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CHARGED PESTICIDE SPRAY SWATH AND VOLUMETRIC DROPLETS DISTRIBUTION IMPACT BY NOZZLE TYPES, SPACING AND HEIGHT

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ABSTRACT

Understanding charged pesticide spray swath and volumetric droplets distribution in a spray continuum is an innovative strategy to reduce spray overlap and improve spraying efficiency. Pesticides spray overlap and accumulation on substrates from single or multiple nozzle(s) do not only waste chemicals but also increase lethal dosage. The parameters to enhance uniformity of in-situ droplet deposition at reduced surface overdose are required for efficient pesticide application. A factorial experiment arranged in a Completely Randomised Design comprising flat-fan (FF) and hollow-cone (HC) nozzle types, 2, 3, 4 bar flow pressures, 50, 75, 100 and 120 cm nozzle spacings (S) and 40, 50, 60 cm spraying heights (H) at three replicates were investigated to determine charged spray swath (W_n) and volumetric (Q_n) droplets distribution from a developed inductive nozzle cap mounted on a telescopic boom. The FF-nozzle produced relatively smaller charged droplet sizes, $D_{V0.5}$ (67.4-79.2µm), wider spray swath W_n ($R^2 = 98.37$ %; max. 185 cm) and higher Q_n distribution (C_{37} collectors, 15.86 mls^{-1}), than HC-nozzle of $D_{V0.5}$ (70-92.5 µm), narrow spray swath W_n ($R^2 = 85.45$ %; max. 115 cm) and lower Q_n distribution (C_{23} collectors, 15.72 mls^{-1}) respectively. A spray Uniformity Index (UI) allowed permissible spraying of FF-nozzles at 0.4 and HC-nozzles at 0.3-0.42, but spraying above 0.33 increased overlap and application rate, and below 0.08 decreased spraying efficiency. Hitherto, spraying from FF-nozzles at 0.12-0.18 yielded uniformity of Q_n distribution, while HC-nozzles were effective at 0.25, corresponding to 25-50 % spray overlap. Therefore, to reduce pesticide spray overlap on substrates, FF-nozzles should be mounted at 50 cm H × 100 cm S or HC-nozzles at 60 cm H × 75 cm S on the boom under 4 bar flow pressure, as the electrostatic spraying system provides timely and effective pesticide application in crop protection.

Keywords: *Pesticide spray, charged spray swath, volumetric droplets, nozzle types, uniformity index.*

INTRODUCTION

Pesticide spray coverage and overlap over leaf surfaces play an important role in plant protection because they influence the volumetric proportion of spray droplet distribution on substrates (Owen-Smith *et al.*, 2019; Appah *et al.*, 2020). An area of spray coverage largely depends on the application system parameters and nozzle orientation. The effectiveness of a particular spraying system is determined by nozzle types and tip angles, liquid flow rates, and spray swathes. In contrast, spray droplet drift is influenced by droplet sizes and the flow velocity from nozzle types (Appah *et al.*, 2020; Nogueira Martins *et al.*, 2021). Similarly, spray canopy penetration and surface deposition are characteristic function**s** of droplet sizes and velocity, in which maximum penetration and deposition are achieved by smaller droplet sizes than larger ones (Sun *et al.*, 2017). The combined effect of spraying system parameters and droplet sizes produced by nozzle types determines the swath pattern of spray (Elwakeel *et al.*, 2021). To overcome excessive lethal doses and chemical wastage, spray uniformity on plant surfaces is needed in pesticide spraying (Appah *et al.*, 2019a; Xiao *et al.*, 2020; Hu *et al.*, 2022). This uniformity of spray is enhanced by spraying at optimum parameters combination and the superposition of charges on the spray droplets to enhance the wraparound deposition effect on substrate architecture (Patel *et al.*, 2016; Patel *et al.*, 2017).

Injecting charges into droplets will facilitate droplet-substrate polarity attraction such that maximum droplets overlap and repeatability can be reduced to enhance the efficiency of pesticide spraying (Apppah *et al.*, 2019a). Mainly, repetition and accumulation of droplets on plant surfaces emanate from the settings of sprayer parameters and nozzle positioning. In comparison, a flat fan nozzle produces fewer spray droplets than hollow cone nozzles (Derksen *et al.*, 2008; Kumar, 2019) at a given pressure and volumetric flow rate. However, hollow cone nozzles produce larger droplet sizes that reduced spray drift than flat fan nozzles under similar spraying conditions (Bueno *et al.*, 2017; Wang *et al.*, 2023). In a study by Appah *et al.* (2020), 110º flat fan nozzles produce maximum surface coverage at a spraying height of 50-60 cm and nozzle spacing in the range of 50-75 cm or 25-100 cm on the boom. Spray drift is minimised when the nozzle height is lowered from 50 cm to 30 cm at various spraying parameters such as droplet sizes, pressure, flow rate, and chemical properties in conventional spraying systems (Al Heidary *et al.*, 2014; Pan *et al.*, 2025). There is therefore the need to investigate for optimum parameter combination of spraying height, nozzle type and spacing that enhance spray swath and volumetric droplet distribution at reduced drift. This is because, in pesticide application, nozzle configuration and pump pressure affect droplet sizes while ground coverage is determined by spraying height and liquid flow rate (Cerruto *et al.*, (2021; Elwakeel *et al.*, 2021; Ferguson *et al.*, 2016). Pesticide spraying is accomplished by single or multiple nozzle(s) spray jets from either backpack, tractor-mounted, manned aerial or unmanned aerial vehicle (UAV) boom sprayers (Yamane and Miyazaki, 2017; Zhang *et al.*, 2017). To overcome chemical wastage and off-target deposition, uniformity of spraying is required at a minimum application rate. Hence, charging droplets at an optimum spraying height and nozzle spacing is remarkable in modern plant protection technology. Since droplet charging is composited, reducing maximum overlap spray droplets is invariably a welcomed innovative strategy.

To maximise spraying efficiency and uniformity of surface coverage at reduced application rate, requires electrostatic spraying technology at an optimum application pressure, nozzle type, spacing and spraying height regimes. Though the superposition of electrical charge on pesticide spray droplets is ongoing (Patel *et al.*, 2017; Appah *et al.*, 2019b; Cerruto *et al.*, (2021); Amaya and Bayat, 2023; Lin *et al.*, 2023; Appah *et al.*, 2024), information on the effect of charged pesticide droplets on spray swath and volumetric droplet distribution is limited. Hypothetically, electrostatic technology is necessary to reduce spray pockets and overlap in a conventional spraying of pesticide. The objective of the study was to determine the effects of charged pesticide spray swath (W_n) and volumetric droplets distribution (Q_n) in a continuum of spraying at variable nozzle types, nozzle spacing (S) and spraying height (H) regimes, under a constant applied voltage of 8 kV.

