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Optimisation of Spraying Parameters for Boom Sprayers

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Abstract

In order to investigate the influence of factors on the spray deposition of the spray bar sprayer, using the designed mobile spray bar spray device, the spray height, spray bar travelling speed and spray pressure were selected as the test factors, and the deposition amount of seductive red per unit blade area Y_1 and the deposition coefficient of variation Y_2 were taken as the evaluation indexes for the test, and the 3-factor, 3-level orthogonal rotary spray deposition test was carried out. The Box-Behnken response surface method was used to analyse and obtain the mathematical model of the spray deposition characteristics of spray height H, spray rod travel speed v and spray pressure P. The influence of each factor on the spray deposition characteristics and the optimal working parameters of the spray machine were obtained according to the regression analysis results. The results show that the forward speed, working height and spray pressure have a significant effect on the spray deposition characteristics, and the degree of influence in the order of the factors from the largest to the smallest is the spray pressure, the working height, the forward speed, the spray pressure, the working height and the spray pressure. The mean value of droplet deposition per unit area is negatively correlated with forward speed and nozzle working height, and positively correlated with spray pressure. The coefficient of variation of deposition is negatively correlated with the spray pressure, positively correlated with the forward speed, and decreases and then increases with the increase of the working height, which indicates that in the case of a certain working height, increasing the spray pressure or reducing the forward speed can effectively improve the uniformity of droplet deposition of the sprayer.

Keywords: forward speed, working height, spray pressure

1. Introduction

With the acceleration of the process of agricultural modernisation, mechanisation and automation technologies are increasingly used in agricultural production. This trend not only improves the efficiency of agricultural production, but also meets the urgent needs of farmers for reducing the labour burden and improving the working environment(Sun, 2024). Against this background, the spray bar sprayer, as an advanced plant protection equipment for large fields, has gradually become a popular choice for agricultural production (Sun et al., 2024).

With the advantages of its high efficient operating capability, excellent droplet coverage effect and uniform deposition distribution, the spray bar sprayer excels in pesticide, fertiliser and plant growth regulator spraying operations in large agricultural fields. Its efficient operational performance significantly improves agricultural production efficiency, while optimising the fog droplet deposition effect, thus enhancing the effectiveness of pest control(Yao, 2024). Droplet deposition and deposition uniformity are key indicators for assessing the spraying quality of a boom sprayer, and they directly affect the effective utilisation of pesticides and the growth protection effect of crops.

However, the droplet deposition effect is not fixed, but is affected by a combination of factors. The adjustment of parameters such as the travelling speed of the sprayer, the working height of the nozzle, and the spray pressure can have a significant effect on the amount of droplet deposition and distribution uniformity (Sun et al., 2009a; Zhang et al., 2016; Jiang et al., 2022). Therefore, optimisation of these operating parameters is essential to improve the spray quality of the spray bar sprayer. Through the in-depth study and reasonable regulation of these factors, the application effect of the spray bar sprayer in agricultural production can be further enhanced to provide strong support for the sustainable development of modern agriculture.

