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Design and Performance Evaluation of Self-propelled Intra-Canopy Boom Spraying System

Bhabani Shankar Dash[1*], Arun Kumar[2], Rajesh U. Modi[3] and Sharad Kumar Namdev[4]

[1]M. Tech. student, [2]Professor, Department of Farm Machinery and Power Engineering, College of Technology, G. B. Pant University of Agriculture and Technology, Uttarakhand- 263145, India. [3]Scientist, Division of Agricultural Engineering, ICAR-Indian Institute of Sugarcane Research, Lucknow-226002, India. [4]Research Scholar, Farm Machinery and Power Engineering, Vaugh Institute of Agricultural Engineering and Technology, Sam Higginbottom University of Agriculture, Technology and Sciences (Prayagraj), Uttar Pradesh (India)-211007. *Corresponding author email address: dash.bhabani2009@gmail.com

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ABSTRACT

A self-propelled intra-canopy boom spraying system was designed for spraying chemicals in small height row crops. The performance of the spraying system was evaluated both under laboratory and field conditions to assess the efficacy and minimize the loss of spray liquid. Flat fan and hollow cone nozzles were tested to determine the boom volumetric distribution, swath and spray angle at different combinations of pressure and height. The flat fan nozzle gave better volumetric distribution at 2.5 kgf.cm^{-2}, while the hollow cone nozzle gave at 2.0 kgf.cm^{-2} pressure corresponding to 300 mm nozzle height. The spraying system was tested on soybean crop at forwarding speeds of 1.5, 2.0 and 2.5 km.h^{-1}. With an increase in forwarding speed, the mean percentage of coverage decreased significantly (30.30 - 15.37 % for top and 20.01- 4.12 % for bottom part of the leaves), and the mean droplet density varied significantly (277.35 - 243.40 no.cm^{-2} for top and 262.87 - 78.44 no.cm^{-2} for the bottom part of the leaves) at 5 % level of significance. A good percentage of leaf area coverage (30.30 % and 20.01 % for top and bottom of the plant) was obtained at low forward speed (1.5 km.h^{-1}) while compromising more spray volume and less field capacity as compared to higher forward travel speeds. The effect of forwarding travel speed, position of tags and nozzle types were significant ($p<0.05$) for mean droplet size, number median diameter, percentage coverage of leaf area and droplet density. The field capacity of the spraying system ranged between 0.22 and 0.36 ha.h^{-1} with an increase in forward travel speed from 1.50 km.h^{-1} to 2.50 km.h^{-1} at an average swath of 1.8 m.

Keywords: Boom spraying system, droplet size, intra-canopy spraying, spray nozzle, swivel body

India produces a large quantity of pulses and vegetables as they constitute a significant proportion of daily diet of its' population, and it also ensures crop and livelihood security of the farmer. The total production of pulses in India was more than 25.23 Mt from an area of 29.99 Mha during the year 2017-18 (Anon., 2020a). Vegetable production in India during the year 2018-19 was above 187.47 Mt in an area of about 10.44 Mha (Anon., 2020a). Plant protection is an essential operation among the basic practices of crop production. Data show that diseases, insects and weeds put together cause 31 - 41 % damages to the crops produced worldwide (Anon., 2016a). Various plant protection measures are followed throughout India; among them, the chemical method is most widely used. Presently, India is the fourth-largest producer of pesticides after the USA, Japan and China. Pests and diseases destroy 15-25 % of the food produced by Indian farmers every year (Anon., 2016). Therefore, plant protection becomes a vital operation to be taken into consideration.

The average size of operational farm landholding in India declined from 1.15 ha to 1.08 ha between the year 2010-11 and 2015-16. The small and marginal holdings taken together (less than 2.0 ha) constitutes 86.08 % of the total holdings during the year 2015-16 as against 85.01 % during the year 2010-11 (Anon., 2019a). Small-sized lands pose operational difficulties in operating tractor-drawn sprayer. Acute labour shortage, along with increasing labour wages, made manual spraying costly. Thus, farm mechanization in spraying can be a better option for effective farm operations. Farm mechanisation level in India is about 40 %, and about 34 % of pulse cultivation is mechanised. Intercultural and plant protection operations account for 20 % mechanisation in pulses, and are relatively low as compared to major cereal crops such as rice (30 % mechanized) and wheat (50 % mechanized) (Mehta *et al.*, 2019). A low level of mechanisation in plant protection operations can be attributed to the small landholdings and poor economic conditions of farmers.

There is a vast array of sprayers available for the farmers in the Indian market. Sprayers like knapsack type (both manual and power operated), hand compression sprayers, motorised knapsack mist blower-cum-duster, tractor mounted sprayers, self-propelled lightweight boom sprayer, self-propelled high clearance sprayer, etc. are available in India (Anon., 2020b). Leading manufacturers like ASPEE, Honda and Kisankraft, along with local manufacturers, have flooded the market with excellent and cheap sprayers. However, most of the commercial sprayers spray the solution from the top of the canopy leading to improper distribution of chemicals on the crop foliage. Leaves and canopy that are exposed receive most of the substances, while those parts which lie beneath receive less or no chemicals. Such improper spray distribution reduces the effectiveness of spray, and leads to higher chemical concentration in certain parts of the plants. The insects or pests that remain inside or underneath the canopy cover are thus not directly affected by the spray. It is challenging to achieve under-leaf coverage with regular spraying equipment as the leaves intercept and block the flow of chemicals inside the canopy. Rear-mounted sprayers also block the visibility and accessibility of the operators.

Narang *et al.* (2013) reported that an air-assistance sprayer gave significant droplet deposition at the underside of the cotton plant leaves as compared to almost negligible by conventional sprayers. They also developed a front-mounted power tiller-operated air assistance intra-canopy sprayer and obtained about 18.0 % of coverage on the front and backside of the leaves of pigeon pea crop. Patel *et al.*(2016) evaluated an electrostatic sprayer for cotton crop in Punjab, India. The area covered by droplets of the electrostatic sprayer was 44.55 % at the top, 55.26 % at the middle, and 68.68 % at the bottom leaves of the canopy. The droplet density and bio-efficiency were also higher as compared to other sprayers like tractor-operated gun-type sprayer, lever-operated knapsack sprayer and power-operated knapsack sprayer. Dhaliwal (2018) worked on an engine-operated walk-type drop-down sprayer for cotton crop. Area covered by droplets on the underside and upper side of plant leaves at 1.0, 1.3 and 1.7 m height varied between 0.91-9.79 %, 0.28-11.19 % and 0.22-10.17 %, respectively. It was concluded that with an increase in forward speed, leaf area coverage and droplet density reduced significantly. Above studies thus showed significant results in obtaining higher leaf area coverage, droplet density, etc. in crops using alternative means as air assistance, electrostatic charging and drop-down arrangement. Modi *et al.*, (2020) expressed the need for an improved boom floatation and nozzle design to enhance the input-use efficiency of pesticides.

