Journal of Scientific & Industrial Research
Vol. 81, January 2022, pp. 5-12

Studies on Operational and Plant Parameters Affecting the Deposition of Charged and Uncharged Spray Droplets on Cabbage Plant Canopy

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Received 23 January 2021; revised 26 November 2021; accepted 02 December 2021

The existing method of pesticide application has resulted in wastage of chemicals and environmental pollution. Electrostatic spray charging system for impregnation of charge on spray droplets and its subsequent transfer to the precise plant target can mitigate the problems in conventional spraying. The operational parameters of spraying system and plant characteristics play an important role in deposition of spray droplets on plant canopy. In view of that, an experimental electrostatically spray charging system was developed to assess the deposition on plant surface. At electrode voltage (4kV), flow rate (250 ml/min) deposition was maximum for forward speed (1.0 km/h) and height of application (0.55 m) at charge to mass ratio of 1.53 mC/kg.

Keywords: Charge to mass ratio, Electrode voltage, Electrostatic, Pesticides, Plants

Introduction

Pesticides are important component of agricultural production system to enhance the production and quality of crops.[1] Pesticides are mainly applied in atomized droplets ranging from 50-500 µm. Researchers have developed various pesticide application equipments for control of pest based on climatic conditions, width of coverage and plant configurations. In India, water based sprayers are mainly used for disease, weed and pest control, where atomization of liquid is imparted through hydraulic, air assisted or centrifugal force. The conventional spraying system produces beneficial results as long as recommended volume and doses of pesticide formulation is used in pesticide application.[2–3] This conventional method of applying pesticide is ineffective considering excessive pesticide requirement in practice than the theoretical recommended dosage.[4]

Pesticide application through conventional methods can often lead to excessive wastage of chemicals causing environmental pollution by off target deposition of spray chemicals. The existing methods of chemical application on plant surface often result in only 20% deposition of spray droplets on the intended target.[5] Increased cost of chemicals, environmental concerns and risks to the human health have stressed researchers around the world for improvement in existing methods of chemical application for safe and on target dispensing of spray chemicals.

Electrostatic charging of the spray droplets can be a viable option for mitigating the above mentioned problems. Electrostatic charging of spray droplets can result 1.5 to 2.5 folds of deposition compared to uncharged droplets.[6] In the past few decades several studies have been conducted to understand the fundamentals of atomization and imparting of charge on the spray droplets for chemical application in agriculture.[7–11] Charge impingement of spray droplets by virtue of electrostatic forces requires smaller droplets to overcome gravitational forces to enhance deposition with reduced drift.[12–17] Furthermore, researchers discovered that charged spray droplets have a higher rate of deposition, distribution, penetration, and biological efficacy than uncharged spray droplets.[10] The electrostatic sprayers are efficient in deeper penetration and full coverage of plant canopy in addition to prevention of off target drift and environmental wastage of spray pesticides.[18,19]

In India, the spraying operation in horticultural crops remains a challenge due to diversity in canopy size, shape and orientation. The existing conventional

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air assisted sprayers have remained incapable for addressing the pest and diseases attacks in horticultural crops, where pest infestation mainly occurs in underside (abaxial) of leaf surface. The advantages of electrostatic sprayer over conventional air assisted sprayer can serve the purpose by underside deposition of spray droplets and minimised air drift. Despite the fact that most research on charged spray droplets and their effect on deposition has been published, no significant work has been done to understand the effect of operational parameters and their interactions on spray droplet deposition on the adaxial and abaxial surfaces of the plant target. As a result, the purpose of this research is to determine the impact of operational parameters on the deposition and droplet density of charged spray droplets. The deposition characteristics of charged spray droplets will be helpful for understanding the target parameters for better deposition efficacy and reduced wastage of chemicals.

Materials and Methods

Experimental Test Setup for Deposition Measurement of Charged and Uncharged Spray Droplets

An experimental electrostatic spray charging system was developed to assess the deposition on plant surface. The charging system was mounted on the main frame placed over a movable trolley system driven by a variable induction motor (Fig. 1). The electrostatic spray charging system had an induction charging nozzle, high voltage generator (Output voltage: 15kV, Power: 35W), liquid spray tank, hydraulic pump, pressure control valve, flexible hose connections and 12 VDC supply. The induction spray charging nozzle was connected at the end of the hose. The induction charging nozzle consisted of circular copper electrode was axially mounted around a high pressure hydraulic nozzle. The spray liquid was atomized into spray droplet near the orifice of nozzle into droplets of 52–250 µm at a flow rate of 250 ml/min and pressure of 60 psi.