MATERIALS AND METHODS

Experimental Design and Set-Up

A factorial experiment arranged in a Completely Randomised Design was conducted in a laboratory to determine charged spray swath W_n and volumetric Q_n droplet distribution at the Key Laboratory of Plant Protection Engineering, Jiangsu University, China from March to April 2019, replicated in May to June 2019, and processed in 2022. The experiment was carried out using teejet nozzle types (TP11003 Flat fan, FF; and TXR8003 Hollow cone, HC), liquid flow pressures (2 bar, 3 bar, 4 bar), spraying heights (40 cm, 50 cm, 60 cm) and nozzle spacings (50 cm, 75 cm, 100 cm, 120 cm) at three replications. All other factors were kept constant at a pump air pressure of 4 bar and applied voltage of 8 kV (or 0 kV control where appropriate) under laboratory conditions. The spraying parameters were selected as adopted by Yamane and Miyazaki (2017) and Appah *et al.* (2019a), and applied voltage of 8 kV based on research recommendations (Martin and Latheef, 2017; Appah *et al.*, 2019c). Electrostatic inductive nozzle caps were developed and coupled with a high-voltage generator of 12 kV capacity to charge the droplets at discharge. The caps were made from high-density polypropylene material, and each was embedded with two rectangular flat electrodes of dimension 40 mm × 15 mm × 5 mm. The electrodes were slotted at 2 mm spacing across the edges of the nozzle tip gap in each cap, with one electrode connected to a conducting wire, and insulated with resin glue to prevent electric charge leakage. The electrode was coupled with the negative conducting terminal of the high voltage generator to superpose negative polarity charge to droplets by induction charging mechanism, while the positive terminal was grounded to complete the circuit. The caps were fitted at the required spacing on a boom and mounted on a telescopic metallic stand that regulates the spraying heights. The boom was connected to the outlet suction hose via the liquid flow pressure gauge of the formulation tank, while the inlet section was linked to the air pump pressure. A circular wire mesh, high voltage generator, Industrial Laser Particle Size Analyzer (LPSA) model (Winner 318) and a Patternator test bench of 80 grooves and collectors (Figure 1), were used to determine the charged spray droplet sizes, spray swath and volumetric droplets distribution from glyphosate *N*-[(phosphonomethyl) glycine] pesticide spray. A Keithley picoammeter (Model No. 6485- refer to Appah *et al.*, 2019b) coupled with circular wire mesh was used to detect entrained droplets' charge (-5.424×10^{-8} mCs^{-1}).

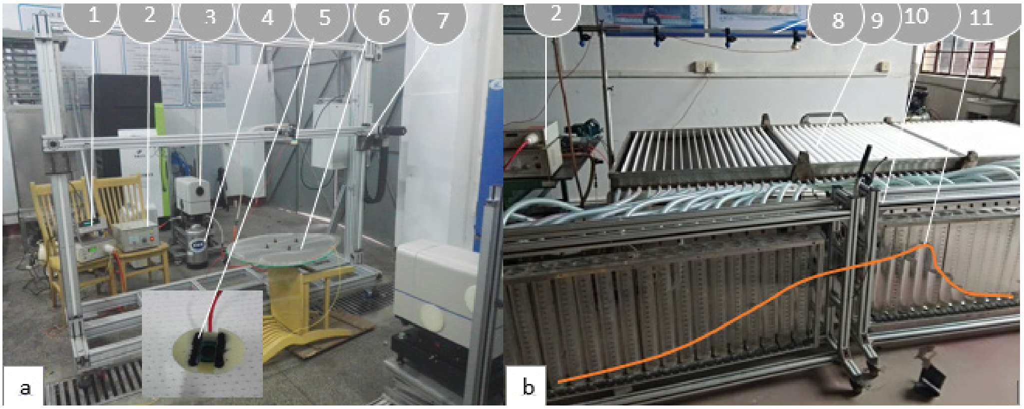

Figure 1: Experimental Set-up for (a) measurement of charged droplet sizes with laser particle size analyser and (b) determination of spray swath and volumetric droplets on patternator test bench [1. Keithley picoammeter, 2. High voltage generator, 3. LPSA, 4. ESS tank, 5. Nozzle cap with electrodes, 6. Wire mesh, 7. Telescopic mover, 8. Boom nozzles, 9. Patternator test bench, 10. Cylinder collectors, 11. Volumetric flow rate distribution in cylinder collectors

Procedure

There was an initial measurement of charged pesticide spray droplet sizes and volumetric spray from FF and HC nozzles at different liquid flow pressures and spray heights. This was carried out to select an ideal liquid flow pressure for the determination of spray W_n and Q_n droplets distribution from single and multiple nozzle(s) orientations on the boom (Figure 2). Each nozzle type was slotted into the electrode cap at a time and the flow pressure was set to throttle before spraying. A 10 ml volume of glyphosate was diluted in one litre of tap water for each application. The formulation at a conductivity of 0.042 Sm^{-1}, surface tension of 0.0058 Nm^{-1} and pH 6.6 was superimposed with 8 kV applied voltage at each parameter setting. The characterisation of droplet sizes was acquired by directing a charged spray plume from each nozzle type across a diffracted LPSA ray and logging the data into a computer system to analyse the variability of spray droplets (Table 1). A graduated cylinder of 1000 ml volume capacity was used to capture the charged spray jet (in 120 s) for volumetric droplet quantification. The charged droplet sizes and volumetric spray droplets from both FF and HC nozzles are presented in Figure 3.

