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Parametric Optimization of Solar Powered Remote-Controlled Sprayer using RSM and TAGUCHI Method

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Abstract: Green energy-based appliances, gadgets and machines are taking over conventional counterparts in many of the sectors and agriculture is no different. Lighter farm operations such as spraying, weeding and fertilizer broadcasting can be carried out using agricultural machines powered by solar PV system. In this context, a solar powered remote-controlled sprayer was developed and was evaluated for its performance under laboratory conditions. The laboratory evaluation of SPRC sprayer was carried out according to BIS code IS: 11429 -1985. Chilli plants were raised in pots and all six nozzles were used for spraying the liquid so as to determine the droplet size and droplet density. Spray droplets were collected on glossy photographic papers fixed over the plant leaves. Deposit Scan software was used to measure droplet size and droplet density of spray. Height of spray was adjusted using adjustable stands while operating pressure was varied using pressure control valve. Three types of nozzles namely hollow cone, solid cone and flat fan nozzle were selected for evaluation. Influence of selected independent variables *viz*., height of spray, operating pressure and type of nozzle on performance parameters such as droplet size and droplet density were studied using optimal design in RSM. The droplet size varied between 165.80 and 236.40 µm whereas droplet density varied from 28.40 to 93.30 No's cm^{-2} for different combinations of selected influencing variables. Taguchi method was used to optimize the operating parameters and the optimum combination of variables was found to be 40 cm height of spray, 5 kg cm^{-2} operating pressure with hollow cone nozzle performing the best.

Keywords: Droplet size, Droplet density, Remote Controlled solar sprayer, RSM, Taguchi method

The next generation agriculture is unfolding across the globe. Today, agricultural activities are focused more on scientific and technological approaches so as to intensify the crop production. Reduction in cropping area and non-availability of timely labour has given impetus to introduction of highly sophisticated and efficient farm machines. Diminishing fossil fuels and increase in climate change conditions has compelled mankind to switch over to the cleaner and non-conventional energy sources such as solar, wind and biomass (Md. Rahman et al 2022). Solar energy is the most prominent source of renewable energy, its abundance over and across most parts of the earth makes it a potential resource besides being eco-friendly. There have been numerous applications of solar energy such as fireless cooking, space heating, water heating and steam generation using heat energy of solar radiation (Hussain and Lee 2015). Solar photovoltaic technology is probably the revolutionary development which is used for generation of electricity for various applications starting from domestic lighting to running large industry machineries.

Recent trends of technological innovations in agriculture are also focusing on using solar energy to carryout various farm operations and to develop machineries and solar motors for various agricultural applications including post harvest handling of agriculture produce (Kumar et al 2018, Gorjian et al 2021). Introduction of automation and robotics in agriculture has enormous potential to lower cost of production, reduce the drudgery involved in manual operations, to raise the quality of fresh produce and to improve the environmental conditions (Bawden et al 2017, Ghobadpour et al 2019, Oliviera et al 2021). In agriculture, spraying of pesticides is an important task to protect the crops from insect pest ensuring high yield. However, farmers are mainly using traditional/conventional techniques like hand operated and power operated sprayers for spraying pesticides (Ritiesh et al 2015). Exposures to pesticides both occupationally and environmentally cause a range of human health problems (Damalas and Koutroubas 2016). The farmers reported excessive sweating, burning/stinging/ itching of eyes, dry/sore throat and excessive salivation all more prevalent among sprayers (Chitra et al 2006).