Wang et al. (Wang and Qi, 2006) study the pressure loss in sprayer spray rods and its effect on spray quality. Through theoretical analysis and experimental verification, the article discusses in detail the pressure loss of liquid flow in the spray bar of the spraying machine, and analyses the specific impact of this pressure loss on spray quality. Qi et al. (Qi and Fu, 1999) studied the effects of nozzle type, nozzle height and spray pressure on the uniformity of droplet distribution. The uniformity of spray distribution under different conditions was explored through experiments and the effect of each factor on spray quality was analysed, and it was found that the difference in CV of various nozzles tended to decrease with the increase in nozzle height, and that the ideal droplet distribution was not achieved at nozzle heights below 30 cm. In addition the effect of spray pressure on distribution uniformity was not significant at three different heights. However, in general, increasing the spray pressure contributes to the improvement of droplet distribution uniformity. Sun et al (Sun et al., 2009b) studied the optimisation of spraying parameters of spraying rod sprayer, aiming to find out the main factors affecting spraying quality by analysing many spraying parameters, and put forward the optimised range of values of spraying parameters under different spraying operation conditions, including nozzle type, pressure, flow rate and nozzle height, etc., so as to provide technical references for the rational use of pesticides. The article discusses in detail the requirements of spraying parameters for different spraying operations (e.g., field and fruit trees) and different medicinal objects (e.g., insecticidal, fungicidal and herbicidal), and puts forward specific parameter selection suggestions. AHMAD et al. (Ahmad et al., 2020) take the unmanned aerial spraying system as the object of research, and find that different flight altitudes and speeds will have a significant impact on the spray deposition characteristics. WAWRZOSEK et al. (Wawrzosek and Parafiniuk, 2021) designed a nozzle for spray bar sprayer according to the European spraying standard, optimised the spray deposition coefficient of variation of spray bar sprayer, and improved the spray uniformity. Song et al (Song et al., 2006) conducted spray tests with different mist flow direction angles, different spray pressures and forward speeds as factors, and the results showed that the forward speed would have an effect on the optimal mist flow direction angle. Xu et al (Xu et al., 2020) studied the effect of self-propelled spray bar sprayer spraying parameters on pesticide utilisation and droplet deposition distribution in rice at different growth periods, and the results showed that the spray pressure and the amount of applied liquid had a significant effect on the pesticide utilisation, distribution uniformity and droplet density at the base of rice stalks. In summary, it can be seen that the current research on self-propelled spray bar sprayer is generally aimed at a certain aspect of the spray bar sprayer, and less involved in the study of the influence of multiple factors on the spray deposition characteristics of the spray bar sprayer on the foliage of the actual crop. In this paper, the self-propelled sprayer is taken as the research object, and the actual pepper plant is taken as the spray deposition object, and the Box-Behnken response surface method is used to analyse the mathematical model of the influencing factors such as the forward speed, the working height and the spraying pressure and the spray deposition characteristics on the basis of orthogonal test, according to the results of the regression analysis, in order to obtain the results of the maximum amount of deposit per unit area, the maximum spray volume and the maximum coefficient of variation of the spray volume, and the maximum spray volume and the maximum spray volume. Based on the results of regression analysis, it is hoped to find out the working parameters of spraying machine with the largest deposition per unit area and the smallest coefficient of variation of deposition.

2. Method

Capsicum annuum L. (Capsicum annuum L., Tianshuai 101) was selected as an experimental subject. The peppers were grown in a greenhouse in Zhenjiang City, Jiangsu Province, China, and after 90 days of careful cultivation were transplanted to pots to continue growing for 10 days. Ten healthy and pest-free pepper plants were selected and three developed leaves on each plant were chosen as experimental materials. The experiment was carried out in the laboratory, where the temperature was maintained at 26°C±1°C and the relative humidity of the air was controlled between 57% and 70% to ensure that the leaves were in optimum condition, measures that are essential for obtaining accurate and reliable experimental data.

The laboratory test rig (Fig. 1) is designed to measure the continuous spray deposition distribution from a nozzle under controlled conditions. The test rig consists of a guide rail, motor driver, microcontroller, transformer, liftable truss, nozzle, pump, pressure gauge, and droplet collection device. The motor driver receives a signal from the microcontroller to control the guide rail to achieve a forward speed of 0.1 m/s, 0.5 m/s, 1 m/s, 1.5 m/s, with an effective travel of the rail of 200cm, and the IDK120-02 fan nozzle is selected to be mounted on the lifting truss and the nozzle is connected to a hydraulic circuit similar to the one used in the aerosol dispenser in which the nozzle pressure is kept constant by a pressure controller and controlled by a precision digital manometer, the spray nozzle is connected to the hydraulic circuit similar to the one used in the aerosol dispenser and the pressure gauge is used. A precision digital manometer was used to control the nozzle, which was placed vertically over the droplet collection device, with the height of the nozzle from the collection device being H. The fan-shaped liquid surface of the droplets produced by the fan nozzle jet was parallel to the ground and perpendicular to the direction of travel of the nozzle, which was suspended over the centreline of the rows of pepper plants. The direction of the forward speed is the x-axis positive direction, and the vertical direction from the collecting dish to the nozzle is the z-axis positive direction.

