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Parameter Optimization of Newly Developed Self-Propelled Variable Height Crop Sprayer Using Response Surface Methodology (RSM) Approach

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Abstract: The number of spray deposits plays an important role in effective and efficient spraying. The spraying equipment is one of the most significant factors that affect the number of spray deposits. Therefore, the study was focused on the parameter optimization of a newly developed self-propelled variable height crop sprayer. Response surface methodology (RSM) along with Box–Behnken design (BBD) was used to study the effect of the independent variables (forward speed, spray height, and spray pressure) on response variables such as droplet density, coverage per-centage, and Volume Median Diameter (VMD). The experiment was conducted in the cotton field. Additionally, the RSM model was validated in this research. The results revealed that the coefficient of determination (R2) values was good for all response variables in the quadratic polynomial model. The optimized parameters were 6.5 km/h, 60 cm, 4 bar for fungicide application, and 8 km/h, 70 cm, 3 bar for insecticide and herbicide application. The predicted response variable values at the optimal conditions were 60.4 droplet/cm^2, 27%, 230 µm for fungicides and 37.8 droplet/cm^2, 19.1%, 225.4 µm for insecticide and herbicides application. The model validation is confirmed by the mean of actual response variable values at the optimal condition for insecticide and herbicides application, which was 41.35 ± 3.67 droplet/cm^2, 21.10 ± 1.72%, 227.43 ± 1.22 µm, and the prediction error was 8.46%, 9.2%, and 0.9% for droplet density, coverage percentage, and VMD, respectively. This study can provide support for further optimizing the parameters of the sprayer.

Keywords: self-propelled sprayer; response surface methodology; forward speed; spray height; spray pressure; droplet density; coverage percentage; VMD

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Citation: Khan, F.A.; Ghafoor, A.; Khan, M.A.; Umer Chattha, M.; Kouhanestani, F.K. Parameter Optimization of Newly Developed Self-Propelled Variable Height Crop Sprayer Using Response Surface Methodology (RSM) Approach. *Agriculture* **2022**, *12*, 408. https://doi.org/10.3390/agriculture12030408

Academic Editor: John M. Fielke

Received: 22 February 2022
Accepted: 10 March 2022
Published: 14 March 2022

1. Introduction

Plant protection products are mainly used to control pests and diseases. However, the implementation of Integrated Pest Management Programs (IPMs) in recent years has optimized the application of these products [1–4]. Even so, IPM practices are still only applied on a small scale, and the risk of environmental pollution due to pesticide use has increased. Some studies found the residue of pesticides in the soil [5,6] as well as in surface and groundwater. In general, a small percentage of the sprayed liquid retains on the plant canopy whilst the rest of it is either deposited to the ground or drifted. The foliar application of plant protection products is considered an inefficient process [7,8]. Likewise, when the spray deposition on the plant canopy is close to the control threshold for the infestation or disease with minimal losses to deposition or drift, this foliar application is considered adequate [8,9].

Several studies have shown that spraying equipment is one of the most significant factors affecting the efficient use of plant protection products on different types of crops [10–12]. The spray losses to ground, the quantity of the pesticide retained by the canopy, and uniform distribution depend on the type of spray equipment [13], the position and type of nozzle [13], and the application rate [12].

Several efforts have been made to optimize the operating parameters of spraying equipment. The optimum forward speed of field sprayers was reported between 6 and 8 km/h for pesticide applications and lower forward speeds were suggested during high wind speeds [14]. In constant-volume anti-drift nozzles, surface coverage rate, droplet density, and spray efficiencies were increased with increasing forward speed (6.4, 13.0, 19.0, and 26.0 km/h) [15]. The maximum boom heights recommended for nozzles with 50 cm constant spacing and 65°, 80°, 110°, and 120° nozzle angles are 75 cm, 60 cm, 40 cm, and 40 cm, respectively [16]. The droplet evaporation will increase by increasing spray heights with the impact of temperature and humidity. Such cases ultimately increase pesticide losses [17]. The optimum boom height was reported as 38 cm for standard low-pressure nozzles [18]. The recommended spray height for 110° spray angle is between 40 and 80 cm and the height for 80° spray angle is between 80 and 120 cm [19]. Sanchez-Hermosill et al. reported that the average deposit was higher at 10 bar and 15 bar spray pressure compared with 20 bar spray pressure [20].

The optimization of operating parameters of spraying equipment is mainly dependent on spray coverage quality standards. The spray coverage quality standards aim to improve the spraying effectiveness. Several spraying parameters define the coverage quality of the target area, these parameters include the number of droplets, coverage percentage, and droplet size [21]. By increasing the number of droplets per unit area, the effectiveness of the spray increases by improving the probability of reaching a certain threshold for pest control [21]. According to Syngenta Crop Protection AG, the critical limits are 20–30 droplets per cm^2 for insecticides or pre-emergence herbicides, 30–40 droplets per cm^2 for postemergence herbicides, and 50–70 droplets per cm^2 for fungicides [22–24]. The spray VMD classification according to the American Society of Agricultural and Biological Engineers (ASABE) S572.1 standard are extremely fine (<60 μm), Very fine (61–105 μm), Fine (106–235 μm), Medium (236–340 μm), Coarse (341–403 μm), Very coarse (404–502 μm), extremely coarse (503–665 μm), and Ultra coarse (>665 μm) [25]. The fine and medium size spray class is the most commonly used spray type and used for insecticides, herbicides, and systematic-acting fungicides [25].

To make an optimized spraying, several studies were focused on prediction methods for optimal and effective application of chemicals. Prediction methods are categorized into three main groups, including computer software models, regression equations, and mathematical equations [26]. To predict different parameters, computer models and simulation programs save costs and time related to field experiments [26]. The response surface methodology (RSM) is a statistical and mathematical method to analyze and optimize independent variables in various processes [26]. Furthermore, to investigate several factors and their interaction with response variables, the RSM would be used in the agriculture sector [26].

Sun et al. conducted experiments to optimize the parameter of the variable spraying liquid fertilizer machine. The spray parameters such as forward speed, spray flow rate, and plot distance was analyzed using RSM with Box–Behnken center-united design principles. The droplet distribution uniformity was evaluated as an output variable. The Design-Expert 8.0 software was used in this study [27]. Huo et al. optimized the operating parameters of a profile-modeling spray-bar on the characteristics of a high-spindle apple tree to achieve effective profile modeling. The parameters were optimized using RSM. The spray distribution coefficient of variation and effective collection rate was evaluated as response variables in this research [28]. Weicai et al. optimized the spraying parameter of the cotton defoliant sprayer. The RSM with the Box–Behnken center-united design principle was used to optimize the parameters. Droplet coverage was evaluated by creating a quadratic polynomial equation using horizontal boom height, hang boom height, and nozzle angle. The Design-Expert 8.0 software was used in this study [29].

In Pakistan, mostly manual knapsack sprayers and tractor-mounted sprayers are used to apply agrochemicals [30]. However, the manual knapsack sprayers have drawbacks such as light spray deposition, uneven distribution, heavy losses to the soil [31], and serious chemical exposure to the workers [32]. The tractor-mounted boom sprayers have relatively higher spray deposition and lower chemical exposure, but a small farm size with divided plots and complex terrains limits the use of these sprayers. In addition, the power mismatch between the boom sprayer and tractor is another issue that increases operational costs. Therefore, a self-propelled variable height crop sprayer was developed and tested to resolve the issues of small farmers.

This study focused on optimizing the combination of forward speed, spray height, and spray pressure of the newly developed self-propelled variable height crop sprayer using RSM, aiming that to minimize the cost, time, and environmental pollution.

2. Materials and Methods

2.1. Spraying Machine

The self-propelled variable height crop sprayer was used in this research (Figure 1). The sprayer consisted of a mainframe, engine, hydraulic system, and spraying mechanism. The frame material was mild steel (material grade SAE-4130). The length and width of the mainframe were 2845 mm and 1017 mm, respectively. The engine size of the sprayer was a 20-hp engine (model 2105D). The sprayer was equipped with a battery-operated hydraulic system (model 121613-08L), to control the up and down movement of the spray boom. The spray mechanism of the sprayer consisted of the liquid tank, pumps, boom, and nozzles. The liquid tank capacity was 300 L. There were four spray pumps (model BYT-7A111) with four filters (50-mesh size) in the sprayer to generate the maximum discharge of 22 L/min. The length of the horizontal boom was 6 m and there were eight hollow cone nozzles (ASJ-HC8002, Size 15 × 7 mm) at the spray boom. The flow rate of the nozzle was 0.8 L/min at 3 bar pressure. The sprayer specifications are shown in the table (Table 1).