In present context, shortage of man power for spraying is a major constraint. Escalating costs of gasoline fuels and hiring charges of heavy machineries are also major challenges faced by the farmer. The conventional method of spraying (hand operated spraying) results in excessive application of chemicals ultimately leading to environmental pollution, less uniformity rendering to more operational cost and also continuous spraying operation leads to fatigue of the operator. Thus with the application of pesticides using remote control spraying technology powered by the use of non-conventional sources of energy that is abundantly available would prove to be environmentally friendly by eliminating fuel operated engines, human interventions in the field and also by reducing health hazards. The electrical energy obtained through solar PV cells can be utilized for doing lighter field operations such as spraying, shallow depth soil working, and thinning. Off late, automated ground vehicles with spraying attachment, powered by solar energy are making their way in agricultural field. Mousazadeh et al (2010) evaluated alternative technologies for a solar assisted plug-in hybrid electric tractor and reported that life cycle cost of valve regulated lead acid (VRLA) battery was highest followed by Ni-MH, Li-ion and Ni-Cd batteries when coupled with a solar photovoltaic (PV) cells. The attempt has been made to develop a solar powered remote-controlled sprayer and optimize the operational parameters to suit varied field conditions.

MATERIAL AND METHODS

Description of the machine: The developed solar powered remote-controlled sprayer consisted of chassis, solar photovoltaic (PV) module of 220 W capacity, spray tank of 100 litre capacity, lead acid storage batteries, DC motors, pneumatic wheels, foldable spray boom with four nozzles, signal receiver, transmitter and electronic circuit board (Fig. 1). The chassis was separated into three sections namely, the base, middle and the spray boom section. In the base, two dry batteries were mounted below the tank with a wheel track and wheel base of 825 and 1020 mm respectively are connected to rear tyres through individual motors having enough capacity to carry 350 kg total weight including 100 kg fluid payload through chain and sprocket mechanism ultimately converting rotational energy into energy required to produce thrust, hence driving action taking place. On the left-hand side of the chassis, one dry battery is also connected to the servo motor whose function is to convert rotary motion into angular motion of front tires which are connected through tie rod mechanism rendering to steer simultaneously.

The middle section of chassis carries spray liquid tank, spray motor with pump, hose pipes, electronic circuit board and pressure gauge. Above all these components, the solar PV panel of 220W capacity (1580 x 810 mm) was mounted on a frame through nut and bolt system at a height of 610 mm. The outlet of the fluid tank pipe was connected to the inlet of the 12 V DC spray motor with pump which generates enough pressure to spray the liquid. The outlet pipe of the spray motor with pump was connected to spray nozzles through a pressure gauge by hose pipes. The spray boom section was mounted to the rear side of the developed prototype sprayer at a distance of 520 mm from the chassis with a provision of variable height adjustment for the spray boom. Total of three pairs of nozzles were used, each pair covering one row of the crop respectively. The spray boom was foldable at a distance of 800 mm from both the ends for easy transportation to the field (Fig. 2).

The electronic circuit board consisted of receiver board, battery charging box and controller board. The transmitter used was a wireless radio frequency device which controls the operating and spraying mechanism of the sprayer. FLYSKY transmitter and receiver is a 6-channel operation remote controlled device with a reliability of 2.4 GHz signal range which receives the signal from the transmitter and further processes the signal to micro controller unit for further action.