The circular electrode received a strong electric potential from the high voltage generator. Charges were transferred to spray droplets around the droplet formation zone as a result of the electric field acting between the electrode and the spray jet. The outlet of the spray tank was fitted with a 12VDC hydraulic pump of 4 l/min flow rate capacity and pressure of 100 psi. The spray liquid with specified properties was atomized using the hydraulic pressure provided by the pump, Table 1. Discharge of the induction charging nozzle was regulated by the pressure regulating valve of 150 psi. Spray lance of the spraying system was at a desired angle of 45° to the horizontal. The electro mechanical properties of water used for electrostatic charging are shown in Fig. 1.

To adjust height of the nozzle from the leaf surface hydraulic jacks were provided at adjacent ends of the main frame actuated by wheel placed at the center of the frame. The heights of the nozzle from the leaves' top surface were varied at 1.15, 0.85 and 0.55 m respectively. The forward motion to the main frame along with the sprayer unit was delivered by means of endless rope and pulley system, driven by an electric motor of 7.5 kW. This three phase variable induction motor was coupled with variable speed AC drive to set the forward speed of operation at selected levels of speed namely 1.0, 1.5 and 2.0 km/h. The selected speed was achieved by varying the frequency of the variable speed drive (Fig. 2).

A series of artificial cabbage plants were created to simulate field circumstances in the laboratory in order to examine spray deposition properties of

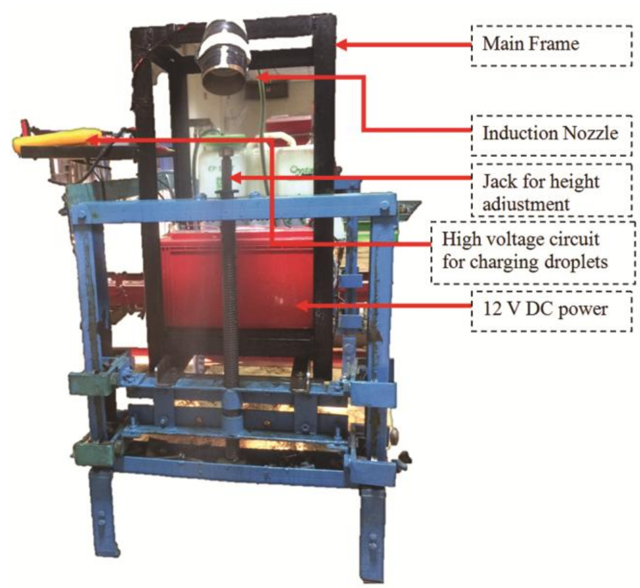

Fig. 1 — Experimental Induction based electrostatic sprayer for evaluating operational parameters using soil bin

Table 1 — Electro mechanical properties of water

S. No	Electro-mechanical properties	Value
1.	Density, kg/m^3 (ρ)	1056.84
2.	Viscosity, kg/m/s (µ)	0.92103
3.	Surface tension, N/m (Γ)	0.07201
4.	Electrical Conductivity, µs/cm (σ)	563
5.	Dielectric Constant (ε)	80.5

Fig. 2 — Experimental setup to study effect of operational parameters on deposition efficiency of spray droplets on artificial leaves

spray droplets on electrically and geometrically homogeneous plant targets. The Pusa Sugandha variety was used to create typical cabbage plant leaf proportions. Aluminum sheet, 0.5 mm thick, was used to create artificial leaves (Fig. 3). Aluminum had strong conductivity for charge flow and was malleable enough to allow the leaf to be positioned at various angles. Six artificial leaves were put as a plant branch on an aluminum pole. To support the target at ground level, the entire artificial plant assembly was installed on a 4.0 mm thick mild steel rectangular base. The artificial plants were spaced 50 cm apart, as specified by the agronomist. Each branch's leaves faced the horizontal surface at 30° above, 0°, and 30° below. With the use of a goniometer, the artificial leaves were bent at a specific prescribed angle. The grounded artificial plants provided a potential difference for charged spray droplets and homogeneous distribution over the plant canopy.