The boom was centrally mounted over the horizontal pattern test bench at 10 % inclination (Figure 1b). The grooves on the bench emptied into graduated cylinder collectors, C(1-n) of 50 mm diameter each, and the surfaces of each groove also separated from one another by 5 cm width and 100 cm length. Pesticide formulation was sprayed from either single or multiple FF and HC nozzles orientations for 120 seconds to determine spray W_n pattern and Q_n droplet distribution. In single-nozzle spraying, the charged spray was directed vertically downward over the equidistant grooves on the test bench at each spraying height regime. The captured spray droplets were given ample time of 60 seconds to drain into the collectors by gravity. The grooves that intercepted spray droplets were marked and the space was measured with a rule as spray W_n for each nozzle type (Figure 4). Also, spray swath (W_n) from a single nozzle spray on the test bench was estimated using Equation 1;

$$W_n = d[C_t] \qquad \textbf{eqn 1}$$

Where d = 5 (in this experiment) is the equidistance between any two successive grooves (C_i, C_j), and C_t is the total number of collectors C(i-n) in a spray continuum that captured droplets during spraying. The Q_n droplets distribution was determined using Equation 2;

$$Q_n=\sum[C_i-C_n] \qquad \textbf{eqn 2}$$

Where C_i is the volume of droplets in the initial collector, and C_n represents the volume of droplets in the final collector in the spray continuum of $C(_{1-n})$ that intercepted droplets from the pattern test bench. The Q_n droplets distribution in the spray continuum for both FF-nozzle and HC-nozzle at the different spraying heights is given in Figure 5. For multiple nozzles spraying, two FF-nozzles and HC-nozzles, n_i and n_j were instantaneously sprayed with pesticides at 50-120 cm nozzle spacing and 40-60 cm spraying heights. During spraying, the non-overlap region of n_i, the overlap region of $n_i n_j$ and the non-overlap region of n_j jets were carefully monitored and marked to determine charged spray swath and volumetric droplets in the spray continuum. The overlap spray swath (W_{ninj}) and overlap volumetric (Q_{ninj}) droplets were used to predict W_n and Q_n from a series of multiple nozzle arrangements on the boom (Figure 2 and Equations 3-8). As spray droplets jet from the nozzles, the distance between the extreme grooves on a pattern test bench that captured charged droplets was measured as the spray W_n, while the accumulated droplets in the collectors are quantified as Q_n droplets. Finally, the ratio of overlap ($n_i n_j$) charged droplets to the total spray distribution was expressed as a uniformity index.

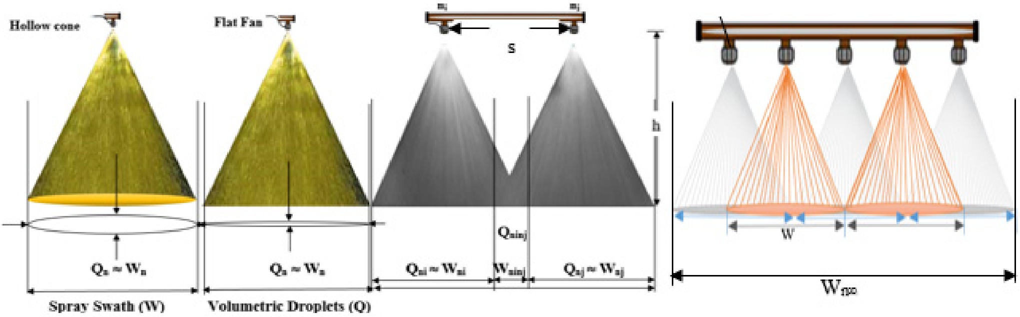

Figure 2: Schematic charged spray swath from Hollow Cone (HC), Flat Fan nozzles (**FF**) and Overlap Spray Swath [S - nozzle spacing, H -spraying height, n_i and n_j- nozzle numbers, $n_i n_j$- overlap spray, 100 % overlap ($n_i n_j = 0.5W_n$); 75 % overlap ($n_i n_j = 0.375W_n$); 50 % overlap ($n_i n_j = 0.25W_n$); 25 % overlap ($n_i n_j = 0.125W_n$) and 0 % overlap ($n_i n_j$=0)].

Data Analysis and Modelling

The overall data on droplet sizes (D_{v01}, D_{v05} and D_{v09}), spray swath (W_n), volumetric (Q_n) droplet distribution and Uniformity index (UI) were subjected to analysis of variance (ANOVA) at 95 % confidence level using Minitab Statistical Software Release 15 (Minitab Inc., 2007). Where necessary, Fisher's pairwise comparison (FPC) test package was used to separate treatment means of the data set. A uniformity index (UI) was modelled using MATLAB statistical software (Version 9.4, R2018a). The results were useful for visualising which parameter combinations produced suitable W_n, Q_n and UI for pesticide spraying.

RESULTS AND DISCUSSION

Charged Pesticide Droplet Sizes and Volumetric spray from Nozzle Types

Figure 3 presents the effect of different nozzle types, application pressures and spraying heights on charged pesticide spray droplet sizes ($D_{V0.5}$). An entrained charged smaller droplet sizes contributed to spray W_n pattern, Q_n droplets distribution and effectiveness of pesticide spraying than in the case of 0 kV. The FF-nozzle produced significantly smaller droplet sizes (67.4 - 79.2 µm) while HC-nozzle gave larger droplet sizes (70.5 - 92.2 µm) irrespective of the spraying height. At each spraying height, droplet sizes significantly decreased with increasing flow pressure, and as flow pressure decreased, the glyphosate spray jet produced large droplet sizes at the breakup point irrespective of the nozzle type, which agrees with the research findings of Appah *et al.* (2019a) and Cerruto *et al.* (2021). The maximum flow pressure of 4 bar yielded fine droplet sizes and more volumetric spray droplets for charged pesticide spraying. Generally, the droplet sizes from both nozzles were within a very fine particulate droplet sizes classification by the ASABE Standard (ASABE, 2020), irrespective of the applied pressure and spraying height in the experiment as in Ferguson *et al.* (2015). The spraying height regime did not significantly affect volumetric droplet distribution for all nozzle types except flow pressure ($p = 0.0003$). Liquid flow pressure of 4 bar, 3 bar and 2 bar respectively produced mean volumetric droplets of 440.0 ml, 410.1 ml, and 340.3 ml from FF-nozzles, and 435.2 ml, 404.2 ml, and 335.1 ml from HC-nozzles per minute.

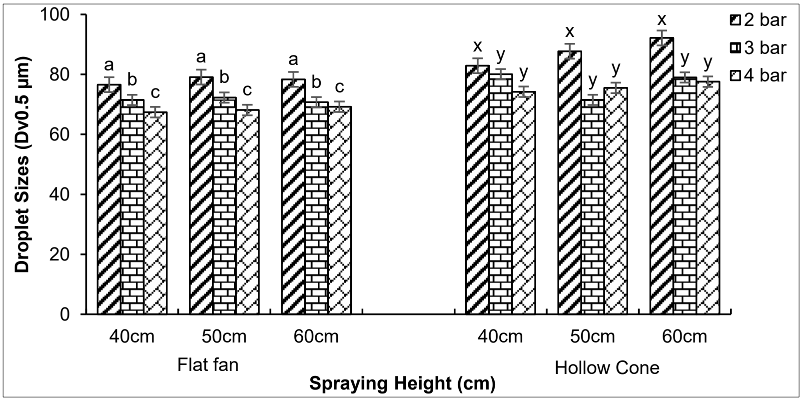

Figure 3: Charged Pesticide Droplet Sizes from Flat Fan (FF) and Hollow Cone (HC) Nozzles at Different Liquid Flow Pressures and Spraying Heights [within each column, means followed by the same letter are not significantly different at α=0.05]

The localisation of charged droplets on substrates is based on droplets minimum variability in the spray jet. The variability of charged glyphosate spray droplet sizes weighed on the basis of relative span (RS) $= [D_{V0.9} - D_{V0.1}]/D_{V0.5}$ in the plume for FF and HC are respectively presented in Table 1, (Ferguson *et al.*, 2015: Appah *et al.*, 2019a). This variability of droplets was not significant under FF-nozzle as compared to HC-nozzle at both spraying height and flow pressures. Hence, flat fan nozzle is considered more suitable for pesticide application than hollow cone nozzle in electrostatic spraying system.