Less coverage at the bottom of the plant leaf allows insects/pests to flourish and cause plant damage,which ultimatelyleads to yield loss. A cost-effective way of performing under leaf and intra-canopy spraying for row crops isthus needed for Indian farming conditions. Therefore, the necessity of a self-propelled spraying system with the ability to spray chemicals both from the top as well as the bottom of the plant in row crops was felt. Thus, a study was undertaken to design a self-propelled boom spraying system for intra-canopy spraying and evaluate its performance in row crops (soybean). It will cover more plant canopy area in an efficient way.

MATERIALS AND METHODS

Achieving intra-canopy and under-leaf spraying using conventional sprayers by spraying from the top of the plant canopy is difficult since spray gets intercepted by the leaves and little amount of chemical penetrates the canopy. It is possible through an air-assisted sprayer, electrostatic sprayer, or any mechanism that sprays the chemical from the bottom of the plant. Electrostatic sprayers are expensive and need technical knowledge to operate. Air assistance sprayer needs a separate blower unit, which reduces the manoeuvrability of the whole spraying system due to its additional weight along with adding an extra cost. Alternate mechanism was, therefore, preferred to improve the boom section while considering intra-canopy and under-leaf spraying in row crop.

Self-propelled Boom Spraying System

The mechanism used here had arrangements for placing nozzles in-between the rows at a low height (minimum 100 mm). Hose-drops were selected to carry the chemical to a suitable nozzle arrangement to discharge chemical at the bottom of the plant.The designed spray boom had four even-flat fan nozzles mounted on the top (facing ground) to cover four rows at a time. Hollow-cone nozzles were placed in between the rows at one-third of canopy height from the bottom (facing up at 45°) with the help of hose-drops and swivel bodies. The boom section was designed such that the hose-drops would pass in between the rows, and the nozzles would spray chemicals in both lateral directions along the forward path. A pressure gauge and a flow control valve were provided to set the working pressure and control the liquid supply, respectively. The boom section was attached to a self-propelled unit with a 5-kW diesel engine. The engine power was transmitted to a piston pump fitted adjacent to the engine through a V-belt drive. Power was conveyed to the front wheels from the same shaft through V-belt and chain drive. The whole unit was a front-mounted walk-behind type self-propelled boom spraying system. Development and fabrication were carried out at the Research Laboratory, Department of Farm and Power Engineering, GBPUA&T, Pantnagar, Uttarakhand, India.

Boom and frame section

The boom frame and body were fabricated to support the boom section as well as allow free movement of the boom to fit the desired height of the crops within a range of 450 to 800 mm above the ground. A dry boom was used as a span to attach the nozzles and provide support to the hose line to carry the spray solution. A dry boom section (Fig. 1a) was made by welding two MS angles (25×25×3 mm) length of 1800 mm to form a rigid hollow bar. The frame had a T-section (MS angle of 350×35×3 and MS flat of 300×35×3 mm) and L-section (250×200×35×3 mm) as shown in Fig. 1 (b) and 1 (c), respectively. The T-section was fixed to the body by welding for support of the boom. Holes were drilled on its surface for attaching the other parts of the frame with a bolted joint. The L-section was connected to the T-section with bolt and nut. The L-section had holes drilled on it to attach the spray bar to it. The L section was adjustable by 350 mm to change the boom height. The nozzle spacing could be changed from 200 mm to 600 mm. The sectional view of the boom is shown in Fig. 2.

Selection of nozzles

Nozzle selection is essential to increase the effectiveness of spray and reduce spray losses. The correct nozzle tip size depends on the required application rate (l), ground speed (km.h^{-1}), and effective spray width of each nozzle (W_i). Flat-fan nozzles were chosen for uniform coverage across the entire width of the spray pattern, and hollow cone for better penetration of droplets (Anon., 2019b).

Conventional knapsack sprayers require 400-600 l.ha^{-1} of spray solution, and high-volume sprayers spray more than 400 l.ha^{-1} of chemical (Singh, 2011). Therefore, considering 500 l.ha^{-1} quantity of spray and different forward speeds of walk-behind type sprayers (1.5, 2.0 and 2.5 km.h^{-1}), discharge of an individual nozzle (Q, l.min^{-1}) was determined by the following expression (Dash, 2016):

$$Q = \frac{V\ S\ W_i}{600} \qquad \ldots(1)$$

Where,

V = Total discharge, l.ha^{-1},

S = Forward speed, km.h^{-1}, and

W_i = Row spacing divided by the number of nozzles per row for directed spraying, m.

Nozzle tips (TP8001E and TXA8001VK) discharging the required amount of spray (0.21-0.35 l.min^{-1}) were selected for the study. The TP8001E wasa category of even flat spray nozzle tip providing uniform distribution throughout the spray pattern. The nozzle tip material was brass with 80^0 angle nozzle tips, and a pressure range of 1.40 kgf.cm^{-2} to 4.22 kgf.cm^{-2}. TXA8001VK wasa hollow cone spray tip with a pressure range of 2.1 kgf.cm^{-2} to 8.7 kgf.cm^{-2} (Anon., 2020c). After the selection of the nozzles, their actual discharge (l.min^{-1}) was measured in the laboratory at different operating pressures. The average discharge obtained from the nozzles in 1.0 min time was taken into consideration, and the total flow requirement (F, l.min^{-1}) calculated as:

$$F = \frac{S_w \times A \times S}{600} \qquad \ldots(2)$$

Where,

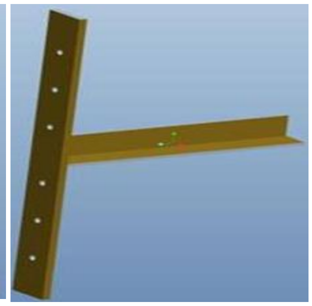
S_w = Swath, m,

A = Recommended application rate, l.ha^{-1}, and

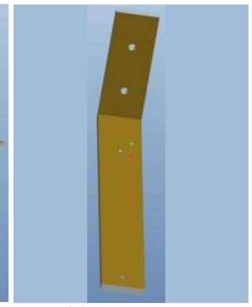
S = Operating speed, km.h^{-1}.