Experimental Parameters

A factorial experiment was designed to estimate the deposition characteristics of the charged and uncharged spray droplets on artificial cabbage plant. The factors namely forward speed (S), height of the nozzle from leave surface (H), Orientation of leave (O) and leaf surface (L) were selected for the experiment. All the experiment was conducted at the discharge rate of 250 ml/min, electrode voltage of 4.0 kV and liquid pressure of 60 psi which produced a CMR of 1.53 mC/kg. The spray angle of the spray lance was set at 45° from the horizontal to dispense spray liquid at uniform nozzle orientation.

Fig. 3 — Adaxial and abaxial deposition of spray liquid on water sensitive paper attached to artificial cabbage leaves

Quantification of Spray Deposits

Water Sensitive Paper (WSP) was used to measure the spray deposition on the intended artificial plant targets. To extract the spray deposits, water sensitive sheets (WSP) with a sampling area of 76 × 36 mm were placed on the centre of the adaxial and abaxial surfaces of the target plant. As a result, 18 samples were taken from each plant at a specific height, with three orientations, two leaf surfaces, and three forward speeds being used. The WSP was allowed to dry after each experimental run before being sampled based on the treatment combination specified at the bottom with marker. The samples were scanned on an HP Scanjet scanner (hardware resolution: 480° × 960° dpi, 48 bit, and optical resolution: 120° (dpi) at 60° dpi) and saved as BMP image files. IMAGEJ software (Open source: Java-based image processing tool that can display, edit, analyze, process, save, and print 8-bit colour and grayscale, 16-bit integer, and 32-bit floating point pictures) was used to analyze the BMP files.

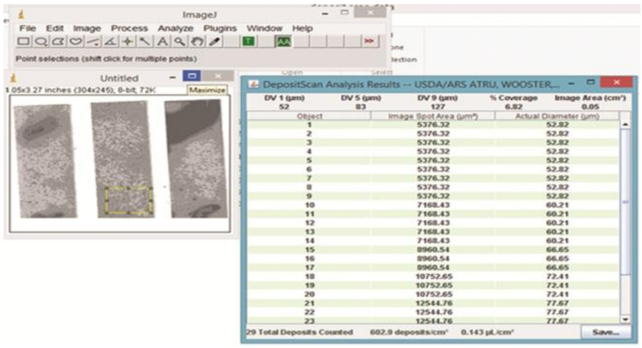

Fig. 4 — Estimation of deposition efficiency using Deposit Scan

The analysis of WSP in IMAGEJ software gave the spray deposition parameters like NMD, droplet density, and cover percentage and deposition efficiency for both charged and uncharged droplets. The number median diameter (NMD) is calculated by using the statistical formula of finding median of a grouped data using the following formula.

$$NMD = L_m + \left[\frac{\frac{n}{2} - F}{f_m}\right] i \qquad \dots (1)$$

The droplet density is defined as the number of droplets per square centimetre of the leaf area (droplets/cm^2).

$$\text{Droplet density} = \frac{\text{Number of droplets in the frame}}{\text{Frame area (cm}^2)} \qquad \dots (2)$$

Results and Discussion

Spray Deposition as Influenced by Forward Speed of Operation

The spray deposition of charged and uncharged spray droplets on adaxial and abaxial surface of plant canopy at varying speed of 1.0, 1.5 and 2.0 km/h are shown in Figs 5 & 6. The deposition of droplets decreased with increase in forward speed for both charged and uncharged spray droplets at different height of plants. Maximum deposition of 2.23 µL/cm^2 and 1.89 µL/cm^2 was observed at speed of 1.0 km/h for both charged and uncharged spray droplets respectively (Figs 5 & 6). The maximum value of abaxial deposition of 0.142 µL/cm^2 was observed at speed of 1.0 km/h height of 0.55m. The plots for charged droplets showed a linear decreasing trend with the increase in speed. In general, the response of deposition at selected forward speed was linearly decreasing with increase in forward speed. The deposition for charged spray droplets varied from 2.23–1.11 µL/cm^2 and 0.2–0.019 µL/cm^2 for adaxial and abaxial surface respectively. The results illustrated higher deposition at lower forward speed. It was attributed to the fact that, at lower forward speed the exposure time of leaf surfaces to the spray