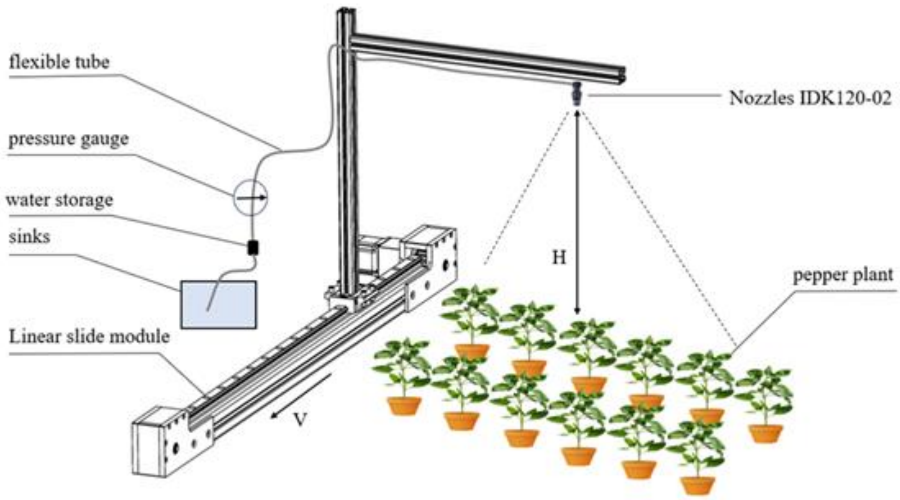

Figure 1. Mobile boom spraying platform

2.1 Self-Propelled Boom Spray in Pepper Leaf Deposition Trials

Prior to the start of the test, 5g of seductive red fluorescent reagent solute was taken using a medication spoon and placed on a precision electronic balance (Sartorius Scientific Instruments, Beijing) on a weighing paper. After the reading was stable, 500 mL of deionised water was placed in a beaker, and the solute was mixed in to make the concentration of the reagent 10 g/L. A magnetic stirrer (model 79-1, Ronghua Instrument Co., Ltd.) was placed on the beaker, and then the mixture was stirred well and stored in a brown reagent bottle for spare use.

This test considers the three experimental factors of spray bar travelling speed, spray height and spray pressure. The spray height of the spraying operation is selected from the vertical height of the nozzle relative to the target blade, and the height of the pepper plants cultivated in the greenhouse with the same length of growth is basically the same, and the height of the crown of the pepper plants is measured to be about 85cm, and the spray height is selected to be 30, 50, and 70cm in total at three levels. The spray bar travelling speed was 0.5, 1, 1.5m/s, and the spray pressure was 0.2, 0.3, 0.4 Mpa for the actual spray measurement. This experiment used a vertical spraying strategy, in order to avoid the influence of the surrounding leaves on the amount of target leaf deposition, the leaves around the target leaf were removed before the start of the experiment. One leaf per plant was selected at each spray height for each experiment, and the relative position of the leaf to the nozzle was recorded. Ten pepper plants were selected for the experiment, arranged in two rows of five plants each, with a row spacing of 60 cm and a peer-to-peer spacing of 35 cm between the two plants. The pepper plant sample droplets were deposited on the surface of the leaf blades, and therefore a new pepper plant was required at the end of each set of experiments to ensure the accuracy of the experimental results. After each spraying, the target leaves were carefully cut and laid flat on the prepared wooden boards, and the leaves with droplets were photographed, and the camera was supplemented with filter paper to ensure that the brightness of the pictures obtained from the camera was consistent, and the whole process needed to be careful not to damage the droplet deposition distribution on the leaf surface. After the test was completed, the obtained images were used to measure the leaf area using ImageJ software.