Table 1. Relative Span (RS) of Charged Pesticides Spray Droplet Sizes from FF and HC nozzles at Variable Spraying Heights and Liquid Flow Pressures

Flat fan Nozzle (FF)				**Hollow cone (HC) Nozzle**			
Spraying Height	Relative Span (RS)	Liquid Flow Pressure	Relative Span (RS)	Spraying Height	Relative Span (RS)	Liquid Flow Pressure	Relative Span (RS)
40 cm	0.8694	2 bar	0.8690	40 cm	0.9514	2 bar	0.8046
50 cm	0.8381	3 bar	0.9104	50 cm	0.9040	3 bar	0.8473
60 cm	0.8581	4 bar	0.8961	60 cm	0.8201	4 bar	0.9137
LSD ($p \geq 0.05$)	0.051		0.043		0.110		0.072

Spray Swath (W_n) from Single Nozzle Pesticide Spraying

Pesticide spray swath shows the extent of spray coverage over crops for maximum pesticide droplets to plant contact. The pesticide spray W_n suitability from FF and HC nozzles spraying was investigated at variable spraying height regimes (Figure 4). Nozzle type and spraying height significantly affected pesticide spray W_n during application. Observation from W_n measurement on pattern test bench (5 cm groove interval) showed significantly higher values from FF-nozzle than HC-nozzle at all spraying heights at 8 kV (0 kV control). The spraying H was linearly correlated with respect to spray W_n, as the coefficient of determination (93.65 %) was higher in favour of FF-nozzle than HC-nozzle (85.47 %) at 8 kV (i.e. $R^2_{FF} > R^2_{HC}$). Charged spray swath from flat fan nozzle increased from 130 cm (= 26 grooves × 5 cm) to 185 cm (= 37 grooves × 5 cm), while that of hollow cone nozzle increased from 80 cm (= 16 grooves × 5 cm) to 115 cm (= 23 grooves × 5 cm) respectively upon raising spraying height from 40-60 cm. For uncharged spray swath, the FF value rose from 124.2 cm to 183.0 cm while the HC value rose from 76.5 cm to 114.0 cm at 40 and 60 spraying heights, respectively.

The injection of charge to droplets increased spray swath over uncharged droplets at 40 cm due to minimal atmospheric charge interference compared to a marginal increase at higher spraying height regimes (Appah *et al.*, 2019a). A regression analysis showed that a centimetre increase or decrease in spraying height (H) resulted in a corresponding maximising or minimising charged W_n of FF-nozzle by 27.5, whereas W_n of HC-nozzle was increased or decreased by 17.5. In effect, the charged spray swath from pesticide spraying increased with an increasing spraying height regime no matter the nozzle type. Thanks to electrostatic injection of charges, the repulsive forces between particulate droplets enabled the increase in swath until approaching substrates with opposite charge for coiling and attraction. Therefore, such an optimum parameter combination that would produce the highest swath should be considered in crop protection. The spray W_n was measured based on the distance between the extreme grooves of collectors, C_i and C_n that intercepted spray droplets from each nozzle spraying as in the case of Patel *et al.*,(2016; 2017).

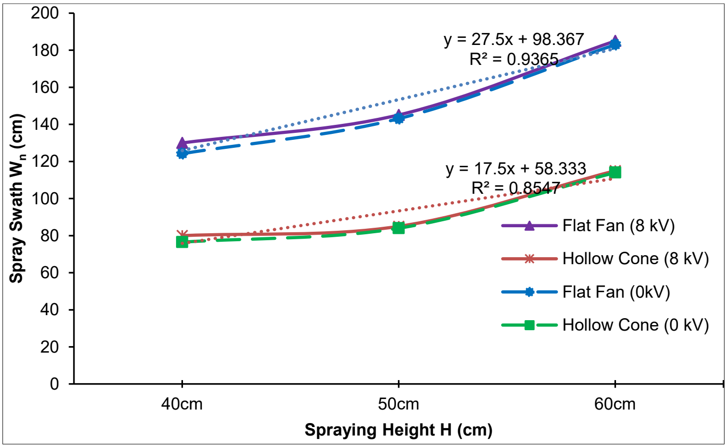

Figure 4. Effect of Nozzle Type and Spraying Height on Charged Spray Swath from Single Nozzle Spraying at 4 bar liquid flow pressure and 8 kV chargeability (control at 0 kV)

Volumetric (Q_n) Droplets Distribution from Single Nozzle Pesticide Spraying

The captured charged volumetric droplets distribution from the spray continuum at respective grooves from the patternator test bench is shown in Figure 5. The total Q_n droplets from each nozzle type at different spraying heights was not statistically different from one another, which conforms to Elwakeel *et al.* (2021). On average, the FF-nozzle yielded a higher Q_n of 951.33 ml compared with the HC-nozzle Q_n of 943.33 ml, corresponding to 7.93 mls^{-1} and 7.86 ml s^{-1}, respectively. Hence, nozzle type determines the volume of application, which confirms that of Legleiter and Johnson (2016). Also, in the experiment, it was observed that the central portion of the spray continuum produced the greater volume of droplets than the peripheral region at all nozzle types, as in the case of Elwakeel *et al.* (2021) for conventional spraying. Hence, a repetition and accumulation of droplets on substrates at central regimes (C_{19}-C_{36}) of both nozzles should be avoided to waste pesticide and enhance the effectiveness of spraying.