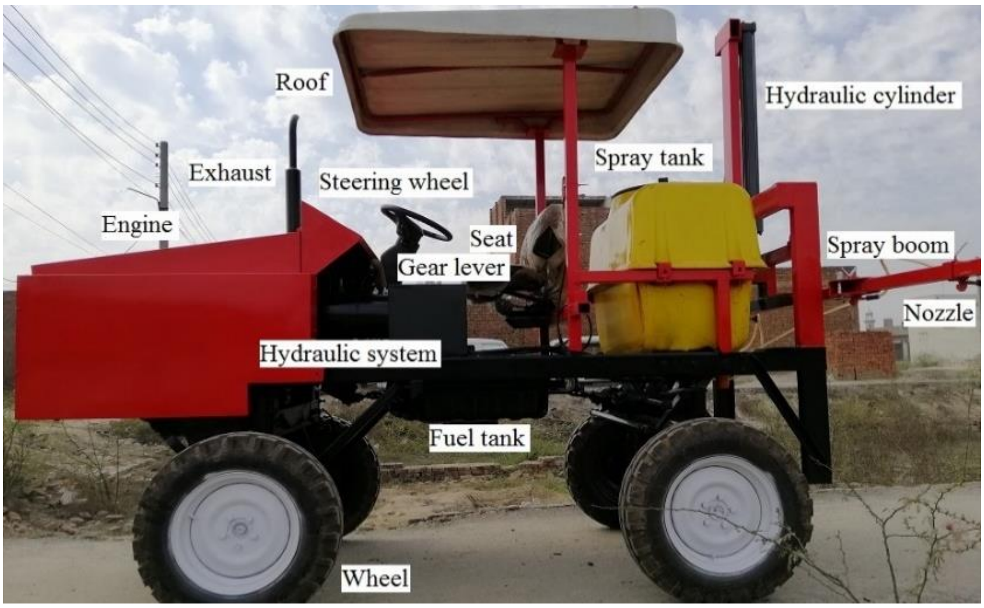


Figure 1. Self-propelled variable height crop sprayer.

Table 1. Spraying vehicle specifications.

Items		Specifications
Structure		Self-propelled
Overall dimensions		2845 mm × 1017 mm × 2440 mm
Weight		1090 kg
Wheelbase		1753 mm
Ground clearance		762–915 mm
Nozzle height from the ground		458–1220 mm
Engine power		20 hp
Driving mode		Automatic gear shift
Wheel		Four wheels
Solution tank capacity		300 L
Nozzle type		Hollow cone
	Lifting mode	Hydraulic drive
Spray boom	Folding mode	Manual drive
	Spray boom	6096 mm
	Type	Diaphragm pump
Spray pump	Pressure	24 bar
	Flow rate	22 L/min

2.2. Field Experiments

The field experiments were carried out in the cotton crop (Figure 2) at the University of Agriculture, Faisalabad, Pakistan, located at a research station (31°26′25″ N, 73°04′13″ E). The test was performed in August 2021. The crop characteristics such as plant height, plant to plant distance, row to row crop distance, and plant population were 60–70 cm, 20 cm, 60 cm, and 36,000 plant/acre, respectively. An area of 165 m × 40 m was selected with crop in uniform height and growing ways, to reduce the effect of leaf area index on droplet coverage. To ensure the sprayer travels stably, water channels were removed from the field before the experiment. To ensure sampling uniformity, water-sensitive papers (WSPs) were fixed at the top of the plant canopy. The experimental area was divided into three blocks, 10 m buffer zones were provided between the blocks. Each block (165 m × 6 m) was divided into 17-plots (each for one trial). Each plot was a 5 m × 6 m area. In each plot, there were seven crop rows, among seven crop rows. WSPs were fixed at three crop rows (Row 1, Row 4, Row 7), and each row was 2.2 m apart (Figure 3). In each row, two WSPs were fixed along the traveling direction, spaced by 5 m (Figure 3). Therefore, there were six WSPs in each plot. To avoid drift pollution, a 5 m buffer zone was also provided between the plots. Each trial was repeated three times (3 blocks). The spray was started and stopped 5 m away from the trial plot to achieve the uniform spraying.

(**a**) (**b**) (**c**)

Figure 2. Field trials: (**a**) Sprayer in the cotton field during trials, (**b**) water-sensitive paper placement at the top of the plant canopy, (**c**) water-sensitive paper after spraying.

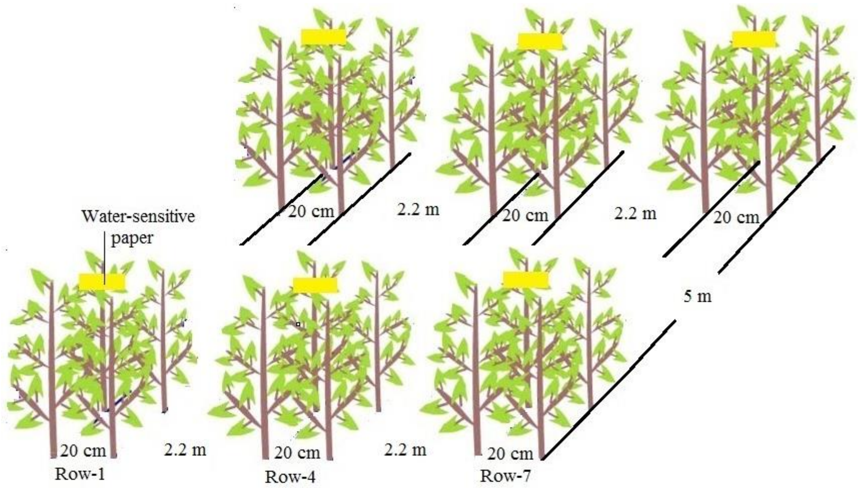


Figure 3. Experimental plan for each plot.

In all spray trials, freshwater was used as a spraying liquid. The forward speed of the sprayer was calibrated manually using measuring tape and a stopwatch. The spray height above the plant canopy was controlled with a hydraulic system and measured with measuring tape before each trial. The spray pressure was regulated using a pressure regulation valve and measured with a pressure gauge.

After nearly 30–40 s of spraying, WSPs at each plot were collected and stored in a separate labeled sealed bag, the label describing spray treatment, replication, and location information. Immediately after collection sampling bags were placed into a light-proof seal [33] box and transported to the laboratory for analysis. In the laboratory, the WSPs were scanned using a 600-dpi scanner, and droplet deposits were analyzed employing Depositscan software [23]. Depositscan software was used to measure the droplet deposits in the digital image and analyzed the droplet density, coverage percentage, and VMD. When software starts, first open the ImageJ window then the user is required to scan the WSP. After scanning, the image is converted into an 8-bit grayscale image. In the next step, to activate the command "count black and white pixels" and select the area for analysis, the ANALYSIS feature in ImageJ is used. The results are generated as the percentage area covered by the spots and the total number of spots. In the last step, the software calculates the droplet size such as DV1, DV5, and D9, DV1 indicates that 10% of the volume of spray is in droplets smaller than the expressed values, DV5 means that 50% of the volume of spray is in droplets either smaller or higher, DV9 reveals that 90% of the volume sprayed is in droplets smaller than the given values. A DV5 was used as VMD in this study.

2.3. Weather Conditions

The environmental parameters were collected from the University of Agriculture, Faisalabad, Pakistan, Metrological Cell. The digital Kestrel device (model NK-5500, Nielsen-Kellerman Co., Pennsylvania, PA, USA) with a collection frequency of 2 s was used in the test, the temperature, humidity, and wind speed was recorded from 10:00 AM to 6:00 PM. During the test the maximum and minimum temperature was 41–23 °C, the maximum and minimum relative humidity was 45.2–35%, and the maximum and minimum wind velocity was 6.8–4.3 km/h.

2.4. Response Surface Methodology Approach

The response surface methodology (RSM) is used to optimize the independent variables. In RSM, the optimization of independent variables consisted of five steps. (1) selection of response variables; (2) selection of independent variables and allotting codes to them; (3) development of experimental design for response variables; (4) regression analysis and development of a quadratic polynomial (response generation); (5) generating 3D surface of the observed response surface and analysis of optimal conditions. The RSM along with

Box–Behnken design (BBD) was carried out with 17-trials (5 sets of center tests and 12 sets of factorial tests) using Design-Expert v13.0 software (Stat-Ease, Inc. Minneapolis, MI, USA). In RSM, the forward speed X_1, spray height X_2, and spray pressure X_3 were used as independent variables. Independent variables and their code levels are given in Table 2. The 17-trials were performed according to the BBD methodology requirement (Table 3). The droplet density, coverage percentage, and VMD were used as the response variables to evaluate the performance of the sprayer.