Immediately after taking pictures, the sampled leaves were put into a certain amount of water to fully soak, so that the seductive red on the leaves was completely dissolved, and then the absorbance of the elution solution was measured by a visible spectrophotometer at a wavelength of 504 nm, and then the concentration of the seductive red in the elution solution was calculated according to the standard curve of ‘concentration-absorbance’ of seductive red standard sample. The concentration of seductive red in the solution was calculated according to the standard curve of ‘concentration-absorbance’ (Xu et al., 2024).

$$\beta_{dep} = \frac{(\rho_{smpl} - \rho_{blk}) \times F_{cal} \times V_{dii}}{\rho_{spray} \times A_{col}} \times 1000 \tag{1}$$

Where: β_{dep} is the amount of droplet deposition per unit area, µL/cm^2; ρ_{smpl} is the concentration of the sample eluent, mg/L; ρ_{blk} is the concentration of the blank sample eluent mg/L; F_{cal} is the calibration coefficient (equal to the reciprocal of the recovery), which is 1.05 for pepper leaves; V_{dii} is the volume of liquid used to elute the samples, ml; ρ_{spray} is the concentration of the spray masterbatch of seductive red, mg/L; A_{col} is the area of the pepper leaves, cm^2.

2.2 Blade Surface Recovery Measurement Test

Five healthy, intact pepper leaves were selected, and a standard seductive red solution with a concentration of 10 mg/L was prepared. 0.5 ml of the seductive red solution was dropped on the leaves and left to stand for 3 min (estimated according to the time between the completion of the spray test and the immersion of the leaves in the eluent solution). After reaching the set time, the leaves with the seductive red solution were put into a centrifuge tube and appropriate amount of deionised water was added to separate the seductive red solution adsorbed on the surface of the leaves from the leaves. The centrifuged solution was transferred to a cuvette, and the absorbance value of the supernatant was measured at 504 nm using a spectrophotometer, and the concentration of seductive red in the supernatant was calculated according to the pre-drawn standard curve of seductive red. The total amount of seductive red adsorbed on the leaf surface was calculated from the concentration and volume of seductive red in the supernatant. The formula for calculating the recovery was: recovery (%) = (amount of lurex adsorbed on the surface of the leaf/amount of lurex added initially)×100.

2.3 Response Surface Methodology Test Programme

Box-Behnken response surface method is mainly used to explore the interaction between factors in a multi-factor system by designing multiple sets of experiments, which can effectively construct a response surface model for describing the interaction between factors and obtaining the functional expression between factors and response values, so that the optimal combination of factors and the optimal response values can be obtained.(李东红 et al., 2018)

Taking the forward speed *v* of the sprayer, the working height *H* (the vertical distance of the nozzle from the target blade) and the spray pressure *P* as the influencing factors, and taking the mean value of the deposition amount per unit area of droplets Y_1 and the deposition coefficient of variation Y_2 as the evaluation indexes, a one-way test was conducted, and then Box-Behnken Response Surface Method was designed using the Design Expert software on top of the one-way test. The experimental programme was designed and data were processed in Design Expert software using Box-Behnken response surface method. The factors and levels of response surface design are shown in Table 1.

Table 1. Factors and levels of response surface teat design

	P/Mpa	*H*/cm	*v*/ms^{-1}
-1	0.2	30	0.5
0	0.3	50	1
1	0.4	70	1.5

The amount of droplets deposited per unit area can be used to reflect the number of droplets sprayed on the crop by the sprayer, which is an important criterion to measure the spraying performance of the sprayer, and the uniformity of droplet distribution is a key indicator to determine the quality of spraying. The coefficient of variation, as an important parameter to measure the degree of data dispersion, can reflect the uniformity of droplet deposition per unit area when spraying with a self-propelled sprayer (Wang et al., 2022). The formulae for the droplet deposition per unit area *X* and the coefficient of variation *CV* for each group of tests are as follows:

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{2}$$

$$S = \sqrt{\frac{1}{n-1}}\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2} \quad (3)$$

$$CV = (S / \overline{X}) \times 100\% \quad (4)$$

Where: $\overline{X}$ is the mean value of droplet deposition per unit area collected in each group of tests, μL/cm^2; X_i is the droplet deposition per unit area of each collection point in each group of tests, μL/cm^2; n is the number of collection points in each group of tests; S is the standard deviation of the data in the same group of tests; CV is the coefficient of variation of the data in the same group of tests.