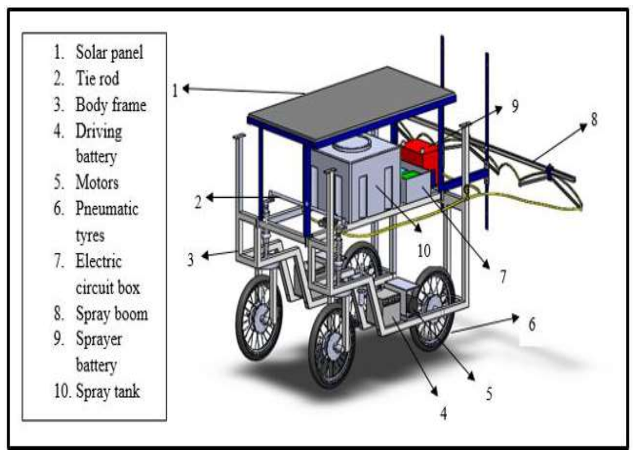

Fig. 1. Conceptual view of solar powered remote-controlled sprayer

Fig. 2. Stationary view of solar powered remote-controlled sprayer

Laboratory evaluation of SPRC sprayer: The developed solar powered remote-controlled sprayer was evaluated in laboratory conditions to study the effects of selected influencing variables *viz*., height of spray (H), operating pressure (P) and type of nozzle (N) at three levels each on performance parameters namely droplet size (D_s) and droplet density (D_d) (Table 1). Droplet size and droplet density were selected as they are the cardinal characteristics in determining the effectiveness of spray over the target crop. Height of spray was varied by varying the position of spray boom on the vertical plate made for the purpose whereas the operating pressure was varied using a pressure control valve at the spray pump. Three types of nozzles namely hollow cone, solid cone and flat fan were used for evaluation.

The laboratory evaluation of SPRC sprayer was carried out according to the procedures as mentioned in BIS code IS: 11429 -1985. Chilli plants were raised in the polyethylene bags and after certain age, the plants were placed in pots (Gholap and Mathur 2012). All the six nozzles were used for spraying the liquid and to determine the droplet size and droplet density. Height of the spray nozzle was maintained at 20, 30 and 40 cm above the plant canopy. The operating pressure was varied at 3, 4 and 5 kg cm^{-2}. The three types of nozzles used for the study were hollow cone, solid cone and flat fan nozzle (Senthilkumar and Kumar 2007).

Droplet size (D_s): Volume mean diameter (VMD) and number mean diameter (NMD) are two commonly used measures of droplet size. As the measurement of VMD and NMD is affected by the proportion of large and small droplets respectively, the ratio between these parameters indicates the ranges of sizes *i.e.* more the uniform the size of droplets are more the nearer is the ratio to unity (Matthews 1992). For evaluating VMD and NMD, glossy photographic paper of size 7.5 × 2.5 cm was selected as it has low spreading factor and was placed on upper and underside of leaves at top, middle and bottom portion of plants. They are fixed to leaves at location horizontally. Methylene blue MS dye mixed @ 5 g l^{-1} in water and photographic paper were the same as that used by Jassowal et al (2016). Deposit Scan is a portable scanning program for spray deposit quantification that can quickly evaluate spray deposit distribution on water sensitive paper or kromokote paper. Glossy papers were scanned using a PC connected high resolution scanner. In this program, the scanning resolution was chosen up to 2400 dpi or 10.58 µm per pixel length. When the Deposit Scan program is started, it opens an image-processing program, and prompts the user to scan the sample. The program then reports the individual droplet sizes, their distributions, the total number of droplets, and the percentage of area covered. The program batch file calculates $DV_{0.1}$, $DV_{0.5}$ and $DV_{0.9}$ and displays the results from the area of the selected section, the total number of spots and the percentage area covered by the spots. $DV_{0.1}$, $DV_{0.5}$ and $DV_{0.9}$ represent the distribution of the droplet diameters such that droplets with a diameter smaller than $DV_{0.1}$, $DV_{0.5}$, and $DV_{0.9}$ compose 10 per cent, 50 per cent and 90 per cent of the total liquid volume, respectively.

Table 1. Variables and levels selected for laboratory evaluation

Parameters	Levels		
	1	2	3
Independent parameters			
Height of spray (H), cm	20	30	40
Operating pressure (P), kg cm^{-2}	3	4	5
Type of nozzle (N)	Hollow cone (HC)	Solid cone (SC)	Flat fan (FF)
Performance parameters			
Droplet size (µm)			
Droplet density (No's cm^{-2})			

Droplet density (D_d): By using droplet analyzer, the number of droplet spots on one square centimetre (cm^2) area of water sensitive paper was obtained. The number of droplets per square centimetre area is termed as droplet density. The droplet density was also measured in Deposit Scan software.

Experimental design and statistical analysis: Response Surface Methodology (RSM) is one of the popular statistical tools used for analysis of variable data and to examine the extent of relationship between independent variables and performance parameters (Lee et al 2006). There are various designs in RSM including Central Composite Rotatable Design (CCRD), Box-Behnken Method and Optimal (Custom) Design. The variables selected for the study consist of both numerical and categorical factors. Hence, Optimal design best fits for the experimentation.