Table 2. Independent variables and their code level in RSM.

Independent Variables	Code	Actual	Levels		
			−1	**0**	**1**
Forward speed (km/h)	x_1	X_1	4	6	8
Spray height (cm)	x_2	X_2	40	55	70
Spray pressure (bar)	x_3	X_3	3	5	7

Note: $x_1 = (X_1 - 6)/2$; $x_2 = (X_2 - 55)/15$; $x_3 = (X_3 - 5)/2$.

Table 3. Experimental values of the independent variables. Mean and standard deviation of the response variables.

Run No.	Independent Variables			Response Variables *		
	X_1	X_2	X_3	Droplet Density	Coverage Percentage	VMD
	km/h	cm	bar	Droplets/cm^2	%	µm
1	6 (0)	40 (−1)	7 (1)	93 ± 3.32	49.2 ± 1.55	252.5 ± 2.27
2	8 (1)	55 (0)	7 (1)	59.8 ± 3.41	28.1 ± 1.67	232.1 ± 2.05
3	6 (0)	70 (1)	7 (1)	74.8 ± 3.65	35.1 ± 1.76	238.1 ± 2.13
4	6 (0)	40 (−1)	3 (−1)	76.3 ± 2.97	36.4 ± 1.82	235.1 ± 2.21
5	4 (−1)	40 (−1)	5 (0)	94.2 ± 3.15	52.9 ± 1.43	259.8 ± 2.48
6	4 (−1)	55 (0)	7 (1)	92.6 ± 2.87	48.8 ± 1.62	255.5 ± 2.39
7	8 (1)	55 (0)	3 (−1)	44.6 ± 3.46	20.5 ± 1.51	225.4 ± 2.16
8	6 (0)	55 (0)	5 (0)	70.3 ± 3.09	32.3 ± 1.64	235.6 ± 1.97
9	4 (−1)	55 (0)	3 (−1)	86.5 ± 2.91	44.7 ± 1.74	247.1 ± 2.27
10	6 (0)	70 (1)	3 (−1)	56.9 ± 3.23	26.6 ± 1.38	230.5 ± 2.31
11	6 (0)	55 (0)	5 (0)	72.9 ± 3.54	34 ± 1.46	239.2 ± 2.54
12	6 (0)	55 (0)	5 (0)	72.4 ± 2.83	33.5 ± 1.31	237.3 ± 2.42
13	4 (−1)	70 (1)	5 (0)	83.9 ± 3.21	42.6 ± 1.52	248.8 ± 1.99
14	6 (0)	55 (0)	5 (0)	68.7 ± 3.57	30.9 ± 1.59	233.7 ± 1.95
15	6 (0)	55 (0)	5 (0)	69.5 ± 2.98	31.7 ± 1.61	233.5 ± 2.43
16	8 (1)	70 (1)	5 (0)	49.1 ± 3.36	22.8 ± 1.49	226.4 ± 2.22
17	8 (1)	40 (−1)	5 (0)	65.6 ± 2.95	30.1 ± 1.35	231.3 ± 2.09

* All the trial data were mean values of triplicate determinations.

In the Box–Behnken design, independent variables are symbolized by X_1, X_2, and X_3; +1, 0, and −1 represent the high, middle, and low levels of each independent variable. The independent variables are coded by Equation $x_1 = (X_1 - X_0)/\Delta X$, where x_1 is the code value for an independent variable, X_1 is the actual value for an independent variable, X_0 is the actual value for an independent variable at the experimental center point, ΔX is the step size.

According to the BBD model, the quadratic polynomial regression formula is given in Equation (1).

$$Y = \beta 0 + \sum_{i=1}^{n} \beta i X_i + \sum_{i=1}^{n} \beta ii X_i^2 + \sum_{i<j}^{n} \beta ij X_i X_j \quad (1)$$

$$(i = 1, 2, 3 \ldots, n; j = 1, 2, 3 \ldots, n)$$

In above equation, Y are the response values, X are the independent values, $\beta 0$ = intercept, βi = Linear coefficient. βii = Quadratic coefficient. βij = Interaction term coefficient.

Moreover, the model validation was also carried out to check whether the predicted model agrees with actual results. For that purpose, after developing the model, three more experiments were performed in the cotton field with the same experimental procedure.

2.5. Data Analysis

To determine the relationship between the responses and model validation, several statistical parameters such as correlation coefficient of determination (R^2), predicted R^2, and adjusted R^2 were used [26,34]. Analysis of variance (ANOVA) was performed to determine the significance of the quadratic model at α = 0.05.

3. Results and Discussion

3.1. Regression Model

Regression models, including the studied parameter (forward speed, spray height, and spray pressure), were developed to predict the response variables (Equations (2)–(4)). The experiment design and results are shown in Table 3, where run No. 8, 11, 12, 14, and 15 are for sets of center tests to estimate the experiment error and all other run No. are for factorial tests.

$$Droplet\ density = +181.22799 - 5.73083\ X_1 - 1.94256\ X_2 - 3.17500\ X_3 \tag{2}$$

$$Coverage\ percentage = +142.35097 - 12.91750\ X_1 - 1.76378\ X_2 + 0.01315\ X_2^2 \tag{3}$$

$$VMD = +333.54708 - 18.29958\ X_1 - 1.34617\ X_2 - 5.58542\ X_3 + 0.836250\ X_1^2 \tag{4}$$

In all the above equations, X_1 is the forward speed in km/h, X_2 is the spray height in cm, and X_3 is the spray pressure in the bar.

3.2. Analysis of Variance (ANOVA)

The results of droplet density, coverage percentage, and VMD were analyzed using Design-Expert software, which is given in Table 3. Three different tests, a sequential model sum of squares, lack of fit, and model summary were carried out, to check the adequacy of the model. Analysis of variance (ANOVA) for the quadratic models revealed that all independent variables were significant as $p < 0.05$. The results are shown in Tables 4–6.

Table 4. ANOVA for droplet density.

Source	SS	df	MS	*F*-Value	*p*-Value	Result
Model	3381.44	9	375.72	39.87	<0.0001	significant
X_1-Forward speed	2383.95	1	2383.95	252.98	<0.0001	
X_2-Spray height	518.42	1	518.42	55.01	0.0001	
X_3-Spray pressure	390.60	1	390.60	41.45	0.0004	
$X_1\ X_2$	9.61	1	9.61	1.02	0.3462	
$X_1\ X_3$	20.70	1	20.70	2.20	0.1818	
$X_2\ X_3$	0.3600	1	0.3600	0.0382	0.8506	
$X_1{}^2$	3.94	1	3.94	0.4182	0.5384	
$X_2{}^2$	48.89	1	48.89	5.19	0.0568	
$X_3{}^2$	4.93	1	4.93	0.5236	0.4928	
Residual	65.96	7	9.42			
Lack of Fit	52.65	3	17.55	5.27	0.0710	not significant
Pure Error	13.31	4	3.33			

Table 4. *Cont.*

Source	SS	df	MS	*F*-Value	*p*-Value	Result
Cor Total	3447.40	16				
Std. Dev	3.07		R^2	0.9809		
Mean	72.42		Adj. R^2	0.9563		
C.V%	4.24		Pre. R^2	0.7569		
			Adeq Precision	22.346		

Table 5. ANOVA for coverage percentage.

Source	SS	df	MS	*F*-Value	*p*-Value	Result
Model	1380.60	9	153.40	45.44	<0.0001	significant
X_1-Forward speed	957.03	1	957.03	283.50	<0.0001	
X_2-Spray height	215.28	1	215.28	63.77	<0.0001	
X_3-Spray pressure	136.12	1	136.12	40.32	0.0004	
X_1 X_2	2.25	1	2.25	0.6665	0.4412	
X_1 X_3	3.06	1	3.06	0.9072	0.3726	
X_2 X_3	4.62	1	4.62	1.37	0.2802	
$X_1{}^2$	11.60	1	11.60	3.44	0.1062	
$X_2{}^2$	36.89	1	36.89	10.93	0.0130	significant
$X_3{}^2$	8.08	1	8.08	2.39	0.1658	
Residual	23.63	7	3.38			
Lack of Fit	17.14	3	5.71	3.52	0.1277	not significant
Pure Error	6.49	4	1.62			
Cor Total	1404.23	16				
Std. Dev	1.84		R^2	0.9832		
Mean	35.31		Adj. R^2	0.9615		
C.V%	5.20		Pre. R^2	0.7975		
			Adeq Precision	24.402		

