with a uniform wind speed down the tunnel of 2.0 m s^{-1} (7.2 km h^{-1}). Measurements were made with three nozzle spray fan angles of 65°, 80° and 110° at different heights measured to the nozzle orifice. Results of this work showed that the use of nozzles having spray fan angles of less than 110° could reduce the risk of drift when using nozzle height greater than 0.5m. Table 1 shows several spray nozzle types and angles were tested by researchers under effect different parameters in controlled conditions using the wind tunnel.

Table 1. Overview of some drift reducing nozzles tested in the wind tunnel.

Nozzle type	Nozzle angle (°)	Nozzle height (m)	Wind speed (m s^{-1})	Air speed (m s^{-1})	Ref.
Hollow cone	45	0.67	1 2.5 5	-	[86]
Flat	110	0.50	2	_	[87]
Flat	110	0.67	2.5 5	-	[88]
Flat	_	0.50	3 6	_	[89]
Cp CP11TT	30 40	-	-	45-63	[90]
Flat	110	-	1 2 3	-	[91]
Flat	110	-	2.57	-	[92]

3. Challenges

In spite of the development and progress of the VRTs and DRTs, some limitations still need to be addressed. Although the proposed new VRTs seem very appropriate as complementary tools to improve the efficiency of spray application, further improvements for target spraying system are still needed [32]. Productivity of the sprayer and achieving optimum spray parameters depend on the driving speed and the spatial application accuracy

(SAA) respectively. Previous studies results showed how the sensing and control systems can greatly impact SAA. Sensing and spraying system used in the current elective sprayer typically has a chronological gap between detection of the target and spraying application, resulting in application errors. In addition, the effect of response time on forward speed of the sprayer is evident. Current target spraying systems have not yet achieved wide acceptance because of their long response time. In addition, this technology does not fulfill the requirements of spraying process that are increasing driving speed and the spatial application accuracy (SAA). Much of the studies thus far have focused on plant sensing and on the overall performance of the selective sprayer; relatively little has focused on the effect of the control system on SAA [30]. In addition, to the best of our knowledge, targeted spraying systems have not been well examined under harsh field conditions and the majority of them were tested in the ideal conditions compared to typical liner applications in the field.

The most difficult challenge that faces DRTs is how to achieve narrow droplet size spectra (fine/medium droplet sizes) with minimum drift. The spray distribution and drift depend on droplet size. Big droplets are a good for reducing drift hazards, while small droplets are a good to achieve optimum spray distribution. The use of drift reduction nozzles should not affect optimum spray parameters such as: spray density (the number of droplets per unit area n/cm^2) and spray deposit (the amount of spray liquid deposited per unit area $\mu g/cm^2$) [93]. In addition, it is sometimes necessary knowing the performance of the drift reduction nozzles during harsh operating conditions. Up to date, there is no practical detailed study examined and addressed the effect of the use of different fine/medium droplet size nozzle types and angles on spray distribution and drift under effect of high driving speeds and wind speeds. Several trails have been carried out in the wind tunnel to test the drift reduction nozzles, but with little success when it comes to solving the above-mentioned problems. According to Hofman and Solseng [79], applicators of chemicals in the field have no enough information about factors affect spray distribution and drift and their interaction to choose the suitable spraying combinations and do their very best in handling the drift reduction nozzles in the field.

4. Future perspectives

The main aim of design VRTs and DRTs is to optimize field sprays. The ideal performance of spray technologies should maximize the spray efficiency by increasing the spray deposition, transfer of a lethal dose to the target, and minimizing losses of spray to the non targeted area. Further research and experimentation to develop VR sprayer are recommended, and modern signal processing algorithms are necessary to overcome the deficiencies of standard ultrasonic sensors. The use of sensors, the controllers and nozzle valves have a higher frequencies would be desirable to reduce response time to increase speed of sprayer. In order to enlarge the international drift database of DRT, there is still a need for accurate, detailed drift measurements. Moreover, additional information about the effect of the weather conditions on spray drift is necessary to compare them with the reference spray [58]. Hence, to achieve the previous objectives, this study also suggests testing and evaluating performance of the VRTs and the DRTs under controlled and harsh conditions (combinations high driving speed and cross wind using the wind tunnel) to simulate the field conditions.

Conclusions

Spraying process in the field raises a lot of problems; the most important is squandering big quantities of pesticides which cause a lot of problems to the ecosystem and farming cost. Plant protection management encourages the applicators to distribute of agrochemicals with minimum spray losses. The present paper reviews and summarizes some of the spray techniques that have been used for spray losses reduction. The two major techniques for reduction of spray losses are: VRTs, and DRTs. The review suggests that these two techniques showed a good potential in reducing spray losses. The majority of spray loss reduction technologies tests carried out in ideal conditions. This review will hopefully lead to increase efforts towards deep studies to improve performance of spray loss reduction technologies to work in harsh conditions. Finally, In order to advance the applications of the VRTs, and the DRTs in the field, further research work in this area is needed and required greater collaboration between researchers working in field sensing systems and spray technologies.

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