Optimal design is a recommended choice when both categorical and numeric factors, constraints, need to fit a cubic or higher order model, or trying to fit a custom model (El-Gendy et al 2016). Three levels of numerical independent variables were selected with coded values of - 1, 0 and + 1. Two nominal levels of categorical factor were chosen. The response function in optimal design is expressed in the following linear equation form and used in data analysis.

$$Y = \beta_o + \sum_{i=1}^{q} \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum_{i=1}^{q} \sum_{j=i+1}^{q} \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

Where,

Y= response, β_o= intercept, β_i, β_{ii}, β_{ij} = regression coefficients, X_i, X_j= coded variables and ε = error

Design Expert (v12.0) statistical software was used for the analysis of data and interpretation of results.

Parametric optimization: Parametric optimization was carried out using Taguchi method to find out optimum combination of independent parameters that maximize the performance of the developed sprayer.

Taguchi method: Taguchi method is one of the robust statistical tools in the design of experiments. It provides lesser numbers of experiments while giving more quantitative information (Kazemian et al 2021). Taguchi orthogonal array can be regarded as a general fractional factorial design process and it can analyze the experimental data based on the SN ratio (Kuo et al 2011 and Girish et al 2019). In present study, Taguchi orthogonal array of L9 configuration was constructed in Minitab 19 software considering height of spray (H), operating pressure (P) and type of nozzles (N) at three levels each (Table 2). Measured values of performance parameters *i.e.,* droplet size (D_s) and droplet density (D_d) were recorded and given as result inputs for further analysis. The goal was to optimize the combination of independent parameters which will minimize the droplet size and maximize the droplet density. Hence, the goal of "Smaller is Better" was set for droplet size and "Larger is Better" was set for droplet density in Taguchi method using following model equations.

(Smaller is better)

$$Z = -10\log\frac{\sum_{i=1}^{n} y_i^2}{n} \quad (2)$$

(Larger is better)

$$Z = -10\log\frac{\sum_{i=1}^{n} \frac{1}{y_i^2}}{n} \quad (3)$$

Where, Z = S/N ratio, y = Response factor

RESULTS AND DISCUSSION

The developed SPRC sprayer was evaluated in laboratory conditions to arrive at optimal combination of affecting parameters and take up the field evaluation under optimized conditions.

Laboratory Evaluation of Solar Powered Remote-Controlled Sprayer

Droplet size (D_s): The maximum droplet size of 236.40 µm was obtained at 30 cm height of spray, operating pressure of 3 kg cm^{-2} for solid cone nozzle. The droplet size varied from 165.80 to 236.40 µm with a mean value of 207.25 µm. The minimum value was observed at 40 cm height of spray, operating pressure of 5 kg cm^{-2} for flat fan nozzle (Table 3). The droplet size decreased with increase in operating pressure and height of spray for all three types of nozzles. This may be because of the fact that droplet size is inversely proportional to the operating pressure and as the height of spray increased, the spray droplets were subjected to more descent time before getting deposited on the target during which a part of the droplet either get evaporated or get halved by air resistance. Droplet sizes of solid cone nozzle were on higher side compared to other two types of nozzles (Fig. 4).

Droplet density (D_d): The droplet density varied between 28.40 and 93.30 No's cm^{-2} with a mean value of 51.62 No's cm^{-2}. The maximum droplet density was obtained at 20 cm height of spray, operating pressure of 5 kg cm^{-2} for flat fan nozzle. The minimum value was observed at 40 cm height of spray, operating pressure of 4 kg cm^{-2} for solid cone nozzle (Table 3). The droplet density increased with increase in operating pressure and decreased with height of spray for all three types of nozzles (Fig. 5). This may be attributed to the fact that operating the sprayer at higher pressure releases a greater number of droplets from the nozzle and hence the density also increases and as the height of spray increases, the deposition rate of droplets over the target plant decreases because of drift caused by prevailing wind. Droplet density of flat fan nozzle had highest values followed by hollow cone