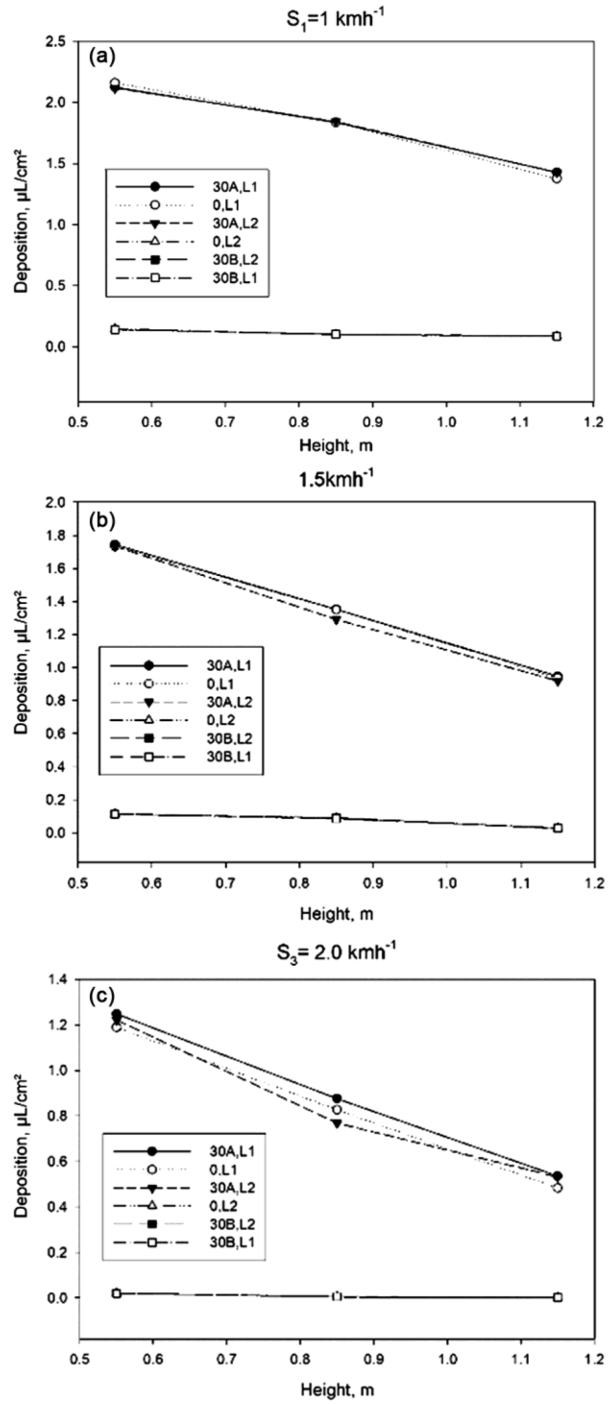

Fig. 5 — Effect of height on deposition of charged spray droplets at speed of (a) 1.0 kmh^{-1} (b) 1.5 km h^{-1} and (c) 2.0 km h^{-1}