The swath was kept at 1800 mm, taking into consideration four rows with 450 mm width each for soybean crop. The total flow requirement for three

(a) Dry boom section



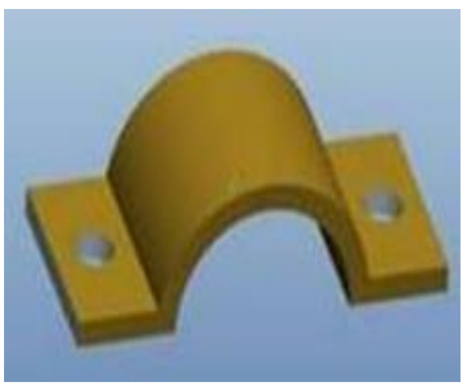
(b) T section



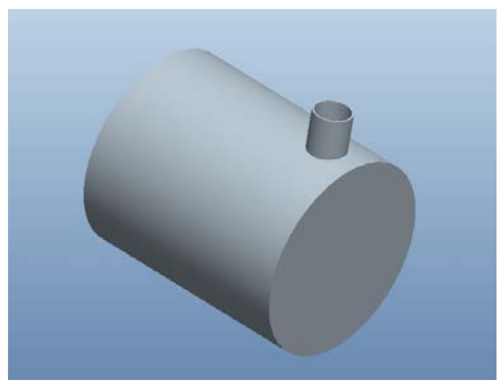
(c) L section

(d) Swivel body

(e) Hose drop



(f) Clamp



(g) Tank

Fig. 1: Various components of spraying system

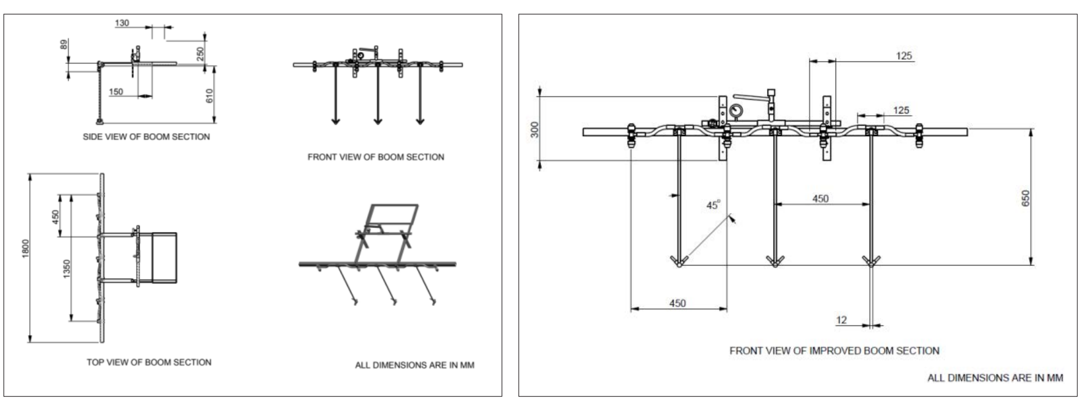


Fig. 2: Sectional views of boom

forward speeds of 1.5, 2.0 and 2.5 km.h^{-1} keeping the application rate (500 l.ha^{-1}) fixed was found to be 2.5, 3.33, and 4.17 l.min^{-1}, respectively.

Selection of flow pump

A pump that can fulfil the total flow requirement of the boom (4.17 l.min^{-1} for spray) and still generate 10 % extra flowfor agitation (8.34 l.min^{-1}) was selected for the study. A reciprocating type three-cylinder piston pump (USHA make, SPRAYMAX 22B) was chosen to produce enough flow for both application rates and tank agitation requirements. The rotational speed was 500-1000 rpm with a suction capacity of 18-22 l.min^{-1} at a pressure range of 10-40 kgf.cm^{-2}.

The pump was tested under laboratory conditions to ensure its proper working and delivering the required flow. The discharge of the pump was calculated by running the pump and collecting the discharged water in a bucket for 1.0 min. The experiment was repeated three times. The flow obtained from the piston pump was measured atdifferent throttle positions (corresponding to forward speeds of 1.5, 2.0 and 2.5 km.h^{-1}) as per the markings on the hand throttle position of the engine. The respective average discharge obtained at three throttle positions was 13.0, 18.2 and 24.4 l.min^{-1}, which satisfied the total flow requirement of the spraying system.

Selection of swivel body, hose drop and clamp

Swivel bodies (Fig. 1d) had nozzle holding arrangements that could rotate in 360^0, and was suitable for spraying in-between row crops. TeeJet's swivel (QJ 8600) nylon bodied (8.0 mm inner diameter) were selected for the boom section to perform intra-canopy spraying. Two hollow cone nozzles were mounted on each swivel body at 45^0 with horizontal for spraying liquid uniformly in opposite directions from the bottom of the canopy. Stainless steel hose-drops, 610 mm long and 12 mm in outer diameter (Fig. 1e), were selected according to the size of the swivel body. They were attached to the horizontal boom section using clamps. Clamps (Fig. 1f) were made using MS sheet (53×2 mm) moulded to hold the hose-drops. An arrangement was made to move the hose-drops vertically (100-400 mm upward) as well as horizontally (200-600 mm) to fit the crop conditions.

Design of spray tank

The design considerations of a sprayer tank include storage capacity that can provide 15 - 20 minutes of continuous spraying, and the actual tank capacity is kept 5-15 % higher than the theoretical capacity to ensure that there is always enough liquid for adequate agitation (Varshney *et al*., 2004; Sharma and Mukesh, 2013).

The tank capacity (Q_t, l) was calculated as:

$$Q_t = D_b \times t \qquad \ldots(3)$$

Where,

D_b = Total discharge rate of all nozzles, l.min^{-1}, and

t = Duration of use, min.

The tank capacity was found to be 83.4 l, considering the nozzle discharge rate of 4.17 l.min^{-1}, which can spray for a duration of 20 min. With an additional 10 % extra flow for agitation, the final tank capacity was found to be 91.74 l (say 92 l).

A cylindrical tank (Fig. 1g) of 500 mm diameter and 600 mm long made of G.I. sheet (18 gauge) was attached to the unit at the front of the frame. The liquid overflow of the pump was bypassed/recirculated to the tank to assist the stirring of the ingredients. The storage tank of 118 litre capacity was sufficient to spray 0.24 ha in one fill.

Laboratory Evaluation of Nozzles

The uniformity of spray distribution across the boom, or within the spray swath, is essential to achieve maximum chemical effectiveness with minimal cost and reduction in non-target contamination. The uniformity of the nozzlespray was determined using a patternator at the Department of Farm Machinery and Power Engineering, Punjab Agricultural University, Ludhiana, India. A patternator of size 2000×2000 mm made of acrylic sheet with inner dimensions of 2000×30×100 mm for each channel (63 rectangular channels) was used for testing, as shown in Fig. 3. The spray channels were inclined at angle of 9-10^0 with horizontal. The nozzles were mounted at the centre of a metallic frame perpendicular to the patternator channels. The height of the nozzle assembly was also adjustable up to 2000 mm. The nozzles were connected to a constant water supply through a piston pump, and a pressure gauge was mounted to check the pressure. The nozzles were tested at different pressures (2.0, 2.5 and 3.0 kg.cm^{-2}) and heights (300, 400 and 500 mm) to check uniformity of distributions and their swaths. Collecting tubes were provided to collect the water from the channels during spraying. The nozzle was given a preliminary run until a constant flow rate was achieved from the patternator, and the readings were subsequently taken (ISI, 1977).