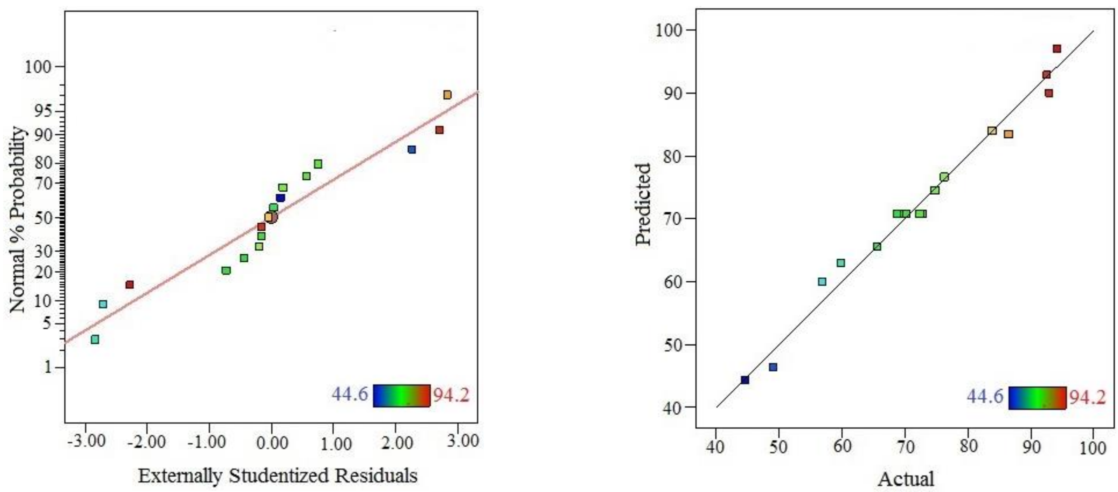
Table 6. ANOVA for VMD.

Source	SS	df	MS	*F*-Value	*p*-Value	Result
Model	1619.25	9	179.92	30.58	<0.0001	significant
X_1-Forward speed	1152.00	1	1152.00	195.78	<0.0001	
X_2-Spray height	152.25	1	152.25	25.87	0.0014	
X_3-Spray pressure	201.00	1	201.00	34.16	0.0006	
X_1 X_2	9.30	1	9.30	1.58	0.2490	
X_1 X_3	0.7225	1	0.7225	0.1228	0.7363	
X_2 X_3	24.01	1	24.01	4.08	0.0831	
$X_1{}^2$	47.11	1	47.11	8.01	0.0254	significant

Table 6. *Cont.*

Source	SS	df	MS	*F*-Value	*p*-Value	Result
X_2^2	23.65	1	23.65	4.02	0.0850	
X_3^2	2.83	1	2.83	0.4811	0.5103	
Residual	41.19	7	5.88			
Lack of Fit	17.66	3	5.89	1.00	0.4788	not significant
Pure Error	23.53	4	5.88			
Cor Total	1660.44	16				
Std. Dev	2.43		R^2	0.9752		
Mean	238.94		Adj. R^2	0.9433		
C.V%	1.02		Pre. R^2	0.8077		
			Adeq Precision	19.363		

The normal percentage probability plot of residuals for droplet density, coverage percentage, and VMD (Figures 4a, 5a and 6a) shows that residuals are lying on a straight line and 95% of residuals are falling within three-sigma limits. This indicates that errors are normally distributed [29]. Figures 4b, 5b and 6b show that the actual values are following the predicted ones calculated from the models. As all the plots for droplet density, coverage percentage, and VMD (Figures 4–6) satisfy the prediction capability criteria and the error normality, it is deduced that ANOVA results for the response variable are reliable.



(**a**) (**b**)

Figure 4. (**a**) Normal % probability plot of residuals for droplet density; (**b**) plot of actual vs. predicted response for droplet density.

The *F*-values of 39.87, 45.44, and 30.58 in Tables 4–6, indicate the model is significant. There is only a 0.01% chance for an *F*-value this large could occur due to noise in the case of droplet density, coverage percentage, and VMD. The confidence interval was 95% in this study. The results show that model factors are significant as *p*-value less than 0.05 for droplet density, coverage percentage, and VMD (Tables 4–6). The lack of fit was non-significant ($p > 0.05$) relative to the pure error for all response variables, which showed that model data was accurate (Tables 4–6). Lack of fit tells us whether a regression model is a poor model, the Lack of fit *p*-value must be greater than 0.05 confidence interval. The lack of fit can be calculated by dividing the lack of fit mean square by the pure error mean square. Furthermore, the coefficient of determination (R^2) is computed to check whether the fitted model truly explains the experimental data. To fit the regression model, the R^2 value must not be less than 0.8 [26]. The R^2 value for droplet density, coverage rate, and VMD was 0.9809, 0.9832, and 0.9752, respectively. The R^2 value indicates that the model is statistically accurate as R^2 values were greater than 0.8. The Predicted R^2 of 0.7569, 0.7975, and 0.8077 is in reasonable agreement with the Adjusted R^2 of 0.9563, 0.9615, and 0.9433 for droplet density, coverage percentage, and VMD, respectively, i.e., the difference is less than 0.2. The Adeq Precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable. The model ratio of 22.346, 24.402, and 19.363 for droplet density, coverage percentage, and VMD, respectively, indicates an adequate signal. This model can be used to navigate the design space. The higher values of R^2 and Adeq Precision indicate that this model can be considered significant for predicting the experimental results. The coefficient of variation (CV) is 4.24, 5.20, and 1.02 for droplet density, coverage percentage, and VMD, respectively, which indicates the reliability of conducted experiment [29].

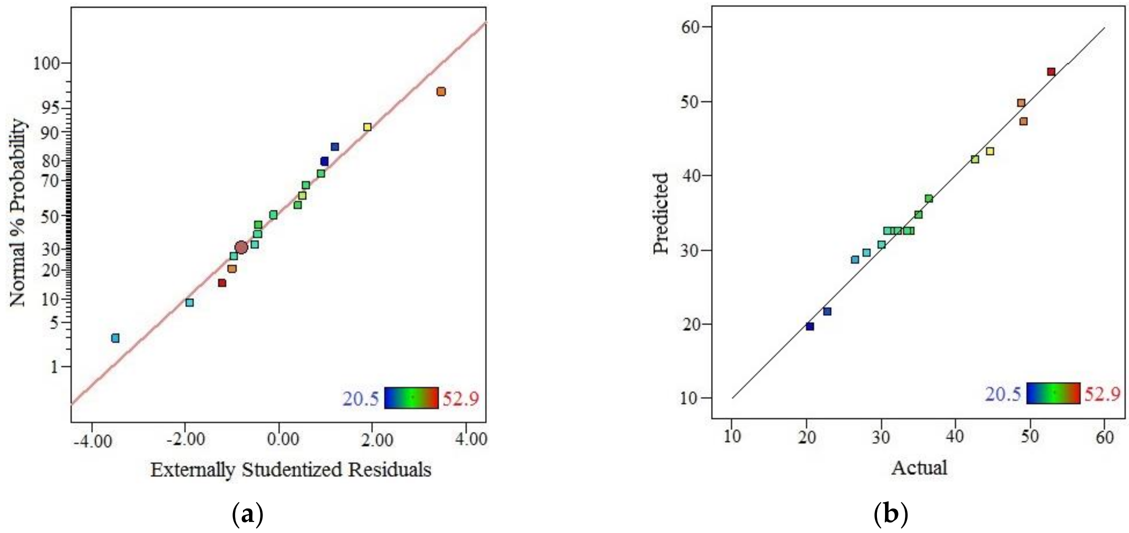


Figure 5. (**a**) Normal % probability plot of residuals for coverage percentage; (**b**) plot of actual vs. predicted response for coverage percentage.