Table 2. Orthogonal array in Taguchi Design

Height of spray (H), cm	Operating pressure (P), kg/cm^2	Type of nozzle (N)
20	3	HC
30	3	SC
40	3	FF
20	4	SC
30	4	FF
40	4	HC
20	5	FF
30	5	HC
40	5	SC

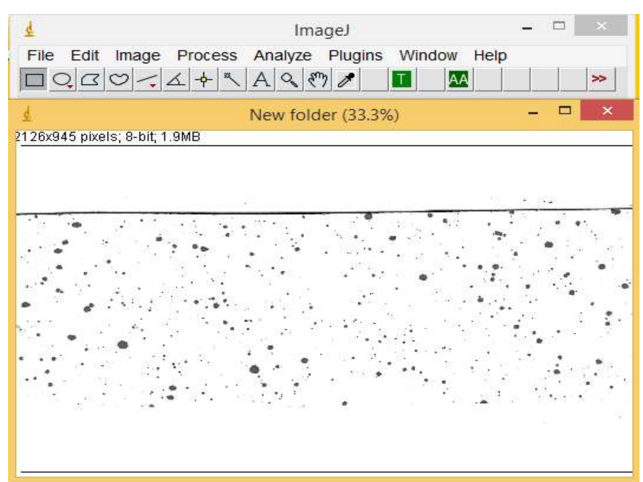

Fig. 3. User interface of image programme in deposit by scan software

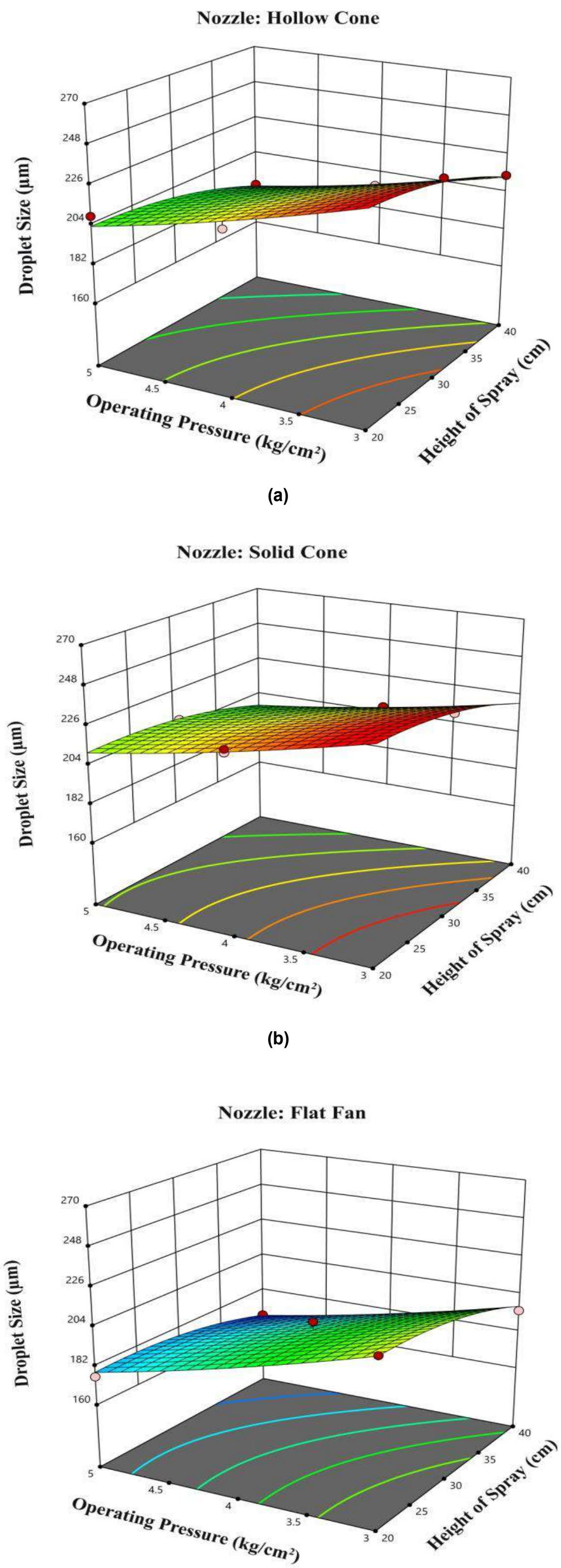

Fig. 4. Effect of height of spray (H) and operating pressure (P) on droplet size (D_s) for hollow cone (a), solid cone (b) and flat fan (c) nozzles