The procedure was replicated thrice. The treatment with the least coefficient of variation (C.V.) was considered as best for field evaluation.

Field Performance Evaluation

Field evaluation of the designed spraying system was carried out at the Breeders Seed Production Centre, GBPUA&T, Pantnagar. Agronomical conditions of the crop (crop height, canopy spread and row spacing) and the functional requirements were considered for the evaluation of the nozzle spray. Before operating in the field, the spraying system was calibrated according to the ISI standards (ISI, 1985) under laboratory conditions to ensure proper working of the components. A preliminary test was conducted on standing cowpea crop (Pant Lobia III, 45 DAS, 400 mm row-to-row spacing, 500 mm plant height). During the preliminary test, the spraying system was found to be working satisfactorily.

The self-propelled spraying system was further tested on soybean crop (Variety: PS 1225) at Crop Research Centre, GBPUA&T, Pantnagar (Fig. 4). At the crop age of 48 days, the average crop height was 350 mm with row-to-row spacing of 450 mm. Three plants along a row were selected at an interval of 3 m for each treatment. Six collector tags (WSPs, 75 × 25 mm) were fixed to each selected plant (Hofmann and Hewitt, 2005). The machine was checked, and an initial run (3.0 m) was given before spraying over the allotted plants. The spray liquid used was pure water with a dye solution (methylene dye @5g.l^{-1}). Dye was used for evaluating the spray deposit on the plant leaves by attaching water-sensitive paper (WSP) on them (Singh *et al*., 2019). The spraying system was run at three forward speeds (1.5, 2.0 and 2.5 km.h^{-1}) at maintained operating pressure of 2.5 kgf.cm^{-2} (245.16 kPa) based on the laboratory study. The tags were collected after spraying, and subsequently dried. Spray deposition analysis was done at Plant Protection Laboratory, Agricultural Mechanization Division, CIAE, Bhopal, using an image analysis software (LEICA QWin).

Analysis of sample tags

Various researchers used different software for analysing the sample tags as per their requirement (Zhu

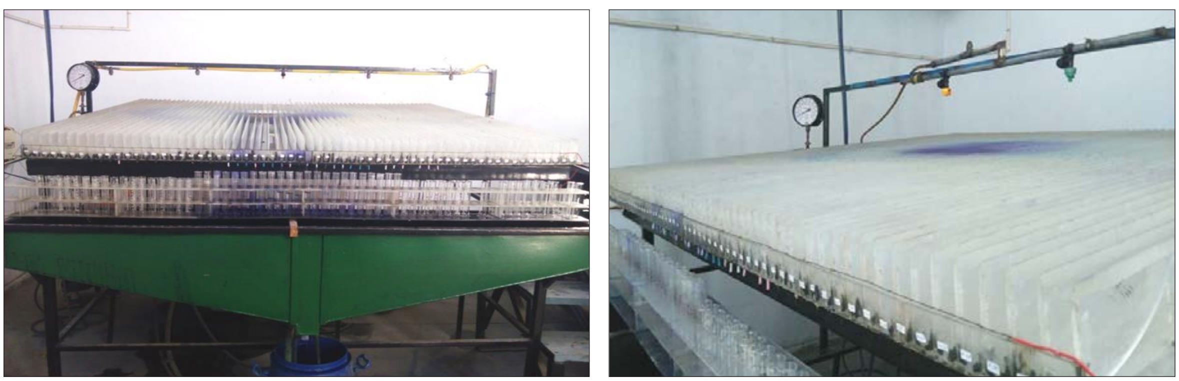


Fig. 3: Nozzles attached at the centre of the adjustable frame over the patternator

Fig. 4: Field performance evaluation of self-propelled boom spraying system in soybean crop

et al., 2011; Mishra *et al.*, 2014). The tags collected from the field test were analysed using "LEICA QWin (QWin Plus) image analysis software" (Narang *et al.*, 2013). It was a swift and sophisticated application capable of addressing and solving the most intricate image analysis tasks functioning in the Microsoft Windows operating environment. The WSP tags were scanned at 600 dpi and exported as BMP image files, followed by their analyses, as shown in Fig. 5. The mean droplet size, number median diameter (NMD), leaf area coverage, and droplet densities were measured using the software and exported in an Excel file.

NMD was calculated for finding the median (M) of a grouped data by using the statistical formula:

$$M = L_m + \left[\frac{\frac{n}{2} - F}{f_m}\right] i \quad \ldots(4)$$

Where,

n = Total frequency,

F = Cumulative frequency before the class median,

f_m = Frequency of the class median,

i = Class width, and

L_m = Lower boundary of the class median.

Droplet density (D, droplet.cm^{-2}) was calculated from the obtained data using the following formula:

$$D = \frac{D_n}{A_f} \quad \ldots(5)$$

Where,

D_n = Number of droplets in the frame, and

A_f = Frame area, cm^2.

The area covered by the droplets on WSP was calculated by dividing the total drop area by that of WSP. The percentage area covered by the droplets was calculated by dividing the total droplet area to that of frame area multiplied by 100.

Leaf area coverage (L_c, %) was determined by

$$L_c = \frac{A_d}{A_f} \times 100 \quad \ldots(6)$$

Where,

A_d = Total area of droplets in the frame, cm^2, and

A_f = Total frame area, cm^2.

The relative standard deviation (RSD, %) values of the four parameters were calculated to compare the data from the mean values by using the following equation:

$$RSD = \frac{S}{|X|} \times 100 \quad \ldots(7)$$

Where,

S = Sample standard deviation, and

|X| = Mode of the sample mean.