3. Results and Discussion

3.1 Box-Behnken Test Method Test Results

Table 2. Box－Behnken response surface test results

	P/Mpa	*H*/cm	*v*/ms^{-1}	Y_1	Y_2
1	0.2	30	1	1.1	6.808
2	0.4	50	1.5	0.19246	4.542
3	0.4	50	0.5	3.42197	6.256
4	0.4	70	1	0.824982	4.283
5	0.2	50	0.5	3.11874	5.605
6	0.2	50	1.5	0.15723	7.374
7	0.3	30	0.5	3.72193	5.295
8	0.3	30	1.5	0.21958	6.781
9	0.3	70	0.5	2.9736	5.496
10	0.4	30	1	1.23123	5.705
11	0.3	70	1.5	0.090464	4.379
12	0.2	70	1	0.795031	6.439
13	0.3	50	1	0.931722	4.061
14	0.3	50	1	0.942241	4.183
15	0.3	50	1	0.951987	4.094
16	0.3	50	1	0.982289	4.310
17	0.3	50	1	0.914763	4.197

In order to obtain the interaction relationship between the factors affecting spray deposition and to obtain the optimal operating parameters of the spray machine, the test protocol and results designed using the Box Behnken test method are shown in Table 2, with a total of 17 sets of tests, of which 1-12 are the analytical factorisation tests, and 13-17 are the central tests, which are used for analysing the out-of-fit term and estimating the test error.

3.2 Sedimentation Modelling

The 17 sets of experimental data in Table 2 were subjected to multiple regression fitting, ANOVA and regression analysis, and the analysis of the response surface regression model for the mean value of fog droplet deposition per unit area is shown in Table 3.From the table, it can be seen that the model significance test of $P < 0.0001$, the P-value of the disfitting term is 0.0529, which indicates that the model is statistically significant ($P < 0.05$), and the disfitting is not statistically significant, and the degree of fit is high. The effects of P, H, v, PH, Pv, and P^2 on the mean value of fog droplet deposition per unit area were statistically significant. In addition, the degree of significant influence on the mean value of fog droplet deposition per unit area was P, H, v in descending order of factors.

The regression model for the mean value of fog droplet deposition per unit area is:

$$Y_1 = 0.9446 - 1.57v - 0.1986H + 0.0625P + 0.1548Hv - 0.067Pv - 0.0253PH + 0.7708v^2 + 0.036H^2 + 0.0072P^2 \quad (5)$$

Table 3. Analysis of the mean value of droplet deposition per unit area

Source	Sum of Squares	df	Mean Square	*F-value*	*P-value*
Model	22.77	9	2.53	1209.28	＜0.0001
P	19.77	1	19.77	9449.31	＜0.0001
H	0.3155	1	0.3155	150.78	＜0.0001
v	0.0312	1	0.0312	14.91	0.0062
PH	0.0959	1	0.0959	45.81	0.0003
Pv	0.0180	1	0.0180	8.58	0.0220
Hv	0.0026	1	0.0026	1.23	0.3049
P^2	2.50	1	2.50	1195.58	＜0.0001
H^2	0.0055	1	0.0055	2.61	0.1503
v^2	0.0002	1	0.0002	0.1046	0.7559
Residual	0.0146	7	0.0021		
Lack of Fit	0.0121	3	0.0040	6.37	0.0529
Pure Error	0.0025	4	0.0006		
Cor Total	22.79	16			

The results of the analysis of the response surface regression model for the coefficient of variation of fog droplet deposition are shown in Table 4.From the table, it can be seen that the model significance test P < 0.0001 and the *P* value of the misfit term is 0.0546, which indicates that the model is statistically significant (P < 0.05), and the misfit is not statistically significant, and the degree of fit is high. The effects of P, H, Pv, Hv, PH, P^2, v^2, and H^2 on the mean value of fog droplet deposition per unit area were statistically significant. In addition, the degree of significance of the influence on the mean value of droplet deposition per unit area in the order of factors from largest to smallest for the spray pressure P, working height H, forward speed v. The regression model of the coefficient of variation of droplet deposition per unit area is:

$$Y_2 = 4.17 - 0.6799P + 0.053v - 0.4991H - 0.8707Pv - 0.2634PH - 0.6508Hv + 1.05P^2 + 0.7271v^2 + 0.5917H^2 \tag{6}$$