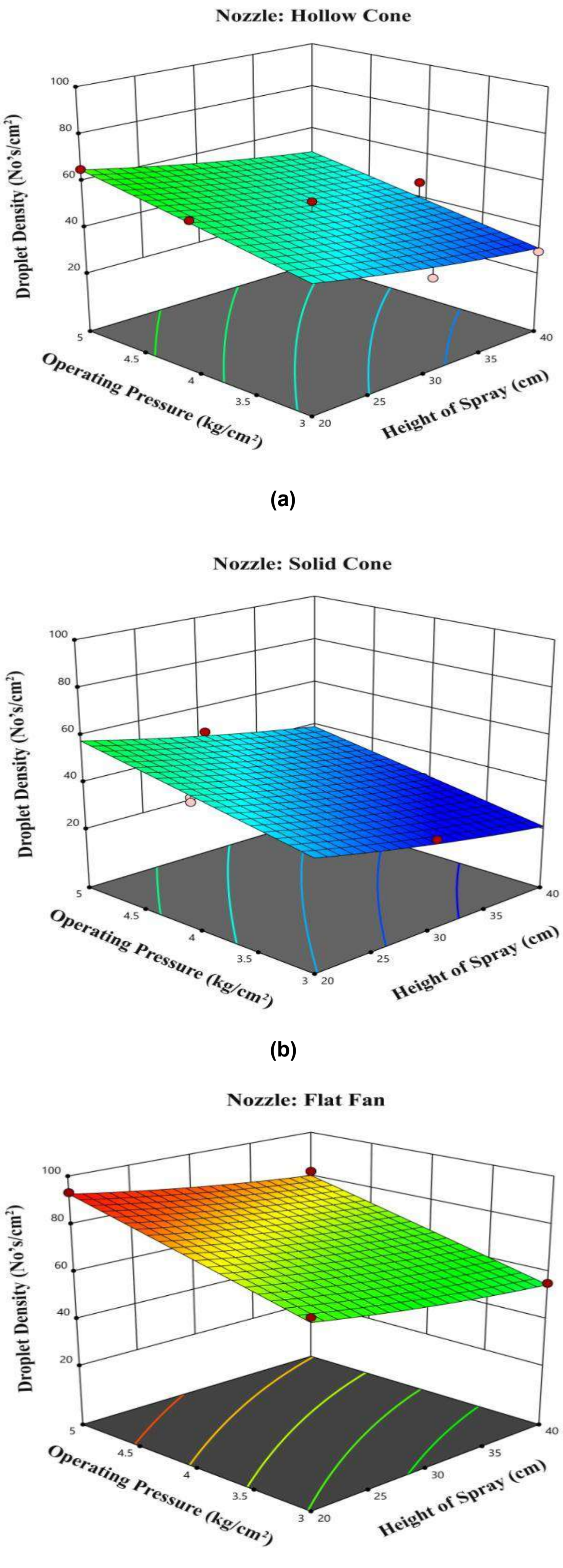

Fig. 5. Effect of height of spray (H) and operating pressure (P) on droplet size (D_s) for hollow cone (a), solid cone (b) and flat fan (c) nozzles on droplet density (D_d)

Table 3. Variables with coded values and of laboratory evaluation using optimal design in RSM