Measurement of other field parameters

The forward speed of the spraying system was increased/decreased using a throttle setting, whereas power was engaged/disengaged from engine to transmission through a lever. Forward speed was measured for 20 m long marked run (using ranging rods) at a constant throttle position, and the time taken to cover the distance was recorded using a stopwatch (precision: 0.01 s). Thus, a forward speed was calculated, and the

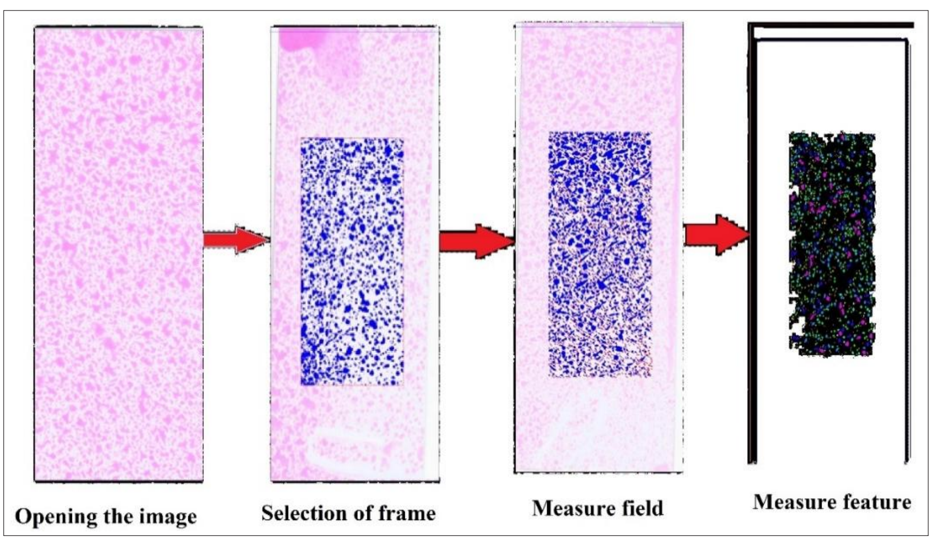


Fig. 5: Steps followed in LEICA QW in software for analysis of tags

throttle position was accordingly marked for forward speed of 1.5, 2.0 and 2.5 km.h^{-1}.

The plant dimensions (row spacing, plant height and canopy width) were measured manually using a meter tape (3.0 m) having least count of 1.0 mm. The canopy spread was the lateral distance measured between two outermost vertical axes touching to the extreme leaf tips using the metre tape. The measurements were taken at several locations (10 random places) in the field, and their average was considered.

Design of Experiment

The experimental field layout was 12 × 36 m (432 m^2), having 18 number of plots of size 20 m^2. The length of each run was 10 m with an additional head land of 1.5 m on two parallel sides for making a run.

Field experiments were laid in a randomized block design (RBD), and data obtained from the field were analysed to determine the effect of independent parameters (forward speed S1 (1.5 km.h^{-1}), S2 (2.0 km.h^{-1}), and S3 (2.5 km.h^{-1}); location of tag L1 (top of plant leaves) and L2 (bottom of plant leaves) individually and their interactions. The dependent variables were mean droplet size (μ), number median diameter (μ), leaf area coverage (%), and droplet density (droplet.cm^{-2}). Tags were attached after a distance of 3.0 m from the headland and at intervals of 3.0 m. Among the six tags collected, three tags with good and clear marks on them were taken for the analysis, and a similar process was followed for both tag locations. The experiment was replicated thrice, and the data obtained from the field were statistically analysed using analysis of variance (ANOVA) at 5 % level of significance with SAS 9.3.

RESULTS AND DISCUSSION

The technical specifications of the spraying system are presented in Table 1. It was field-tested in a soybean (PS 1225) field at three different operating speeds (1.5, 2.0 and 2.5 km.h^{-1}) at constant (2.5 kgf.cm^{-2}) operating pressure and boom height (300 mm). Performance

Table 1. Technical specifications of intra-canopy boom spraying system

Sl. No.	Item/Particulars	Specifications
1.	Name of the machine	Intra canopy boom spraying system
2.	Type	Walk-behind type
3.	Power source	Self-propelled
4.	Engine	
	Type	Diesel, 4-stroke engine
	Power, kW	5.0
	Transmission	V-belt and chain drive
5.	Maximum forward speed of travel, km.h^{-1}	2.8
6.	No. of nozzles	10
7.	Types of nozzles	Hollow cone and flat fan
8.	Nozzle spacing range, mm	200- 600
9.	Operating pressure of nozzles, kgf.cm^{-2}	
	Flat fan	1.40 to 4.50
	Hollow cone	1.50 to 4.50
10.	Length of hose pipe, mm	610
11.	Tank capacity, l	118
12.	Pump type	Piston pump (three cylinder)
13.	Pressure rating, kgf.cm^{-2}	10-40
14.	Pump discharge, l.min^{-1}	13-24.4
15.	Boom height range, mm	750-1000
16.	Front drive wheel (two) diameter, mm	350
17.	Rear guide wheel diameter, mm	350
18.	Ground clearance, mm	450
19.	Overall dimensions, mm	2050 ×1800×1500
20.	Net weight, kg	180

results of the spraying system are discussed in this section.

Crop Parameters

Soybean (*Glycine max*) grown in parts of the plains and *tarai* region of Uttarakhand has a maturity period of 120-125 days. The PS1225 variety is a medium height plant (>500 mm) and resistant to diseases like yellow mosaic virus (YMV), bacterial pustule (BP), and moderately resistant to Rhizoctonia aerial blight. The variety had white flowers, semi-erect growth habit with pointed ovate leaf shape (Anon., 2016).

At 48 days after sowing (DAS), the plant height, canopy spread, and row-to-row spacing were observed as 350, 340 and 450 mm, respectively. It was in the growing (pre-flowering) stage, and the height and canopy width were expected to grow more. Plant height for PS 1225 variety was observed at 735 mm (Singh *et al*., 2015). Negi (2018) marked that the plant height (PS1225) after 40 and 80 DAS was 299 and 501 mm, respectively. Respective values for canopy spread were 424 mm and 527 mm. The package of practices includeda wide range of chemical treatments, including keeping crop free from weeds till 45 DAS. For controlling diseases (Rust, YMV, BP, etc.), the spray includes quick spray after symptoms are visible to the second spray after few days (10-20 days) of the first spray (Anon., 2018).

Laboratory Evaluation of Nozzle and Pump

The nozzles selected for the boom spraying system were Even Flat Spray Tip (TP8001E) and Hollow Cone Tip (TXA8001VK) of TeeJet Technologies (USA). The best volumetric distribution in terms of CV for flat fan nozzle was at the pressure of 2.5 kgf.cm^{-2} and 300 mm nozzle height (18.5 %); while that of the hollow cone nozzle was at 2.0 kgf.cm^{-2} pressure and at 300 mm nozzle height (34.16 %), Table 2. The lower CV values ensure higher uniformity throughout the spray pattern and *vice-a-versa*. With an increase in pressure from 2.0 kgf.cm^{-2} to 3.0 kgf.cm^{-2}, the discharge of the flat fan nozzle increased from 0.29 l.min^{-1} to 0.36 l.min^{-1}.