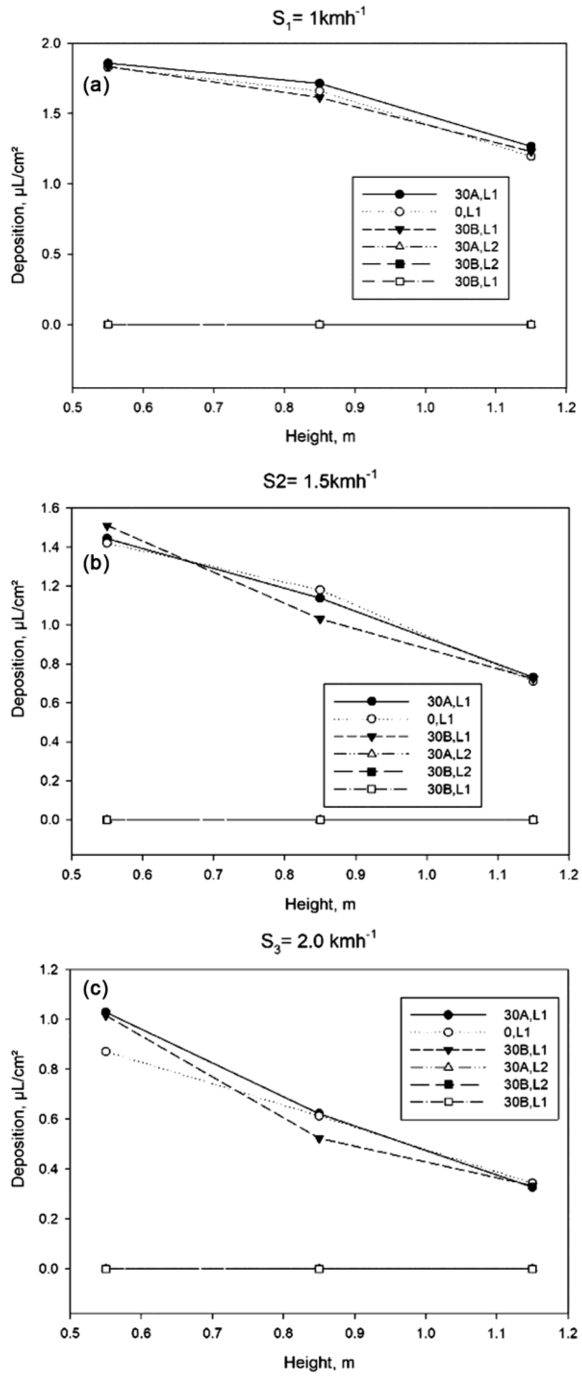

Fig. 6 — Effect of height on deposition of uncharged spray droplets at speed of (a) 1.0 kmh^{-1} (b) 1.5 km h^{-1} and (c) 2.0 km h^{-1}

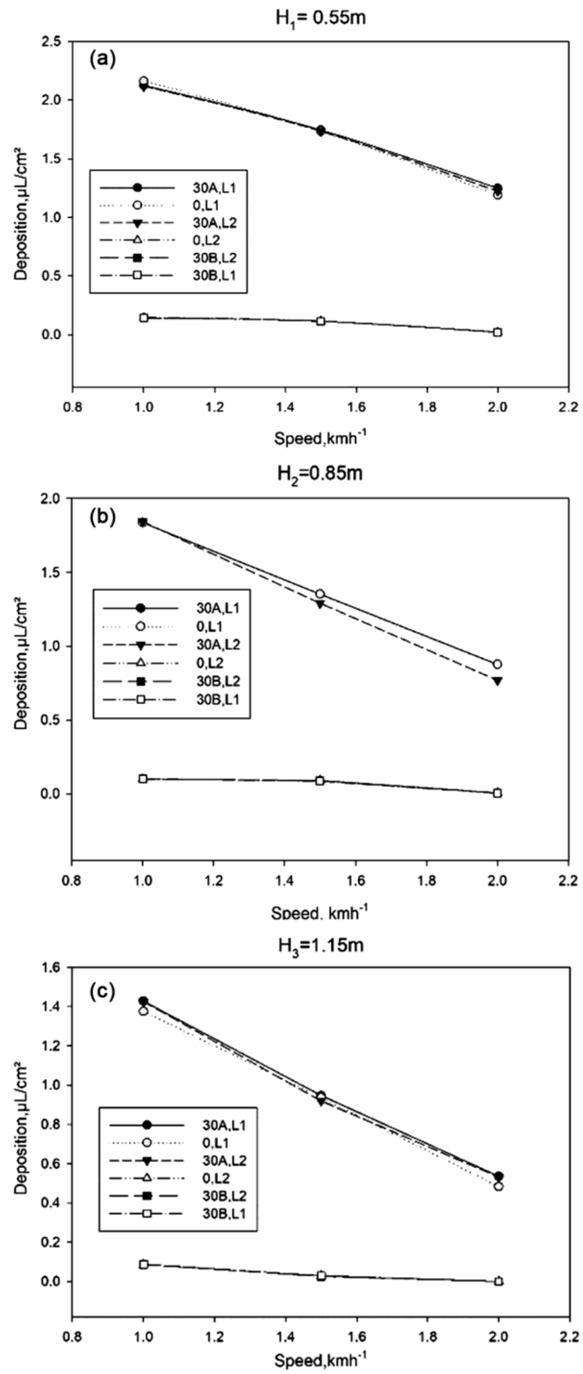

Fig. 7 — Effect of speed on deposition of charged spray droplets at height of (a) 0.55m (b) 0.85m and (c) 1.15m

droplets was higher. In general; the charging of spray droplet resulted in higher deposition of droplet on abaxial and adaxial surface for charged spray droplets. Symmetrical factorial completely randomized statistical design was used for data analysis using SAS software.