Height of spray (H), cm	Operating pressure (P), kg cm^{-2}	Type of nozzle (N)	Droplet size (D_s), μm	Droplet density (D_d), No's cm^{-2}
40 (+1)	3 (-1)	HC	214.10	29.50
30 (0)	4 (0)	HC	211.30	51.60
30 (0)	4 (0)	FF	192.4	70.30
20 (-1)	5 (+1)	FF	176.10	93.30
20 (-1)	4 (0)	HC	215.80	57.20
20 (-1)	4 (0)	SC	224.40	46.30
20(-1)	4 (0)	SC	226.30	48.20
40 (+1)	4 (0)	SC	207.90	28.40
30 (0)	3 (-1)	SC	236.40	30.90
30 (0)	5 (+1)	SC	208.80	49.20
30 (0)	3 (-1)	HC	233.60	33.40
20 (-1)	3 (-1)	FF	216.80	69.20
30 (0)	5 (+1)	HC	195.20	53.80
30 (0)	5(+1)	SC	208.80	49.20
30 (0)	3 (-1)	SC	236.40	30.90
40 (+1)	5 (+1)	FF	165.80	82.30
40 (+1)	3 (-1)	FF	194.50	55.60
20 (-1)	5 (+1)	HC	209.20	65.40
40 (+1)	4 (0)	HC	195.90	47.00
40 (+1)	4 (0)	SC	207.90	28.40
30 (0)	4 (0)	FF	197.50	70.30
40 (+1)	5 (+1)	HC	184.30	45.20

Table 4. Mean droplet size and SN ratios for droplet size and droplet density

Means droplet size (D_s)					
Level	1	2	3	Delta	Rank
Height	229.4	224.1	211.8	17.6	1
Pressure	228.3	222	215.1	13.3	2
Nozzle	217.9	221.3	226.2	8.3	3
SN Ratios (Smaller is better)					
Level	1	2	3	Delta	Rank
Height	-47.21	-47	-46.52	0.7	1
Pressure	-47.17	-46.92	-46.64	0.53	2
Nozzle	-46.75	-46.89	-47.09	0.33	3
Droplet Density (D_d)					
Level	1	2	3	Delta	Rank
Height	48.5	58.07	64.13	15.63	2
Pressure	44.3	59.7	66.7	22.4	1
Nozzle	60.7	52.67	57.33	8.03	3
SN Ratios (Larger is better)					
Level	1	2	3	Delta	Rank
Height	33.59	35.08	36.05	2.46	2
Pressure	32.87	35.38	36.46	3.58	1
Nozzle	35.36	34.22	35.14	1.14	3

and solid cone nozzles, respectively.

Optimization of operational parameters using Taguchi method: The results obtained by experiments were fitted into L9 array given by Taguchi design and analysis was carried out for both droplet size (D_s) and droplet density (D_d). Responses for SN ratio and means of droplet size with a goal of "smaller is better" were obtained. The height of spray (H) had highest effect on droplet size with a rank of 1 followed by operating pressure (P) and type of nozzle (N). Similarly response table for SN ratio and response for means of droplet density with a goal of "larger is better" were also obtained. The operating pressure (P) had highest influence on droplet density followed by height of spray (H) and type of nozzle (N) (Table 4).

The optimum parametric combination was H3P3N1 which corresponds to 40 cm height of spray (H), 5 kg cm^{-2} operating pressure (P) and hollow cone nozzle (N) (Fig. 6, 7). The main effect plot for means and main effect plot for SN ratio of droplet density (D_d) indicate that parametric combination of H3P3N1 gave the optimum combination with "larger is better" goal (Fig. 8, 9).