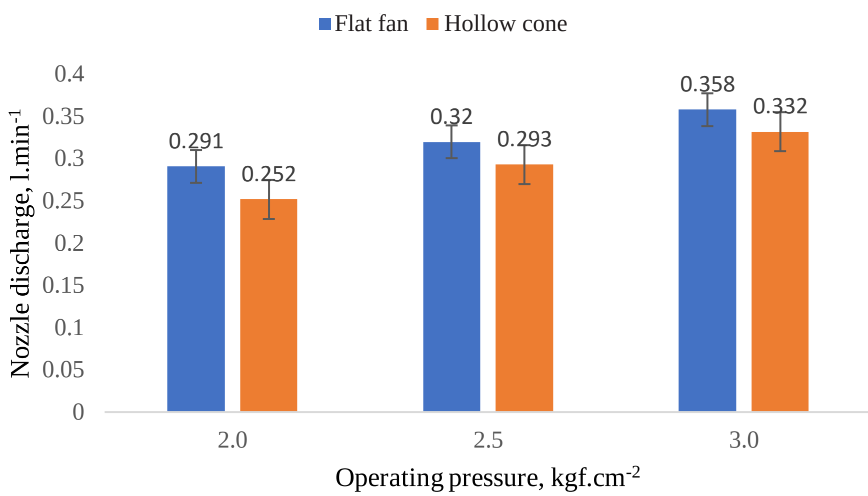


Fig. 6: Effect of operating pressure on nozzle discharge rate

Table 2. Swath and C.V. of hollow cone and flat fan nozzles at different operating pressures and pressure

Nozzle type	Operating pressure, kg.cm^{-2}	Swath width at different height, mm (C.V., %) Nozzle height, mm		
		300	400	500
Hollow cone	2.00	250 (34.16)	275 (42.60)	275 (40.85)
	2.50	275 (44.27)	280 (44.87)	280 (43.87)
	3.00	275 (39.15)	300 (38.33)	300 (45.33)
Flat fan	2.00	300 (27.65)	400 (29.93)	400 (27.19)
	2.50	350 (18.5)	425 (22.8)	425 (34.54)
	3.00	350 (34.52)	425 (26.47)	475 (27.20)

At this pressure range, the discharge rate of the hollow cone nozzle also improved from 0.25 $l.min^{-1}$ to 0.33 $l.min^{-1}$. The average discharge rate of the hollow cone nozzle was lower than the flat fan nozzle by 13.40 %, 8.43 % and 7.26 % at the three operating pressures.

The discharge obtained from the positive displacement pump varied between 13.0 $l.min^{-1}$ to 24.4 $l.min^{-1}$ at the three throttle positions for forward speedrange of 1.5-2.5 $km.h^{-1}$ during field operations.

Field Performance

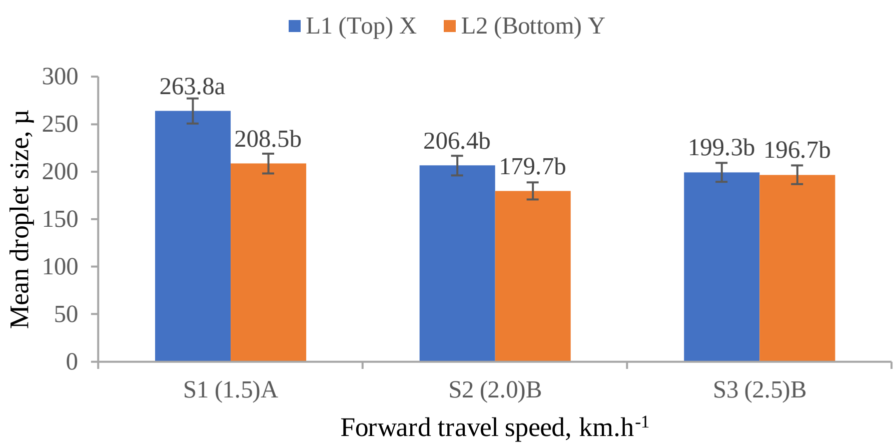
The results obtained from the laboratory (swath, pressure and nozzle height) tests were considered while running the machine in the field (Fig. 4). The swath obtained from the nozzles were simulated as plant canopy widths (340 mm), and the corresponding boom heights (300 mm) and the operating pressure (2.5 $kgf.cm^{-2}$) were fixed for the study. The actual field capacity of the boom sprayer varied between 0.22 $ha.h^{-1}$ to 0.36 $ha.h^{-1}$ (at 80 % field efficiency) with forward speed increasing from 1.5 $km.h^{-1}$ to 2.5 $km.h^{-1}$ with an average swath of 1800 mm. The results on the effect of operating speed on spray characteristics are discussed below.

Mean droplet size

The effect of forward travel speeds and location of tags on the mean droplet size is shown in Fig. 7 and corresponding ANOVA in Table 3. At forward travel speed of 1.5 $km.h^{-1}$ and a top location, the mean droplet size was found to be higher (263.8 μ) due to more exposed canopy area and lower speed resulting in higher spray deposition. All combinations, except the combination of S1L1, were statistically at par for mean droplet size. The individual effect of forward travel speed and location of the tag was found to be significant ($p<0.05$). The droplet sizes varied between 49-800 μ at all forward travel speeds. However, bottom leaves received droplets with relatively smaller size (194.96 μ) as compared to top leaves. It might be due to the presence of a hollow cone nozzle at the bottom side, which produces finer droplets compared to flat fan nozzles.

Number median diameter (NMD)

Figure 8 and Table 4 illustrates the effect of forward speed and location of tags on the NMD of the spray droplets. The NMD of droplets at 1.5 $km.h^{-1}$ (S1L1) forward speed was significantly ($p<0.05$) higher (234.9 μ) from the other combinations. The effect of forward travel speed, location of the tag, and their interactions were non-significant ($p>0.05$). It might be due to the constant operating pressure of the nozzles ensuring less variation among the NMD's.