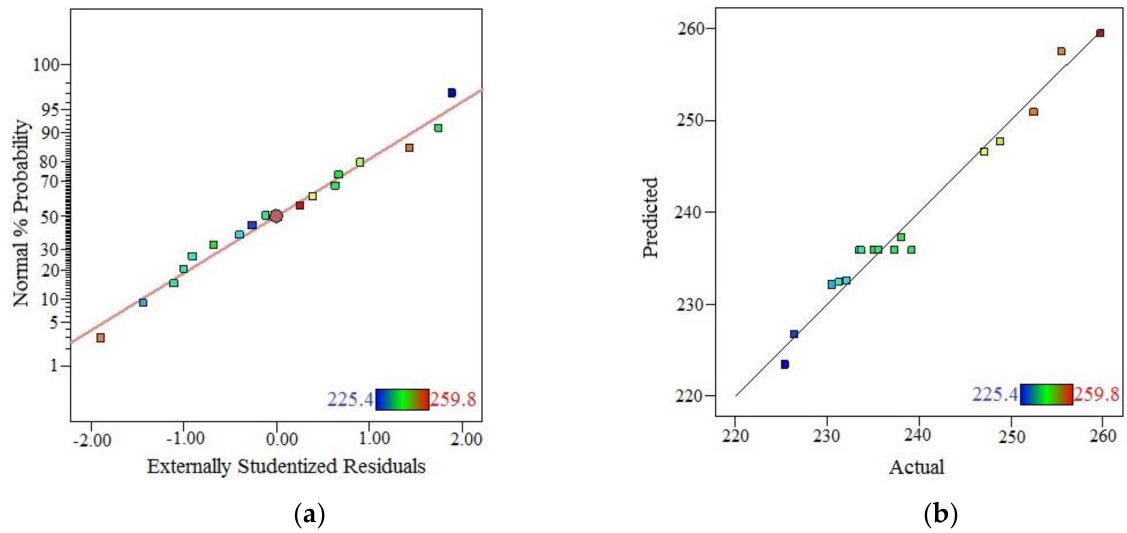
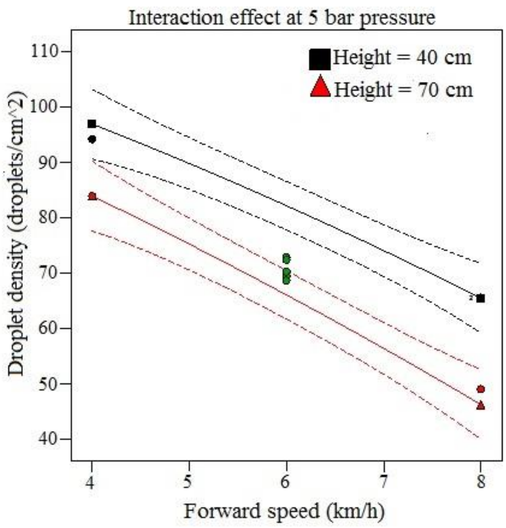


Figure 6. (**a**) Normal % probability plot of residuals for VMD; (**b**) plot of actual vs. predicted response for VMD.

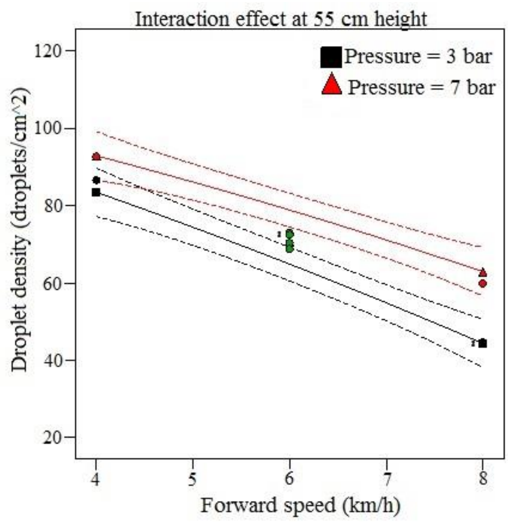
3.3. Effect of Independent Variables on Dependent Variables

3.3.1. Effect of Independent Variables on Droplet Density

The droplet density depended on forward speed, spray height, and spray pressure because of a highly significant effect at linear level ($p < 0.01$). From the regression equation of droplet density (Equation (2)), the maximum predicted droplet density was 102.5 droplet/cm^2 at speed 4 km/h, spray height 40 cm, pressure 7 bar. The minimum predicted droplet density was 37.8 droplet/cm^2 at speed 8 km/h, spray height 70 cm, pressure 3 bar. The maximum value of droplet density was due to spraying near the plant canopy at a low speed. Figure 7a showed that when spray height increased from 40 to 70 cm at the constant forward speed (4 km/h) and spray pressure (5 bar), the 10.93% decrease was observed in droplet density. Similarly, a 25.15% decrease was observed in droplet density when spray height increased from 40 to 70 cm at the constant forward speed (8 km/h) and spray pressure (5 bar). This 14.22% more decrease in droplet density from 10.93% to 25.15% was due to the forward speed effect as speed changed from 4 to 8 km/h. The reduction in droplet density at high speed could be due to boom movement, air turbulence as it passes by the nozzles, and constant application rate. Based on the results it is concluded that droplet density decreases as speed and height increase at constant pressure. Carroll reported that droplet density decreases as forward speed increases [35]. Figure 7b showed that when spray pressure increased from 3 to 7 bar, the droplet density increased from 86.5 to 92.6 droplets/cm^2 at the constant forward speed (4 km/h) and spray height (55 cm). Similarly, the droplet density increases from 44.6 to 59.8 droplets/cm^2, when spraying pressure increases from 3 to 7 bar at the constant forward speed (8 km/h) and spray height (55 cm). The increase in the droplet density was due to a change in application rate, as pressure increases, the application rate also increases. Carroll reported that the application rate increases as pressure increases [35]. Thus, it is concluded that the droplet density increases as pressure increases. Figure 7c showed that when both spray height and pressure increased from lower level to higher level (40 to 70 cm and 3 to 7 bar) simultaneously at a constant speed (6 km/h), a 2% decrease was observed in droplet density. This shows that when both height and pressure change simultaneously at a constant speed, the change in the droplet density will be minor because of the combined effect of both height and pressure.

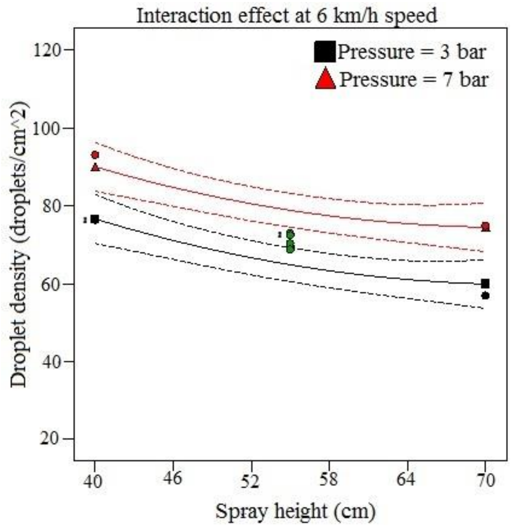


(**a**)



(**b**)

Figure 7. *Cont.*

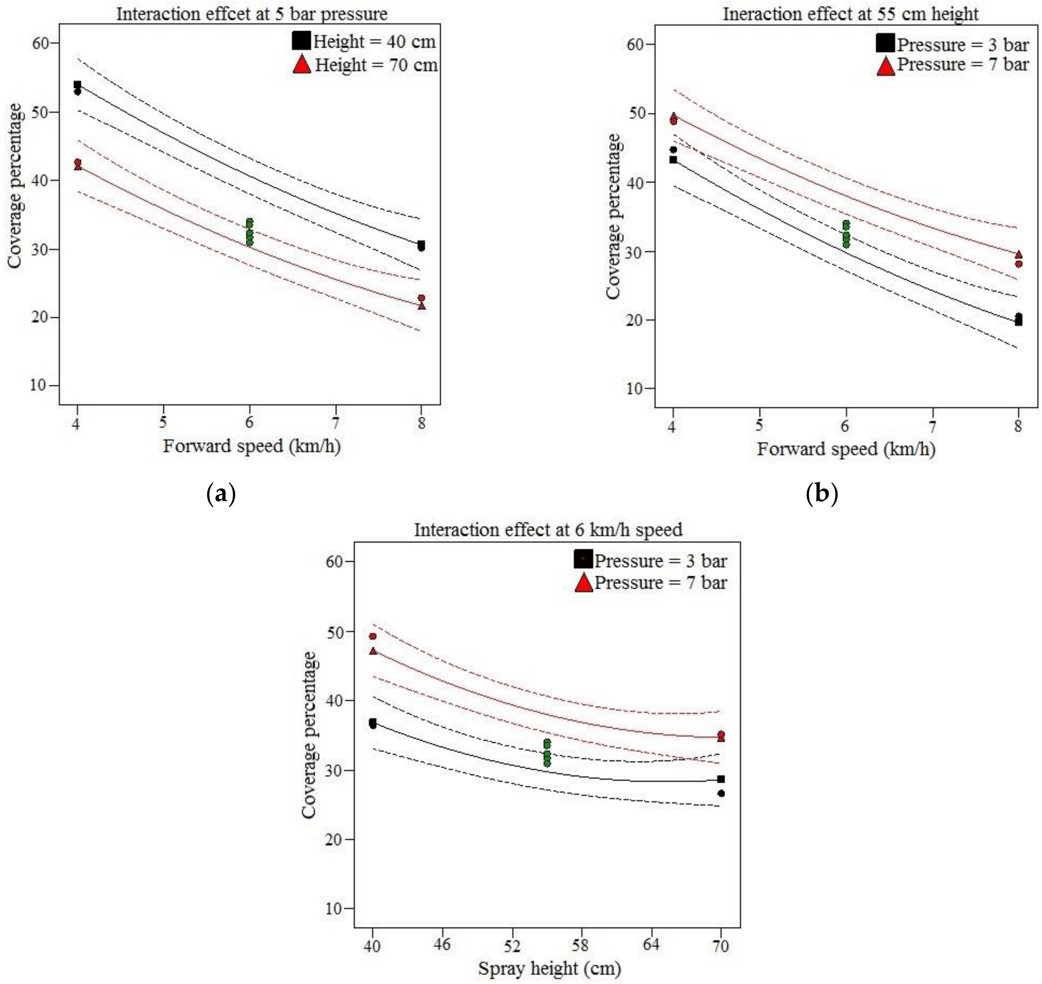


(**c**)

Figure 7. Droplet density: (**a**) relationship between forward speed and spray height at 5 bar pressure; (**b**) relationship between forward speed and pressure at 55 cm spray height; (**c**) relationship between spray height and pressure at 6 km/h speed.