It was observed that the deposition of spray droplets for adaxial surface varied from 2.23–0.462 µL/cm^2 and 1.89–0.237 µL/cm^2 for charged and uncharged spray droplets respectively, Figs 7 & 8. Underside deposition of spray droplets at lower heights was significant due to the wrap around effect by the attraction of the charged spray to the underside of the leaves surface. In case of uncharged spray droplets the underside deposition was almost zero. This behaviour

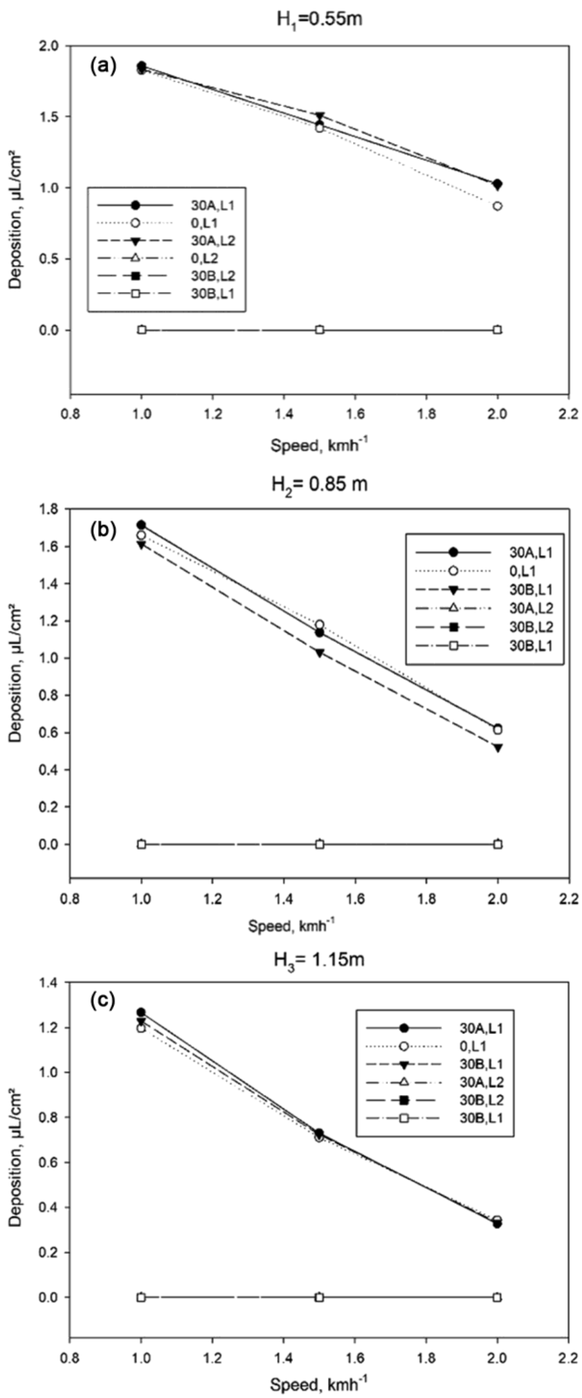

Fig. 8 — Effect of speed on deposition of uncharged spray droplets at height of (a) 0.55m (b) 0.85m and (c) 1.15m

of uncharged sprays was anticipated because in absence of electric force the drag and lift forces acting on the tiny spray droplet results in off target displacement of the atomized spray particles.