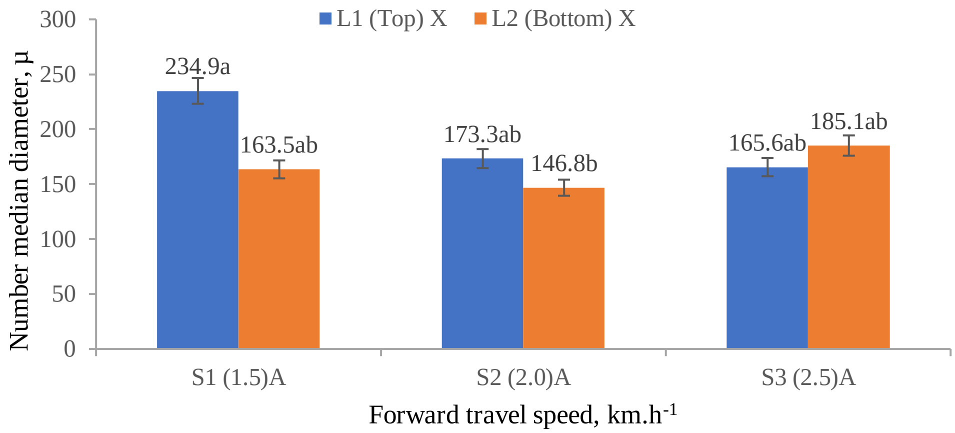


(Mean values and independent parameters with same letters are not significantly different, $p>0.05$)

Fig. 7: Effect of forward speed on mean droplet size

Table 3. ANOVA table on the effect of operating speed and location on mean droplet size

Source	DF	Type III SS	Mean Square	F value	p value
Speed	2	6685.9078	3342.9539	9.90	0.0029
Location	1	3578.5800	3578.5800	10.59	0.0069
Speed×location	2	2088.0300	1044.0150	3.09	0.0827



(Mean values and independent parameters with same letters are not significantly different, p>0.05)

Fig. 8: Effect of forward speed on number median diameter

Table 4. ANOVA table on the effect of operating speed and location on NMD of droplets

Source	DF	Type III SS	Mean Square	F value	p value
Speed	2	4678.5344	2339.2672	2.32	0.1409
Location	1	3068.0556	3068.0556	3.04	0.1068
Speed×location	2	6206.5411	3103.2706	3.07	0.0836

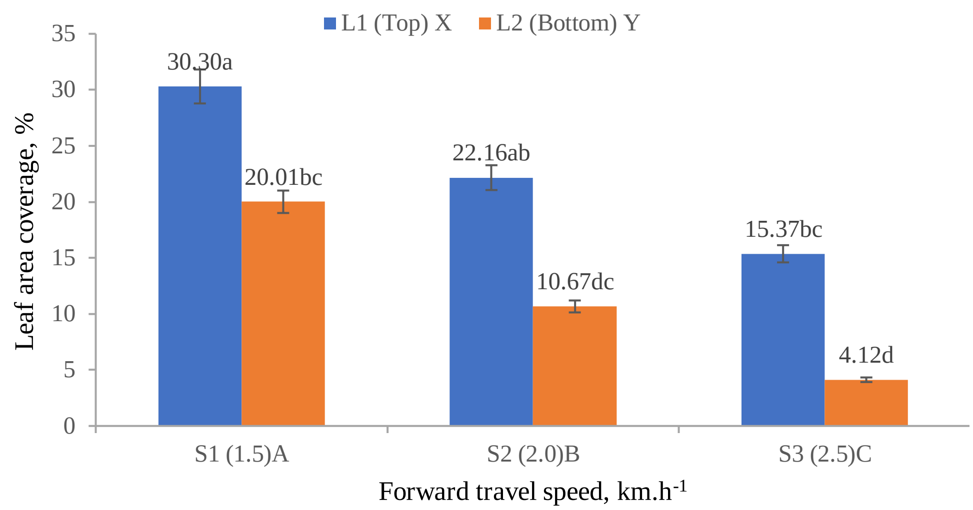
Leaf area coverage

Forward travel speed and location of tag hada significant effect ($p<0.05$) on the leaf area coverage (Fig. 9 and Table 5), whereas their interaction was non-significant ($p>0.05$). The leaf area coverage reduced from 30.30 % to 4.12 % with increasing forward speed from 1.5 $km.h^{-1}$ to 2.5 $km.h^{-1}$ for both top and bottom locations of the tag of the plantcanopy. It was due to the constant rate of application (fixed pressure of 2.5 $kgf.cm^{-2}$) at all forward travel speeds, thereby reducing the duration of spray and strike of droplets with increasing speed. This indicated that a lower forward travel speed of 1.5 $km.h^{-1}$ would give better performance (30.30- 20.01 % coverage) when there are more pest infestations and dense canopy. Coverage obtained on the top portions of the plant canopies were higher from the bottom parts by 51.42 %, 107.68 % and 273.05 %, respectively, at all operating speeds. It might be due to obstructions on the path of droplets (leaves, branches, etc.) from the hollow cone nozzle causing low coverage on bottom sides.

Droplet density

From the ANOVA results, the effect of operating speed and location of tags on droplet density is presented in Fig. 10 and Table 6, respectively. The forward speed, location of the tag, and their interaction were statistically significant ($p<0.05$) on droplet density. The interaction S3L2 was significantly lower (78.44 $droplet.cm^{-2}$) droplet density from its neighbouring values. Droplet density on top portions of the plant canopies was higher as compared to the bottom parts, but the result was not significantly different.The droplet densities on the leaf surface were compared with the recommended droplet densities for various operations and were observed to satisfy the recommended conditions. With these nozzle combinations, the desired droplet density could eradicate pests and diseases. The droplet densities at three forward travel speeds were also compared with the previous researches and recommendations. Observed droplet density fulfilled the criteria that with medium-size droplets, insecticides should have 20-30 $droplet.cm^{-2}$, herbicides 20-40 $droplet.cm^{-2}$, and fungicides with 50-70 $droplet.cm^{-2}$ (Hoffman, 2018). The results also satisfied the recommended number of droplets(20-30 $droplet.cm^{-2}$ for spraying insecticides and 50-70 $droplet.cm^{-2}$) for spraying fungicides (Zhu *et al.*, 2006).

Relative standard deviation (RSD) values of the four parameters are represented in Fig. 11. The least relative standard deviation for leaf area coverage was at forward speed of 1.5 $km.h^{-1}$ for the top portion of leaves (30.30 ± 14.50 %). Relative standard deviation was minimum for droplet densities (243.30 ± 9.44 %), mean droplet