3.3.2. Effect of Independent Variables on Coverage Percentage

The effect of forward speed, spray height, and pressure on coverage percentage was highly significant at the linear level ($p < 0.01$). The effect of height on coverage percentage was significant at the quadratic level ($p < 0.05$). From the regression equation of coverage percentage (Equation (3)), the maximum and minimum predicted coverage percentage was 59.7 and 19.1% at 4 km/h, 40 cm, 7 bar and 8 km/h, 70 cm, 3 bar, respectively. The coverage percentage is dependent on application rate and droplet size. Coverage percentage increases with an increase in application rate [35], on the other hand, coverage percentage increases with fine droplet size [17]. Figure 8a showed that when spray height increased from 40 to 70 cm, the 19.47% decrease was observed in coverage percentage at the constant forward speed (4 km/h) and spray pressure (5 bar). Additionally, when spray height increased from 40 to 70 cm at the constant forward speed (8 km/h) and spray pressure (5 bar), a 24.25% decrease was observed in coverage percentage. This 4.78% more decrease from 19.47% to 24.25% in coverage percentage was due to the forward speed as at high speed, application rate decreases at constant pressure. Carroll reported the same trend [35]. This shows that coverage percentage decreases as speed and height increase at constant pressure. Sayinci et al. reported decreasing coverage percentage with increasing forward speed and spray height [17]. Nansen et al. also reported that spray coverage decreases as sprayer speed increases [36]. Figure 8b showed that when spray pressure increased from 3 to 7 bar, the coverage percentage increased from 44.7 to 48.8% at the constant forward speed (4 km/h) and spray height (55 cm). Similarly, the coverage percentage increases from 20.5 to 28.1%, when spray pressure increased from 3 to 7 bar at the constant forward speed (8 km/h) and spray height (55 cm). This shows that the coverage percentage increases as pressure increases. Ranta et al. reported the same trend [21]. Carroll also reported that coverage percentage increases as pressure increases [35]. Figure 8c showed that at a constant speed (6 km/h), a 3.6% decrease was observed in coverage percentage when both spray height and pressure increased from low level to high level (40 to 70 cm and 3 to 7 bar) simultaneously. This shows that the coverage percentage decreases as the two parameters simultaneously increased at a constant speed. Although the application rate increases at high pressure but at the same time height was also maximum, which is why there was a small change in coverage percentage.



(**a**) (**b**)

(**c**)

Figure 8. Coverage percentage: (**a**) relationship between forward speed and spray height at 5 bar pressure; (**b**) relationship between forward speed and pressure at 55 cm spray height; (**c**) relationship between spray height and pressure at 6 km/h speed.

3.3.3. Effect of Independent Variables on VMD

The influence of independent variables on VMD was highly significant ($p < 0.01$). The influence of forward speed on VMD was significant at the quadratic level ($p < 0.05$). From regression equation of VMD (Equation (4)), the maximum predicted value of VMD was 268.2 µm for speed 4 km/h, spray height 40 cm, pressure 7 bar and minimum predicted value of VMD was 225.4 µm, for speed 8 km/h, spray height 70 cm, pressure 3 bar. Figure 9a showed that the VMD was decreased from 259.8 to 248.8 µm when spray height increased from 40 to 70 cm at the constant speed and pressure (4 km/h, 5 bar). Likewise, a decrease was observed from 248.8 to 226.4 µm in VMD when forward speed increased from 4 to 8 km/h at the constant spray height and pressure (70 cm, 5 bar). This shows that the variation in the VMD data was due to the speed and height as speed and height increase, the VMD decreases at constant pressure. Shirwal et al. reported the same, as spray height increases, the VMD decreases [37]. Figure 9b shows that there was a 3.28% increase in VMD when spray pressure increased from 3 to 7 bar, whereas other parameters were constant (speed 4 km/h and height 55 cm). Similarly, a 2.88% increase was observed in VMD when spray pressure increased from 3 to 7 bar at the constant speed (8 km/h) and spray height (55 cm). This showed that the value of VMD increases as pressure increases. Ranta et al. reported that as pressure increases from 3 to 5 bar, the average droplet size (DV5) increases, followed by a decrease at 7 bar and increase again at 9 bar pressure [21]. Figure 9c showed that a 1.25% increase was observed in VMD when both spray height and pressure increased from low level to high level (40 to 70 cm and 3 to 7 bar) simultaneously at a constant speed (6 km/h). This shows that when both height and pressure change simultaneously at a constant speed, the effect on VMD will be small. All values of VMD of the sprayer were falling under fine and medium class (Table 3) as defined by ASABE [25]. The fine and medium size sprays are the most widely used spray type and used for insecticides, herbicides, and systematic-acting fungicides [25]. The ideal droplet size is 50–300 m. If the droplet size is less than 50 m, the droplets would be easy to drift. If the droplet size is more than 300 μm, the droplets would find it difficult to penetrate the crop canopy and adhere to the target [38].

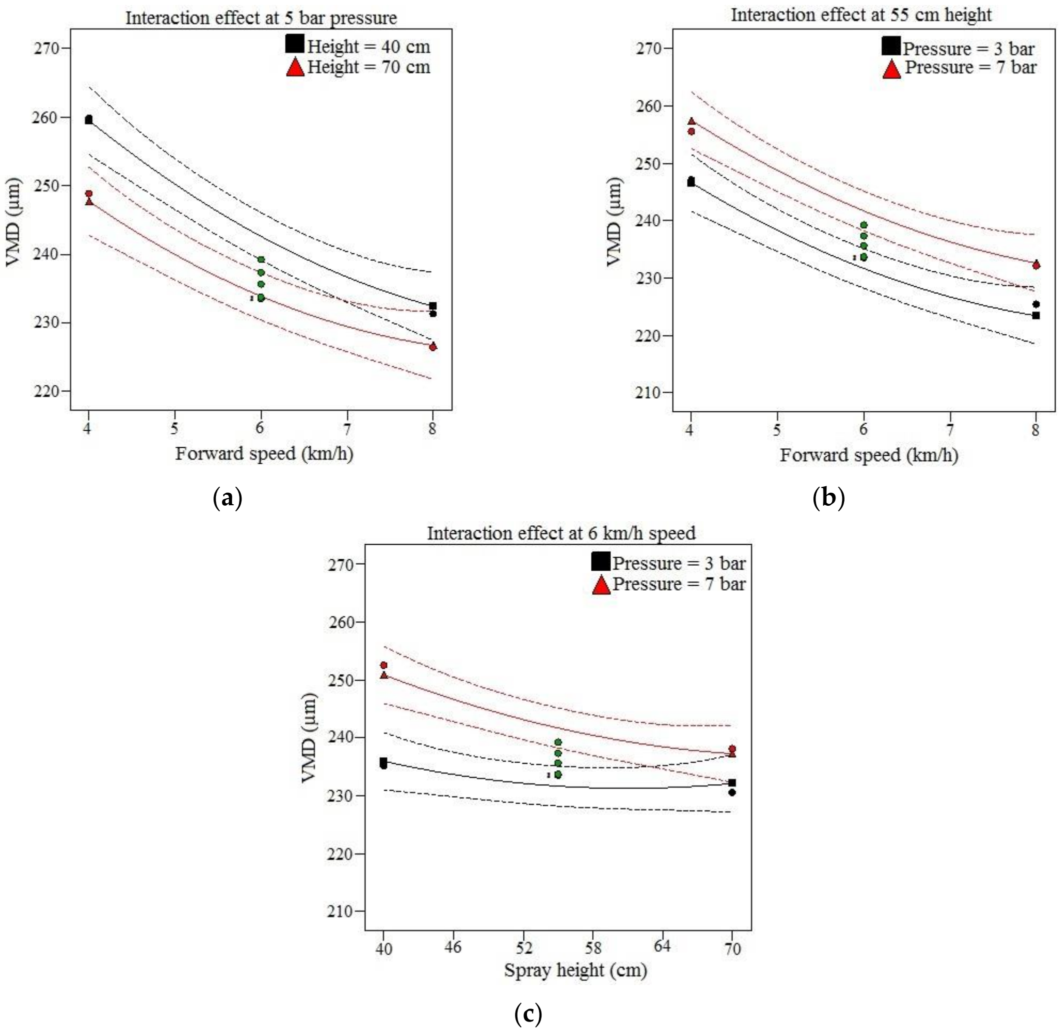


Figure 9. VMD: (**a**) Relationship between forward speed and spray height at 5 bar pressure; (**b**) Relationship between forward speed and pressure at 55 cm spray height; (**c**) relationship between spray height and pressure at 6 km/h speed.