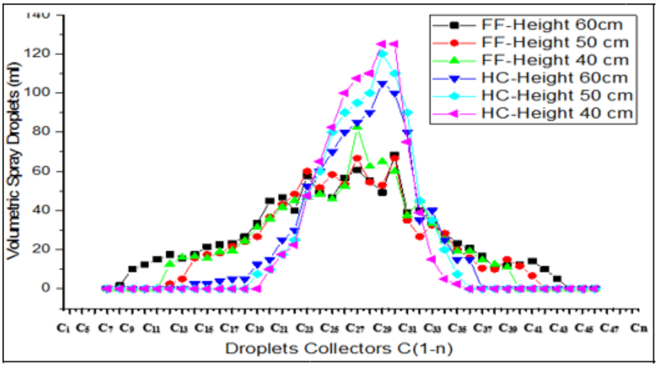

Figure 5: Charged volumetric Pesticide spray Droplets (Qn) Distribution from Single Flat Fan (FF) and Hollow Cone (HC) Spraying Nozzles at Different Spraying Height Regimes in 120s at 4 bar liquid flow pressure (centre of bench at C_{28}).

The charged spray droplets distribution was wider for the FF-nozzle than the HC-nozzle under similar spraying conditions. Though the conical spray pattern gave a greater number of droplets at the centre, the distribution was not wider compared to the flat fan nozzle. As the spray expanded to the extreme ends from the line of symmetry at C_{28}, the volumetric droplets decreased in each groove with respect to a decreasing spraying height for both nozzles. The FF-nozzle had droplet distribution in 37 collectors from $C_8 \leq Q_n \leq C_{44}$, while the HC-nozzle concentrated most droplets within 23 collectors from $C_{14} \leq Q_n \leq C_{36}$ in the spray continuum. From both nozzles, the maximum volume of droplets was obtained between C_{25}-C_{31} (7 collectors), whereas the least was obtained at the regions $Q_n < C_{25}$ and $Q_n > C_{31}$. The differential droplets characterisation could be as a result of the gravitational pull force on the test bench and atmospheric charge interference. Generally, the highest spraying *H* of 60 cm accounted for wider distribution of droplets, whereas 40 cm *H* had peak volumetric droplets of 83 ml (at C_{27}) under FF-nozzle and 125 ml (at C_{28}, C_{29}) under HC-nozzle. This showed that decreasing spraying heights increased volumetric droplets at the central portion of the spray continuum. Therefore, to maximise droplet deposition and uniformity of spray over substrates at the extreme regions, a certain amount of overlap spray at $Q_n < C_{25}$ and $Q_n > C_{31}$ regions corresponding to 25% overlap is required during spraying. This can be obtained by taking into consideration the nozzle *S* and spraying *H* regimes that influence the overlap spray droplets from multiple nozzles on the boom. The pattern of spray from the HC-nozzle makes it unsuitable for pesticide application as compared to the FF-nozzle in electrostatic spraying of pesticide, as the efficiency of spraying and ground coverage is paramount.

Spray Swath and Volumetric Droplets from Multiple Nozzles Spraying

Over the test bench, nozzle n_i was positioned perpendicular to C_{20} while n_j was adjusted at the required spacing on the horizontal boom over the bench. The spray W_n and Q_n droplets distribution in a continuum of multiple nozzles spray was quantified for generalisation and predictive analysis (Figure 2, Figure 6, Figure 7). Depending on the nozzle spacing and spraying height, either overlap ($W_{ninj} > 0$; $Q_{ninj} > 0$) or non-overlap ($W_{ninj} \leq 0$; $Q_{ninj} \leq 0$ spray W_n and Q_n droplets were produced. The W_n and Q_n increased with an increasing nozzle *S* and spraying *H* regimes on the boom for both FF and HC nozzles. In the experiment, FF-nozzle produced atomised fine droplet sizes and more volumetric spray droplets than HC-nozzle (Gaytan *et al.*, 2018). This was contrary to that reported by Bueno *et al.* (2017).

Multiple Nozzle Spray Swath, W_n

In FF-nozzles (Figure 6a), the widest mean W_n of 310 cm (62 grooves × 5 cm) was measured at 120 cm nozzle *S* under a 60 cm spraying *H* regime. There was an overlap swath (W_{ninj}) at each parameter combination, and the degree of W_{ninj} determined the extent of spray W_n. The W_{ninj} decreased with an increasing nozzle spacing at all spraying heights, and it was statistically significant among treatment means. In general, the wider the W_{ninj}, the smaller the non-overlap W_{ni} and W_{nj} portions. Repeating droplet deposition at the overlap regions leads to pesticide wastage and substrate overdose during pesticide spraying; however, in exceeding zero overlap, spray pockets ensued. Therefore, to maximise ground surface coverage, W_{ninj} should be reduced to near zero as droplets are superposed with electric charges. Secondly, in Figure (6b), HC-nozzles produced overlap W_{ninj} at 50 - 75 cm nozzle *S* and 40 cm - 60 cm spraying *H*, as well as overlap W_{ninj} in 100 cm nozzle *S* and 60 cm spraying *H* regime. The remaining parameters yielded non-overlap spray gap $|-W_{ninj}|$ at 100 - 120 cm nozzle *S* under 40 - 60 cm spraying *H* regimes. Overall, the maximum W_n of 215 cm (43 grooves × 5 cm) was obtained at 100 cm nozzle spacing and 60 cm spraying height regime, while the highest non-overlap gap $|-W_{ninj}| = 95$ cm occurred at 120 cm *S* × 40 cm *H*. Such $|-W_{ninj}|$ regions encouraged incoherent and pockets of droplets on substrates during spraying, hence inappropriate for pesticide application. The effectiveness of spraying is based on full surface coverage and chemical efficacy (but efficacy is not considered in this paper). Though W_n from HC was shorter, ensuring an overlap swath in the continuum of spray is desirable for effective application.

Algorithmically, spray swath (W_n cm) was predicted from W_{ni}, W_{ninj} and W_{nj} for 1-*n*th (n ≥ 2) the number of nozzles on the boom, with overlap spray of $0\% < W_{ninj} < 100\%$.

$$\text{For } n=1\ W_{n=1} = W_{n1}\ \text{cm} \qquad \textbf{eqn 3}$$

$$\text{For } n=2\ W_{n=2} = \sum[W_{n1i} + W_{n1n2} + W_{n2j}]\ \text{cm} \qquad \textbf{eqn 4}$$

$$\text{For } n=3\ W_{n=3} = \sum[W_{n1i} + W_{n1n2} + W_{n2} + W_{n2n3} + W_{n3j}]\text{cm} \qquad \textbf{eqn 5}$$

$$\text{For } n=4\ W_{n=4} = \sum[W_{n1i} + W_{n1n2} + W_{n2} + W_{n2n3} + W_{n3} + W_{n3n4} + W_{n4j}]\text{cm} \qquad \textbf{eqn 6}$$

$$\text{For } n=\infty\ W_{n=\infty} = \sum[W_{n1i} + W_{n1n2} + W_{n2} + W_{n2n3} + W_{n3} + W_{n3n\infty} + \cdots + W_{n\infty j}]\text{cm} \qquad \textbf{eqn 7}$$