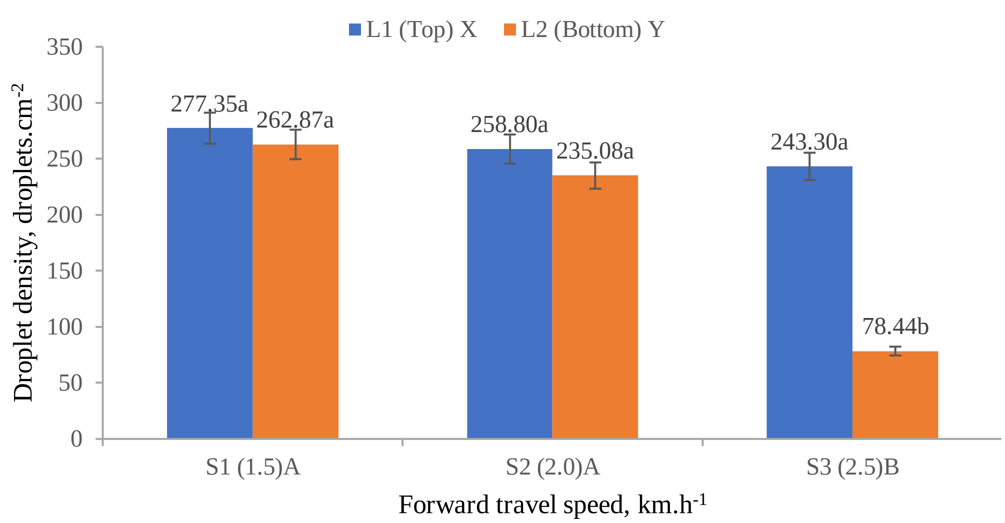


(Mean values and independent parameters with same letters are not significantly different, p>0.05)

Fig. 9: Effect of forward speed on leaf area coverage

Table 5. ANOVA table on the effect of operating speed and location on leaf area coverage

Source	DF	Type III SS	Mean Square	F value	p value
Speed	2	715.8900	357.9450	30.36	<.0001
Location	1	544.5000	544.5000	46.19	<.0001
Speed×location	2	1.1433	0.5717	0.05	0.9529



(Mean values and independent parameters with same letters are not significantly different, p>0.05)

Fig. 10: Effect of forward speed on droplet density

Table 6. ANOVA table on the effect of operating speed and location on droplet density

Source	DF	Type III SS	Mean Square	F value	p value
Speed	2	39765.6411	21316.7211	24.69	<.0001
Location	1	20611.2672	20611.2672	25.59	0.0003
Speed×location	2	21316.7211	10658.3606	13.23	0.0009

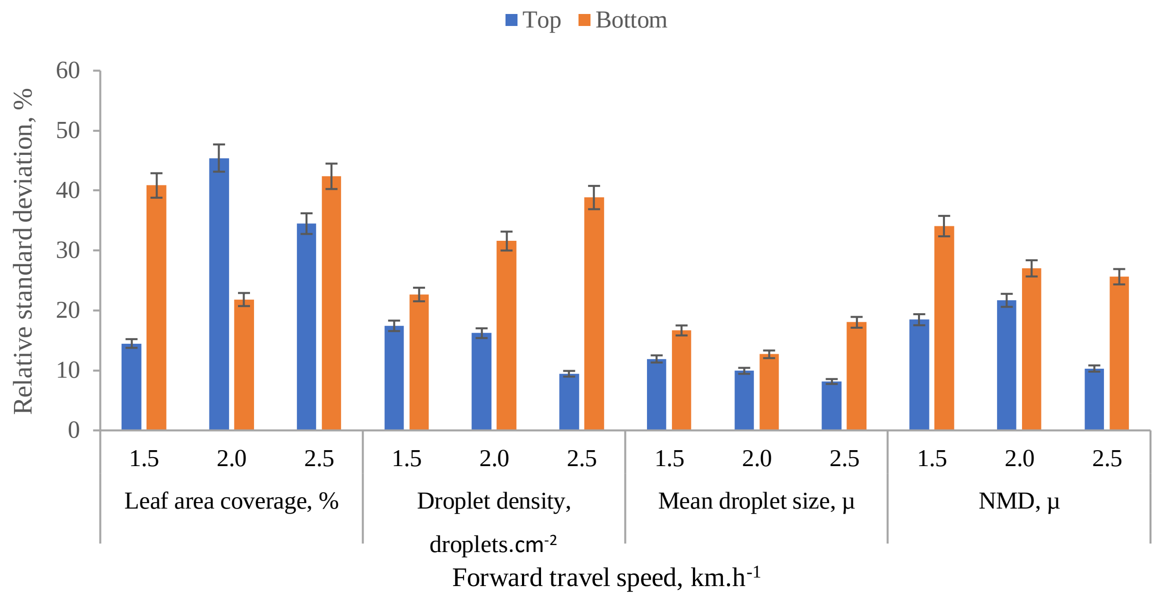


Fig. 11: Relative Standard deviation of dependent parameters of the spraying system

sizes (199.28 ± 8.15 %), and NMD of droplets (165.56 ± 10.32 %) at forward speed of 2.5 km.h^{-1}. The top portion of leaves received more uniform droplets as compared to the bottom part of leaves, and forward speed of 2.5 km.h^{-1} exhibited least RSD values. The total volume of spray liquid consumed during the field trial varied between 400 to 675 l.ha^{-1} with increasing travel speedfrom 1.5 to 2.5 km.h^{-1}.

Manoeuvrability and operational recommendations

The manoeuvrability of the spraying system was better for soybean crops as compared to cowpea due to well-maintained row spacing in soybean crops, while the cowpea crops caused some hindrance to the movement of the unit due to entangled branches and plants. The machine can be well suited for well-maintained row crops with a row-to-row spacing of up to 600 mm. A minimum of 60 mm space between the rows is necessary for easy movement of the spraying system. The spraying system requires a minimum of 1.5 m head lands for successive turning in the field. The machine can accommodate a wide range of row crops (Soybean, cowpea, green gram, black gram, groundnut, vegetable crops) whose crop geometry lie within the operating range of the machine.

CONCLUSIONS

Leaf area coverage on the top side of the leaves was higher as compared to the bottom sideat forward travel speeds between 1.5 km.h^{-1} and 2.5 km.h^{-1}. Mean droplet size on the top and bottom leaf surface reduced from 263.8 µ to 199 µ and 208.5 µ to 196.7 µ, respectively, with increase in forward travel speed of the spraying system. Droplet densities on top leaf surfaces reduced from 277.35 droplet.cm^{-2} to 243.30 droplet.cm^{-2} and 262.87 droplet.cm^{-2} to 78.44 droplet.cm^{-2} at bottom surface with increasing operating speed, and satisfied the required droplet density application criteria at forward travel speed between 1.5 km.h^{-1} and 2.5 km.h^{-1}. The slow and medium forward travel speed (1.5 and 2.0 km.h^{-1}) gave higher (158.13 % and 68.45 %) coverage as compared to the forward speed of 2.5 km.h^{-1}, and hence can be used for spraying for crops with dense canopy or higher pest infestation. Higher forward travel speed of 2.5 km.h^{-1} could provide sufficient droplet density to kill insects / pests, and spraying at this speed could also be performed effectively for less dense crops or crops with less pest infestation. Operation at forward speed of 1.5 km.h^{-1} was thus recommended for proper leaf area coverage, while speed of 2.5 km.h^{-1} produced better droplet density, mean droplet size, and NMD.

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