3.4. Optimization Using RSM Approach

The optimized values of the independent variables (forward speed, spray height, and spray pressure) were selected for the response variables (droplet density, coverage percentage, and VMD) by solving regression equation using Design-Expert software (Figures 10–12). The droplet density, coverage percentage, and VMD of the spray spectrum are the deciding factor for parameter optimization. The droplet density should be within or more than the critical limit for insecticide, herbicide, and fungicide application. The critical limits are 20–30 droplets per cm^2 for insecticides or pre-emergence herbicides, 30–40 droplets per cm^2 for postemergence herbicides, and 50–70 droplets per cm^2 for fungicides [22–24]. The coverage percentage should be maximum or good enough to achieve satisfactory results [36,39], but some studies suggest that reduced coverage percentage from reduced application rate did not affect efficacy with some pesticides [40,41]. Additionally, some studies suggest that a coarser spray nozzle can be selected to maximize the coverage percentage [17,37]. On the other hand, Nansen et al. reported that the highest coverage percentage was not always achieved with the same type of nozzles due to the effect of spray setting (application rate, sprayer speed, and spray height) and weather conditions (temperature, humidity, wind speed, and barometric pressure) [36]. For this reason, the extrapolation of the results based on coverage percentage from this study is difficult. The VMD should fall within the fine or medium class for effective spray [25] as drift is higher for small-sized droplets, but it gives better coverage. On the other hand, too large droplets result in reducing deposition but are not likely to drift. Based on the droplet density critical limits and droplet size class, the optimized parameters were 6.5 km/h, 60 cm, 4 bar for fungicide application and 8 km/h, 70 cm, 3 bar for insecticide and herbicide application. The predicted response variable values at the optimal conditions were 60.4 droplet/cm^2, 27%, 230 µm for fungicide and 37.8 droplet/cm^2, 19.1%, 225.4 µm for insecticide and herbicide application. At both optimal conditions, the droplet density and droplet size were within the recommended range and the coverage percentage was also high enough. The values of droplet density, coverage percentage, and VMD at both optimal conditions are unlikely to continue indefinitely due to environmental factors but were consistent during the experiment.

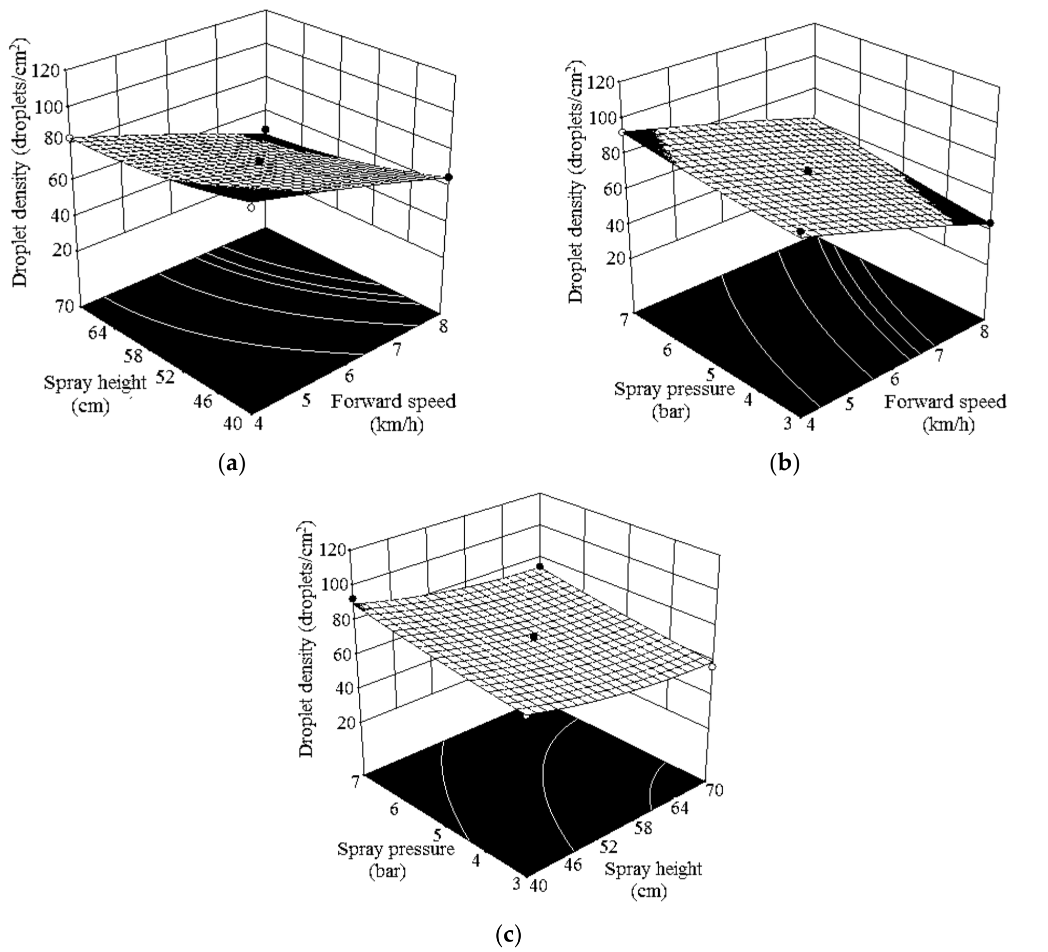


Figure 10. Three-dimensional surface map for droplet density: (**a**) interaction effect of forward speed and spray height at 5 bar pressure; (**b**) interaction effect of forward speed and spray pressure at 55 cm height; (**c**) interaction effect of spray height and spray pressure at 6 km/h speed.