However, at 100% overlap spray ($W_{ninj}=0.5W_n$); of multiple nozzles on the boom, the swath W_n is determined by the relation;

$$\text{For } n=\infty\ W_n=\infty = \sum[W_{n1i} + W_{n1n2} + W_{n2n3} + W_{n3n\infty} + \cdots + W_{n\infty j}]\text{cm} \qquad \textbf{eqn 8}$$

Where; $W_{n\infty j}$ is the non-overlap region of the final $W_{n\infty}$ nozzle on the boom.

$$\text{For } n=\infty\ (\text{odd})\ W_n=\infty = \sum[W_{n1} + W_{n3} + W_{n5} + \cdots + W_{(2n\infty-1)}]\text{cm} \qquad \textbf{eqn 9}$$

$$\text{For } n=\infty\ (\text{even})\ W_n=\infty = \sum[W_{n1} + W_{n3} + W_{n5} + \cdots + W_{2n\infty} + W_{n\infty j}]\text{cm} \qquad \textbf{eqn 10}$$

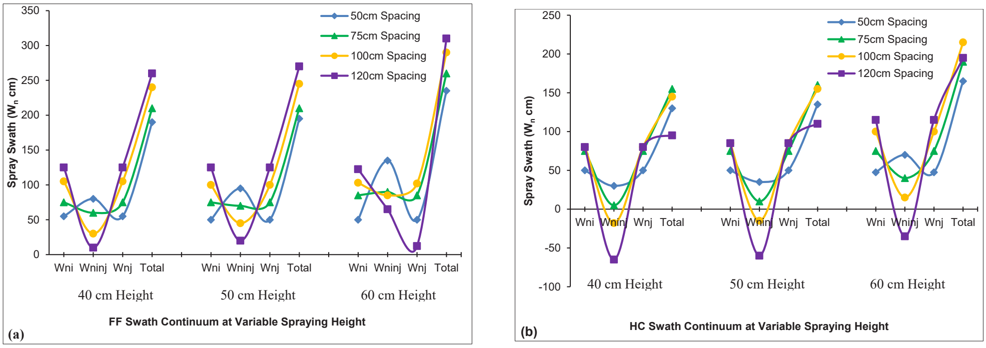

Figure 6: Spray Swath in a continuum of Multiple Nozzles Spraying at different nozzle Spacing and Spraying Heights at 4 bar of (a) Flat fan (FF) nozzles and (b) Hollow cone (HC) nozzles [Note: Negative sign Represents Non-Overlap Gap hence absolute term $|-W_{ninj}|$].

Multiple Nozzles Volumetric (Q_n) Droplets Distribution

The correlation of overlap (Q_{ninj}), non-overlap (Q_{ni}, Q_{nj}) and non-overlap spray gap $|-Q_{ninj}|$ volumetric droplets distribution was forecast. In summary, there was an interrelationship between spray swath (W_n) and volumetric (Q_n) droplets, as wider W_{ninj} indicated more Q_{ninj} volumetric droplets. In all collectors (1-n), the mean recorded volumetric droplets from FF-nozzles was 1915.83 ml, equivalent to 15.97 ml/s, while that of HC nozzles gave 1902.34 ml, corresponding to 15.87 mls^{-1}. The variations in flow rate could be attributed to differences in nozzle type and orifice angle under the same experimental conditions. Under FF-nozzles (Figure 7a), nozzle *S* and spraying *H* were directly proportional to the Q_n droplets distribution. Minimum Q_{ninj} droplets of 118 ml were collected at 120 cm *S* x 40 cm *H* and a maximum of 1805 ml Q_{ninj} droplets was recorded at 50 cm *S* x 60 cm *H*. Comparatively, the 75 cm nozzle spacing produced a uniform overlap Q_{ninj} droplets distribution across all spraying heights. In effect, decreasing nozzle S and spraying H, invariably increased the overlap spray droplets; a phenomenon prone to over-concentration of pesticide spray on substrates to affect spraying efficiency (Appah *et al.*, 2020). In contrast, there was an unusual droplet distribution from HC-nozzles due to an non-overlap gap in the spray continuum (Figure 7b). There was no droplet harvest in the Q_{ninj} region at 100 – 120 cm spacing and 40 cm – 60 cm spraying heights. These pockets of null droplets deposition make it unsuitable for pesticide spraying at those respective spraying parameters. Allowing overlap droplet deposition by choosing suitable nozzle spacing and spraying regime is ideal for pesticide spraying efficiency (Elwakeel *et al.*, 2021).

Arithmetically, as Q_{ninj} approaches zero, the nozzles on the boom are said to be spraying non-overlap, but increasing the values of $Q_{ninj} > 0$ maximises overlap spray droplets at different parameter combinations. The volumetric droplets distribution for 1-nth ($n \geq 2$) number of identical nozzles on a boom spraying at $0\% < Q_{ninj} < 100\%$ overlap is deduced.

For n=1 $Q_{n=1} = Q_{n1}$ ml **eqn 11**

For n=2 $Q_{n=2} = \sum[Q_{n1} + Q_{n1n2} + Q_{n2}]$ ml **eqn 12**

For n=3 $Q_{n=3} = \sum[Q_{n1} + Q_{n1n2} + Q_{n2} + Q_{n2n3} + Q_{n3}]$ ml **eqn 13**

For n=∞ $Q_{n=\infty} = \sum[Q_{n1i} + Q_{n1n2} + Q_{n2} + Q_{n2n3} + Q_{n3} + Q_{n3n\infty} + \cdots + Q_{n\infty} + Q_{n\infty j}]$ ml **eqn 14**

Similarly, spraying at 100% overlap spray of multiple nozzles on the boom, Q_n is computed;

For n=∞ $Q_{n=\infty} = \sum[Q_{n1} + Q_{n1n2} + Q_{n2n3} + Q_{n3n4} + Q_{n4n\infty} + \cdots + Q_{n\infty} + Q_{n\infty j}]$ ml **eqn 15**

Where is the non-overlap region of the nozzle on the boom.