In general, the deposition of spray droplets decreased with increase in application height of sprayer for charged and uncharged spray droplets. The deposition was maximum at lower application height due to the fact that, at lower application height the charged and uncharged spray droplets travel minimum distance to reach the target. Therefore, lower application height ensures smaller travel distance resulting in maximum deposition of spray droplets. Hence, the application height of 0.55 m yielded higher deposition at selected levels of forward speed, orientation of leaf and leaf surface. The depositions of spray droplets were affected by orientation of leaf. This relation was investigated for selected levels of leaf orientation namely 30° above horizontal, 0° with horizontal and 30° below horizontal. The adaxial and abaxial deposition of charged and uncharged spray droplets varied between 2.32–1.41, 1.70–0.909, 1.24–0.462 µL/cm^2 and 1.89–0.854, 1.802–0.426, 1.32–0.3647 µL/cm^2 respectively, at forward speed of 1.0, 1.5 and 2 km/h.

Effect of Leaf Orientation on Deposition of Charged and Uncharged Spray Droplets

The responses of deposition to the target orientations were similar for all selected levels of orientation for selected levels of speed, height and leaf surface. The deposition on the adaxial surface was more with flat surface (0° from horizontal) compared to 30° above and below the horizontal. This may be due to elliptical cross section at 0° the leaf surface induced higher deposition, whereas at 30° above the horizontal the target was perpendicular to the spray path and it was parallel to the spray path at 30° below horizontal. The maximum deposition of 2.23, 2.17 and 2.13 µL/cm^2 was observed for 30° above, 0° and 30° below at speed 1.0 km/h, Fig. 9a.

Effect of Leaf Surface on Deposition of Charged and Uncharged Spray Droplets

At application heights of 0.55 m, 0.85 m, and 1.15 m, the deposition of charged spray droplets ranged between 2.23–1.11, 1.80–0.67, and 1.41–0.52 L/cm^2. With increasing application height, the bar chart plotted between deposition and leaf orientation for a given leaf surface exhibited a declining trend in adaxial deposition. At 0.55 m application height, 1.0 km/h forward speed, and 30° above horizontal leaf orientation, the maximum adaxial deposition of 2.23 L/cm^2 was observed. Uncharged spray droplets followed the same pattern. At application height, forward speed, and leaf orientation of 1.15 m, 2.0 km/h, and 30° below horizontal, respectively, the minimal adaxial deposition of 0.247 L/cm^2 was

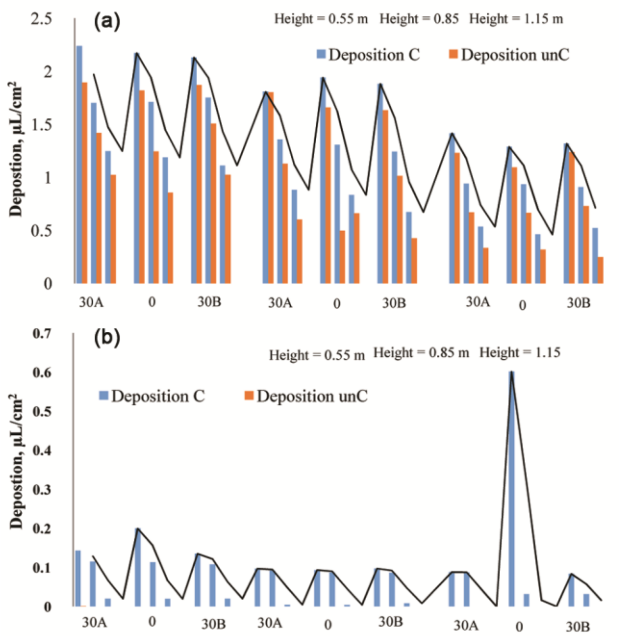

Fig. 9 — Effect of target height and orientations on (a) adaxial and (b) abaxial deposition of charged and uncharged droplets

recorded (Fig. 9b). Charge spray droplets had much stronger adaxial deposition than uncharged spray droplets in general. For charge spray droplets, the abaxial deposition ranged from 0.14 to 0.0316 L/cm^2. Uncharged spray droplets did not have any abaxial deposition. This demonstrates that an increase in deposition on the leaf's underside has resulted in a similar decrease on the adaxial surface. Due to the electrostatic force, a portion of the applied droplets deviated their route towards the underside of the target. At a speed of 1.0 km/h and a height of 0.55m, the greatest abaxial deposition of 0.142 L/cm^2 was measured.