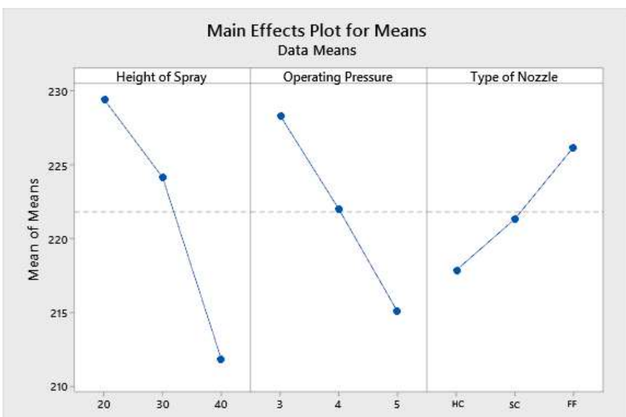

Fig. 6. Main effect for mean (smaller is better) for droplet size (D_s)

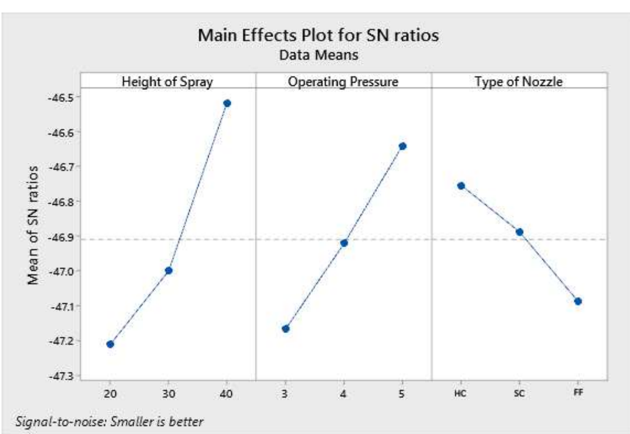

Fig. 7. Main effect on SN ratios (smaller is better) for droplet size (D_s)

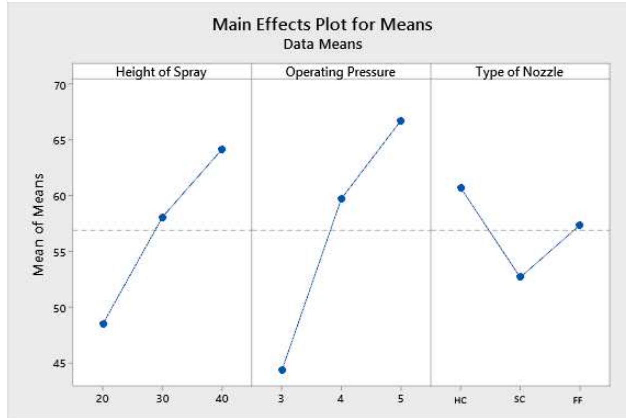

Fig. 8. Main effect for means (larger is better) for droplet density (D_d)

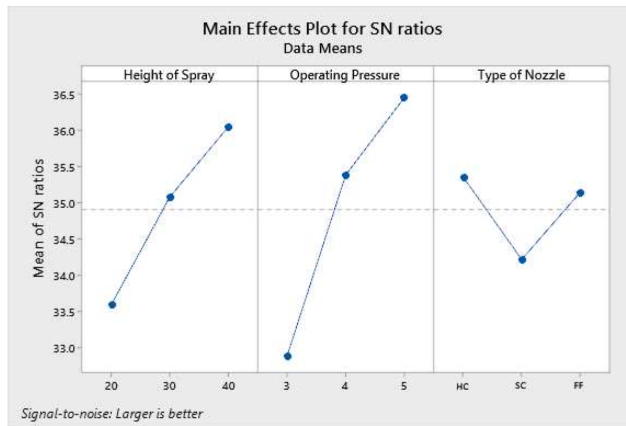

Fig. 9. Main effect plot for SN ratios (Larger is better) for Droplet Density (D_d)

CONCLUSIONS

Droplet size (D_s) was significantly affected by selected independent variables and decrease with increase in height of spray and operating pressure. The hollow cone nozzle produced the smallest value of droplet size. All the selected independent parameters significantly affected the droplet density (D_d). The droplet density decreased with increase in height of spray and increased with increase in operating pressure. Taguchi analysis of parameters revealed that the optimum height of spray was 40 cm, operating pressure was 5 kg cm^{-2} and hollow cone type nozzle was the best among selected parameters to operate the developed SPRC sprayer.

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