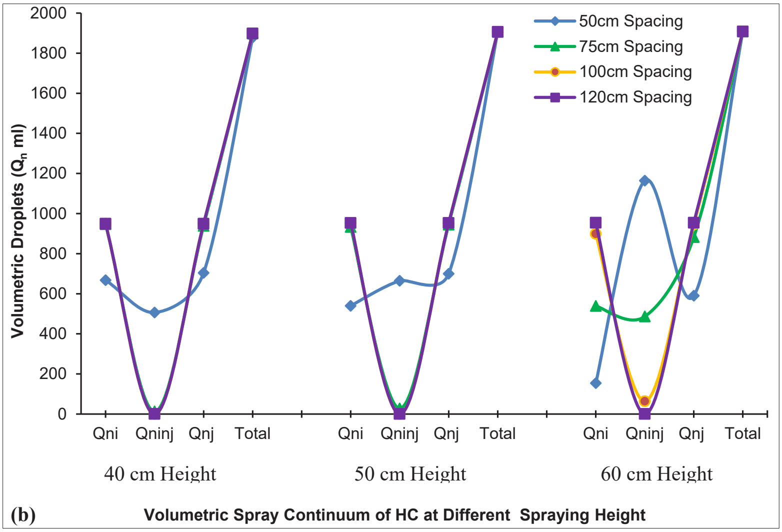

Figure 7: Volumetric Droplets in a Continuum of two Nozzles Spraying at different Nozzle Spacing and Spraying Height at 4 bar of (a) Flat fan (FF) and (b) Hollow cone (HC)

Spray Uniformity Index (UI) of Multiple Nozzle Spraying

The uniformity of spray swath and volumetric droplet distribution (absolute values) depends on the overlap span region in the continuum of spraying (Appah *et al.*, 2020). The Uniformity Index of spray swath (W_n) patternation (Figure 8) and volumetric (Q_n) droplet distribution (Table 2) were computed from Equation 9 and 10 respectively; as a ratio of overlap spray droplets to the total spray plume. The UI is a measure for spray uniformity assessment of droplets distribution at different nozzle spacing and spraying height regimes. The allowable range for pesticide spraying was wider in a flat fan nozzle than hollow cone nozzle at all parameter settings. Also, spraying at approximately 100 % overlap (*red zone*) increased Q_n droplets distribution and, at 0 % non-overlap gap (*light green*) ensues spray pockets in the continuum of pesticide application.

$$\text{Spray Swath Uniformity Index } (W_n\text{UI}) = \left|\frac{W_{ninj}}{\sum(W_{ni}+W_{ninj}+W_{nj})}\right| \qquad \textbf{eqn 16}$$

$$\text{Volumetric Droplets Uniformity Index } (Q_n\text{UI}) = \left|\frac{Q_{ninj}}{\sum(Q_{ni}+Q_{ninj}+Q_{nj})}\right| \qquad \textbf{eqn 17}$$

In the FF-nozzle spraying at different *S* and *H*, an allowable limit for charged pesticide spraying ranged from $0.04 \leq W_n\text{UI} \leq 0.57$ (Figure 8a). The spraying *H* of 50 cm and nozzle *S* of 75 cm produced 100 % overlap at $W_n\text{UI} = 0.33$. As W_nUI increased above 0.33 (*red*), the W_n decreased in the continuum of spraying, whereas decreasing the $W_n\text{UI} < 0.33$ significantly increased the W_n span until W_nUI approached zero. Generally, W_nUI was inversely proportional to the W_n such that smaller W_nUI connotes wider W_n. The widest W_n occurred at a region where W_nUI = 0.04 at 120 cm nozzle *S* and 40 cm spraying *H*, whereas the shortest W_n was measured as W_nUI = 0.57 at 50 cm nozzle spacing and 60 cm spraying height. The ideal W_nUI for pesticide spraying is determined based on the Q_n droplets produced at the overlap regions (Appah *et al.*, 2020). There was no non-overlap gap in the continuum of spray at the respective parameter combinations during FF-nozzle spraying on the patternator test bench. Similarly, W_nUI influenced the W_n of the HC-nozzle in the spraying process (Figure 8b). The longest swath, W_n for HC-nozzle was measured as W_nUI = 0.07 at 100 cm *S* × 60 cm *H*, whereas the shortest W_n, was recorded as W_nUI = 0.23 at 50 cm *S* × 40 cm *H*. Less than W_nUI of 0.03 (*light green*) at 75 cm *S* × 40 cm *H* emanates a non-overlap gap, indicating that spraying could be done with an HC-nozzle within the range of 0.03 ≤ W_nUI ≤ 0.42.

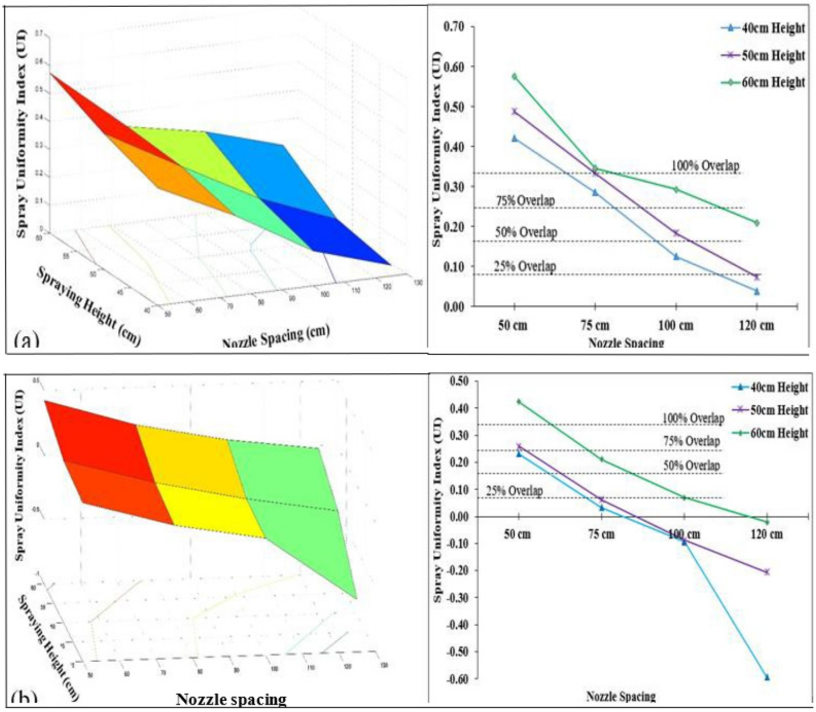

Figure 8: Overlap Spray Swath Uniformity Index (WnUI) of (a) Flat fan nozzle spray swath and (b) Hollow cone nozzle spray Swath [Note: Negative sign Represents Non-Overlap Gap hence absolute term$|-W_{ninj}|$], [100% overlap (red-apricot), $n_i n_j$ = 0.3 < UI ≤ 0.4; 75% overlap (lemon/gold), $n_i n_j$ = 0.2 < UI ≤ 0.3; 50% overlap (emerald-yellow), $n_i n_j$ = 0.1 < UI ≤ 0.2; 25% overlap (Olympic-blue), $n_i n_j$ = 0 < UI ≤ 0.1 and 0% overlap (light green), $n_i n_j$ = UI ≤ 0].