SAS software was used to analyse the data using a symmetrical factorial totally randomised statistical approach. At a 1% level of significance, the statistical analysis on deposition established the effect of primary parameters on deposition of charged spray droplets. At the 1% level of significance, the interaction between speed and leaf surface, as well as leaf orientation and leaf surface, was found to be significant. The spray droplet deposition was unaffected by the application height. When the application height was reduced, the interaction between speed and leaf orientation gradually gained relevance. Because of the varying exposure area of the target to the spray swath, the orientation of the leaf as a key component influenced spray droplet deposition significantly. The deposition of spray droplets on leaf surfaces was similarly influenced by forward speed, as evidenced by the fact that the interaction between speed and leaf surface was significant at the 1% level of significance. The overlapping of deposition responses in the graphical analysis led to the conclusion that the interaction impact of the primary components was non-significant. In contrast to the results obtained from graphical analysis, Table 2, statistical analysis revealed that the interaction of leaf orientation and leaf surface with forward speed was significant at 1% of significance.

Table 2 — Analysis of Variance for deposition at selected operational parameters

SV	SS	df	MSS	F	p Value
Model	27.39	14	1.96	240.79	< 0.001
S–Speed	2.90	1	2.90	356.73	< 0.001
H–height	0.013	1	0.013	1.60	0.2132
O–Orientation of leaf	1.31	2	0.66	80.76	< 0.001
L–leaf surface	20.33	1	20.33	2502.18	< 0.001
S*H	1.917E−03	1	1.917E−03	0.24	0.6299
S*O	2.514E−03	2	1.257E−03	0.15	0.8572
S*L	1.47	1	1.47	181.39	< 0.001
H*O	9.085E−05	2	4.542E−05	5.590E−03	0.9944
H*L	7.966E−03	1	7.966E−03	0.98	0.3282
O*L	1.35	2	0.67	83.02	< 0.001
Residual	0.32	39	8.126E−03		

The results were in confirmation with the above results. Linear term (speed, orientation and leaf surface) of the model had highly significant effect on deposition as associated p–value was less than 0.01. The effect of interactive terms had significant effect on the deposition of spray liquid. The model had adjusted R–square 0.9844 due to other non-significant interactive terms of the model.

Conclusions

An experimental induction based electrostatic spraying system was developed to study the effect of operational (forward speed (S), height of application (H)) and plant (Leaf orientation (O) and leaf surface (L)) parameters on deposition of charged and uncharged spray droplets on plant canopy. Based on the results following conclusions were made

1. The forward speed of application had a significant effect on deposition of charged and uncharged spray droplets, the best forward speed and spray height being 1.0 km/h, and 0.55 m respectively resulting in abaxial deposition of 0.142 µL/cm^2 for charged spray droplets.

2. The deposition of spray droplets for adaxial surface was from 2.23– 0.462 µL/cm^2 and 1.89–0.237 µL/cm^2 for charged and uncharged spray droplets, respectively. The adaxial and abaxial deposition was significant for charged spray droplet for CMR of 1.53 mC/kg at a flow rate of 250 ml/min.
3. The deposition on underside of leaf surface (abaxial) was almost absent for uncharged spray droplets whereas for charged spray droplets, the abaxial deposition was significant at lower heights due to wraparound effect of spray droplets.

The maximum adaxial deposition of 2.23 µL/cm^2 for charged spray droplets was observed at application height, forward speed and leaf orientation of 0.55 m, 1.0 km/h and 30° above horizontal respectively. The application angle of 45° played a significant role in deposition of charged and uncharged spray droplets. Since all the experiments were carried out in laboratory condition; hence further study may be conducted to assess deposition in field conditions.

Acknowledgment

The authors thank Agricultural Engineering Division and PG School, IARI New Delhi for providing equipment, to conduct study and preparation of manuscript.

Nomenclature

µ	Viscosity	L_m	Lower boundary of the class median
σ	Electrical conductivity	30A	30° above the horizontal surface
q	Charge	L2	Abaxial surface
i	Class width	LS	Leaf surface
ρ	Density	VDC	Volt direct current
r	Surface tension	CMR	Charge to mass ratio, mC/kg
ε	Dielectric constant	30B	30° below the horizontal surface
n	The total frequency	L1	Adaxial surface
H	Height, m	C	Charged droplets
f_m	Frequency of the class median	S	Speed, km/h
F	Cumulative frequency before class median	O	Orientation of leaf
0°	Parallel to horizontal surface	AC	Alternating current

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