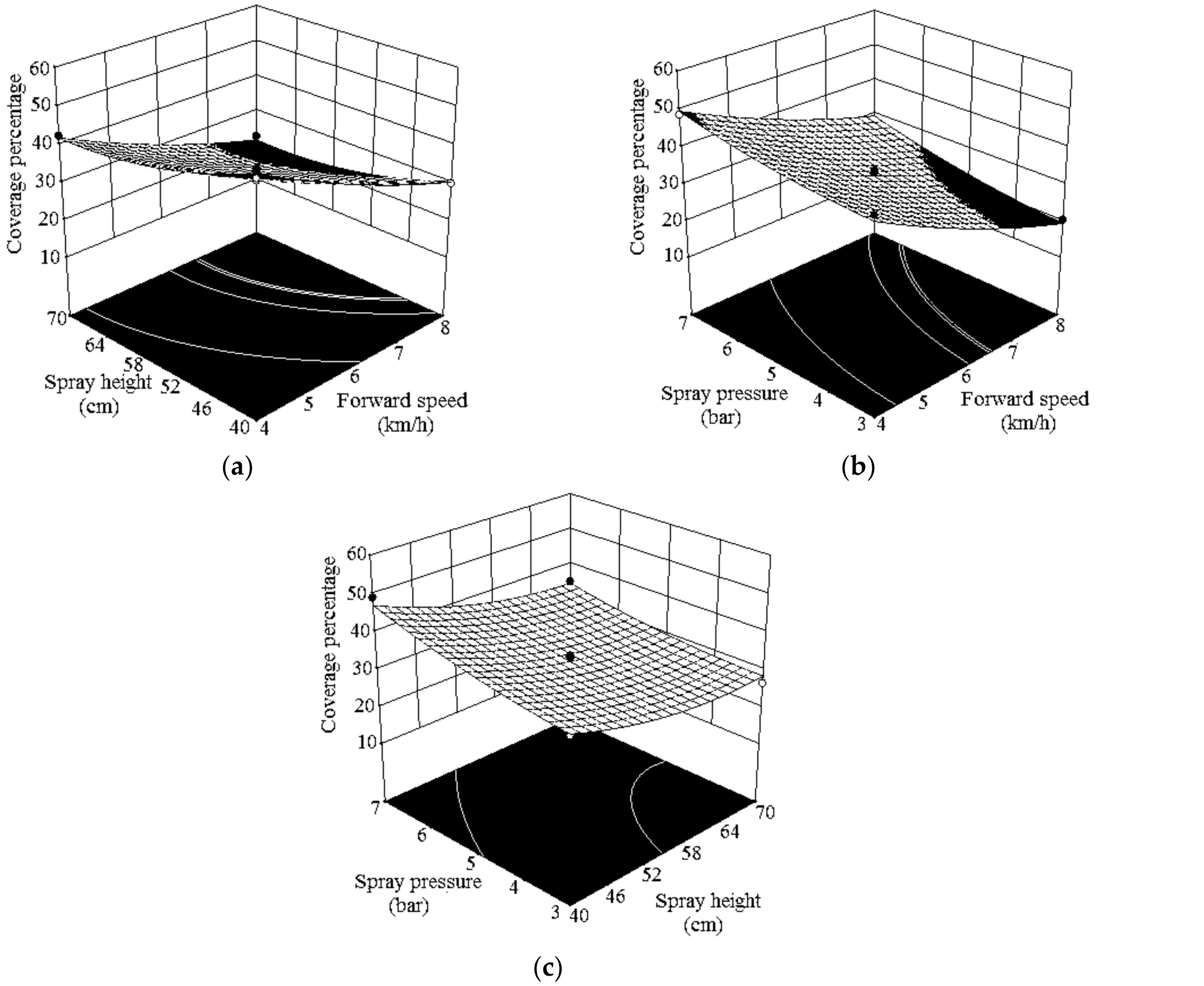


Figure 11. Three-dimensional surface map for coverage percentage: (**a**) interaction effect of forward speed and spray height at 5 bar pressure; (**b**) interaction effect of forward speed and spray pressure at 55 cm height; (**c**) interaction effect of spray height and spray pressure at 6 km/h speed.

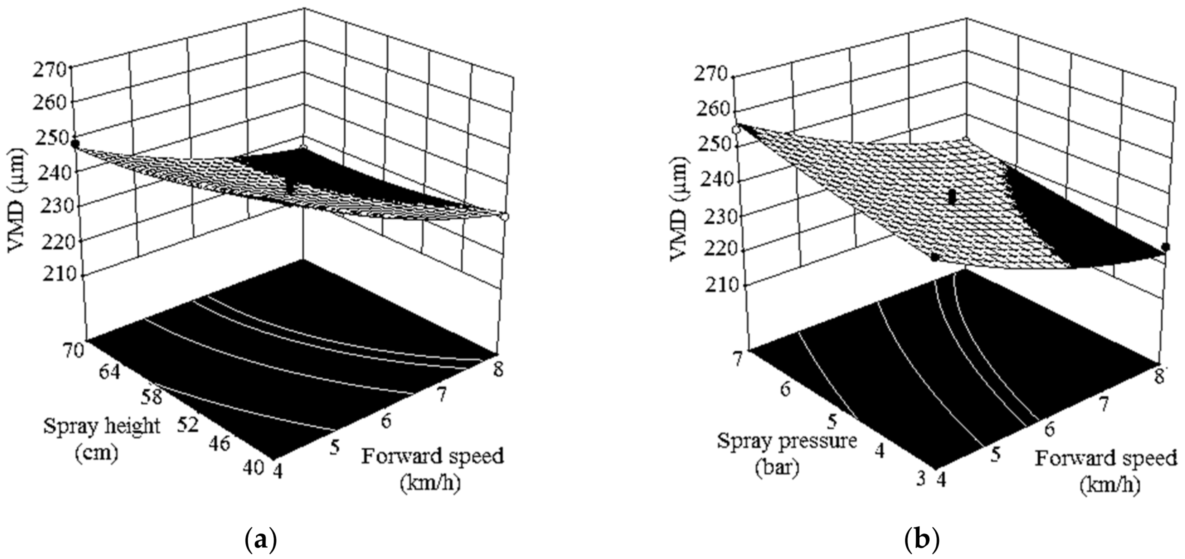
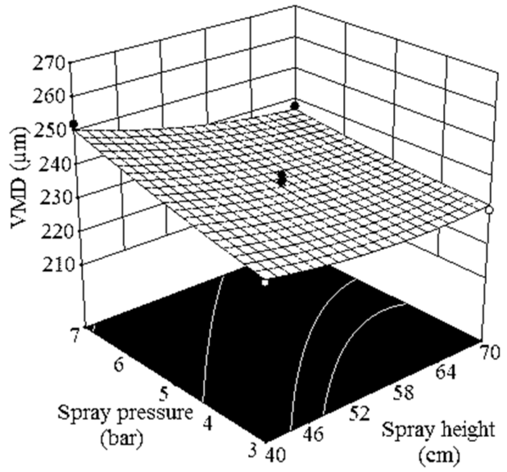


Figure 12. *Cont.*



(c)

Figure 12. Three-dimensional surface map for VMD: (**a**) interaction effect of forward speed and spray height at 5 bar pressure; (**b**) interaction effect of forward speed and spray pressure at 55 cm height; (**c**) interaction effect of spray height and spray pressure at 6 km/h speed.

3.5. Validation of RSM Model

The RSM model was validated by experimenting with the optimal condition for insecticide and herbicide application (8 km/h, 70 cm, and 3 bar). The actual values of droplet density, coverage percentage, and VMD at optimized condition were 41.35 droplets/cm^2, 21.10%, and 227.43 µm, respectively. The results of the predicted and actual response variables are given in Table 7. The prediction error [29] listed in Table 7 was calculated using Equation (5).

$$Prediction\ error\ (\%) = \frac{(Actual\ value - Predicted\ value)}{Actual\ value} \times 100 \tag{5}$$

Table 7. Optimal condition, predicted and actual value, at optimized spray condition.

Response Variable	Actual Value	Predicted Value	Prediction Error (%)
Droplet density (droplets/cm^2)	41.35 ± 3.67	37.85	8.46
Coverage percentage	21.10 ± 1.72	19.15	9.2
VMD (µm)	227.43 ± 1.22	225.41	0.9

As the predicted results found from regression equations agree with the actual results and the prediction errors are less than ±10% [29], the developed models can be considered as reliable for experimental results.

4. Conclusions

In this study, the RSM approach presented a change in the droplet density, coverage percentage, and VMD, caused by a change in forward speed, spray height, and spray pressure at the 3D surface with high accuracy as a graph containing many small pixels. The results conclude that the droplet density and coverage percentage decrease as speed and height increase and pressure decreases. The VMD decrease as speed and height increase. On the other hand, VMD increase in small fraction as pressure increases. The model data was accurate as R^2 values were greater than 0.8 for droplet density, coverage percentage, and VMD. The optimized parameters were 6.5 km/h, 60 cm, 4 bar for fungicide application, and 8 km/h, 70 cm, 3 bar for insecticide and herbicide application. The predicted response variable values at the optimal conditions were 60.4 droplet/cm^2, 27%, 230 µm for fungicide and 37.8 droplet/cm^2, 19.1%, 225.4 µm for insecticide and herbicide application. The actual response variable values at the optimal condition for insecticide and herbicide application were 41.35 ± 3.67 droplet/cm^2, 21.10 ± 1.72%, 227.43 ± 1.22 µm, and the prediction error was 8.46%, 9.2%, and 0.9% for droplet density, coverage percentage, and VMD, respectively. Because prediction errors are less than ±10% so, the developed models can be considered reliable for experimental results. The RSM could be a suitable approach to study the optimal conditions. Optimization of spraying parameters is important to improve the effectiveness of spray while reducing spraying cost, application time, and spray losses to the environment. Furthermore, this study can provide support for further optimizing the parameters of the sprayer.

Author Contributions: Conceptualization, A.G.; Funding acquisition, A.G., F.A.K. and F.K.K.; Methodology, F.A.K.; Supervision, M.A.K. and M.U.C.; Writing—original draft, F.A.K. and A.G.; Writing—review & editing, M.A.K. and F.K.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Higher Education Commission (HEC), Islamabad, grant number NRPU-7583.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Not Applicable.

Acknowledgments: The authors would like to thank Higher Education Commission (HEC), Islamabad, Pakistan for financial support under the National Research Program of Universities (NRPU) of Pakistan (Project No. NRPU-7583). This work has been conducted in the Workshop of Faculty of Agricultural Engineering and Technology, University of Agriculture, Faisalabad-Pakistan.

Conflicts of Interest: The authors declare no conflict of interest.

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