The results in Table 2 show that the volumetric droplets (Q_n) distribution from flat fan and hollow cone nozzles correspond to the Uniformity Index (UI) of the overlap spray droplets in the spray continuum. When the volumetric uniformity index (Q_nUI) is greater than 0.4, there is *overlap* and over-concentration of droplets on substrates from overlap spray of n ≥ 2 but Q_nUI ≤ 0 presents incoherent spray continuity on surfaces. It is therefore appropriate to spray pesticide within the 100 % spray overlap, 0 < Q_nUI ≤ 0.4 zone.

Table 2. Uniformity Index (UI) of the Volumetric Q_n Droplets from Flat Fan (FF) and Hollow cone (HC) nozzles [$0.3 < UI \leq 0.4$ (100 % overlap); $0.2 < UI \leq 0.3$ (75 % overlap); $0.1 < UI \leq 0.2$ (50 % overlap); $0 < UI \leq 0.1$ (25 % overlap); $UI \leq 0$ (0 % overlap) and $UI \geq 0.4$ (*overlap* and over concentration of droplets).

Proportion of Volumetric overlap droplets						
Nozzle Spacing	FF Nozzle Spraying Height			HC nozzle Spraying Height		
	40 cm	**50 cm**	**60 cm**	40 cm	50 cm	60 cm
50cm	0.64	0.77	0.87	0.27	0. 35	0.61
75cm	0.42	0.47	0.57	0.01	0.01	0.25
100cm	0.12	0.18	0.43	NA	NA	0.03
120cm	0.03	0.05	0.23	NA	NA	NA

Note: NA means Not Applicable, which indicates non-overlap regions without droplets

From flat fan nozzles, a Q_nUI of 0.03 and 0.05 relate to pesticide spraying at less than 25 % overlap in the 120 cm *S*; 40 cm - 50 cm *H*, while Q_nUI of 0.12 and 0.18 indicates spraying between 25 % and 50 % overlap droplets at 100 cm *S*; 40 cm-50 cm *H*. Since charges are involved, ensuring relatively minimum uniformity index is ideal to enhance uniformity and efficiency of spraying. Considering W_n and Q_n for effective pesticide spraying, it is recommended to spray at 100 cm S x 50 cm *H* using FF-nozzles. Consequently, HC-nozzles should be used effectively at Q_nUI = 0.25 corresponding to 75 cm *S* x 60 cm *H* to achieve 75 % overlap spray. Spraying at $Q_n UI \leq 0$ leaves pockets of droplet deposition making it inappropriate for pest management programmes in plant protection. The overall effect was that as droplets were superposed with entrained charges to produce smaller droplet sizes, they yielded repulsion in the spray plume, hence, producing wider spray swath. Also, the polarity of the droplets does not necessarily require spray overlap and droplet accumulation on substrates to reduce chemical wastage. With interference of environmental wind factors and prevention of non-spray pockets, a maximum of 25 % overlap would be a novel in pesticide application. A technology desired to applicators to maximise coverage without drift to non-target substrates at a reduced application rate (Appah *et al*, 2019c).

CONCLUSION

The objective of the study was to determine the effects of in-situ charged pesticide spray on total spray swath (W_n), volumetric droplet distribution (Q_n) and uniformity index (UI) in a continuum of spraying at variable nozzle types, nozzle spacing (S) and spraying height (H) regimes, under constant applied voltage of 8 kV. Glyphosate *N*-[(phosphonomethyl) glycine] pesticide droplets were superposed with 8 kV applied voltage from a developed induction nozzle cap. An observation made was that, flat fan nozzle produced smaller droplet sizes ($D_{V0.5}$ = 73.3 µm), maximum spray swath of 185 cm (37 collectors × 5 cm) and higher volumetric droplets (7.93 ml s^{-1}), while hollow cone nozzle yielded bigger droplet sizes ($D_{V0.5}$ = 81.5 µm), minimum spray swath of 115 cm (23 collectors × 5 cm) and lower volumetric droplets (7.86 mls^{-1}). The measured spray W_n and Q_n indicated the need to adopt FF-nozzles for electrostatic pesticide spraying. To reduce pesticide spray overlap on substrates, FF-nozzles should be mounted at 50 cm H × 100 cm S or HC-nozzles at 60 cm H × 75 cm S on the boom at 4 bar flow pressure and superposed charges to spray droplets.

A Uniformity Index allowed FF-nozzles to be sprayed at 0.4 ≤ UI ≤ 0.57, whereas HC-nozzles were permitted at 0.3 ≤ UI ≤ 0.42 zone. The index determines both spray swath and volumetric droplet distribution on the boom. An overlap spray swath UI = 0.33 produced 100 % overlap at FF-nozzles spacing of 75 cm by 50 cm height, whereas an non-overlap swath gap from HC-nozzles occurred at UI ≤ 0 in 100 cm-120 cm spacing and 40-60 cm heights. Spraying from FF-nozzles at 0.12 ≤ UI ≤ 0.18 yielded uniformity of Q_n droplet distribution, while that of HC-nozzles was effective at UI = 0.25, corresponding to 25 % - 50 % spray overlap. FF-nozzle should be mounted at 50 cm *H* × 100 cm *S* or HC-nozzle at 60 cm *H* ×75 cm *S* on the boom to reduce pesticide wastage from overlap application. Spraying above 100 % overlap (UI > 0.33) increased volumetric droplet overdose and application rate, while below 25 % overlap (UI < 0.08) decreased the efficiency of pesticide spraying. Superposing charges on spray droplets creates repulsive forces between particulate droplets to maximise spray swath and droplet accumulation on substrates, an innovation appreciated by pesticide users in crop protection. The entrained droplet charges facilitate droplet-substrate attraction and pinning to reduce chemical wastage at a minimum application rate. The results of the experiment are useful for reducing spray overlap on substrates, and ensuring maximum spray coverage, timeliness and efficiency of pesticide spraying.

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DISCLOSURE OF INTEREST

We, the Authors, declare that, there is no competing interest whatsoever from both financial and non-financial sources, hence the article stands without any external interference.

Data Availability

There is no data availability and link to this manuscript as analyses are presented in the manuscript for easy readability and presentation.

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