Table 4. Analysis of droplet deposition variation coefficient

Source	Sum of Squares	df	Mean Square	*F-value*	*P-value*
Model	19.95	9	2.22	71.63	＜0.0001
P	3.70	1	3.70	119.55	＜0.0001
H	1.99	1	1.99	64.40	＜0.0001
v	0.0225	1	0.0225	0.7264	0.4223
PH	0.2775	1	0.2775	8.97	0.0201
Pv	3.03	1	3.03	98.03	＜0.0001
Hv	1.69	1	1.69	54.75	0.0001
P^2	4.63	1	4.63	149.53	＜0.0001
H^2	1.47	1	1.47	47.65	0.0002
v^2	2.23	1	2.23	71.94	＜0.0001
Residual	0.2166	7	0.0309		
Lack of Fit	0.1784	3	0.0595	6.24	0.0546
Pure Error	0.0381	4	0.0095		
Cor Total	20.16	16			

3.3 Response Surface Modelling Analysis

Fig. 2 shows the response surface of the effect of interaction factors on the mean value of droplet deposition per unit area. From Fig. 2a, it can be seen that with the increase of spray height and forward speed, the mean value of droplet deposition per unit area tends to decrease and reaches a minimum value of 0.09046 μL/cm^2 at the maximum of spray height and forward speed.From Fig. 2b, it can be seen that with the increase of forward speed and the decrease of spray pressure, the mean value of droplet deposition per unit area tends to decrease and reaches a minimum value of 0.15723 μL/cm^2.

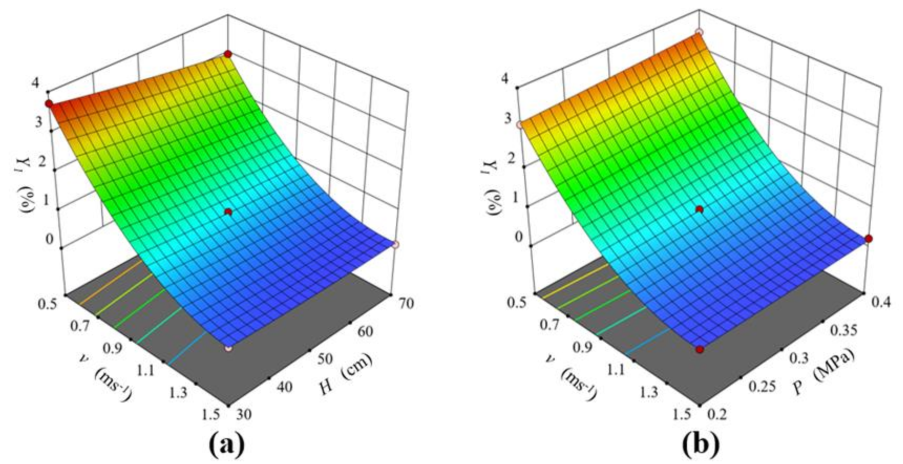

Figure 2. Response surface of effect of interaction on mean value of droplet deposition per unit area

Figure 3 shows the response surface of the effect of interaction on the coefficient of variation of droplet deposition. From Fig. 3a, it can be seen that the coefficient of variation of droplet deposition decreases and then increases with the increase of spray pressure and forward speed, and the minimum value is achieved when the spray pressure is 0.3 MPa and the forward speed is 1 m/s. From Fig. 3b, it can be seen that the coefficient of variation of droplet deposition decreases and then increases with the increase of spray pressure and working height, and the minimum value is obtained when the spray pressure is about 0.3 MPa and the working height of the nozzle is 50 cm. From Fig. 3c, it can be seen that the coefficient of variation of droplet deposition decreases and then increases with the increase of forward speed and working height of the nozzle, and the minimum value is obtained when the forward speed is 1m/s and the working height of the nozzle is 50cm.

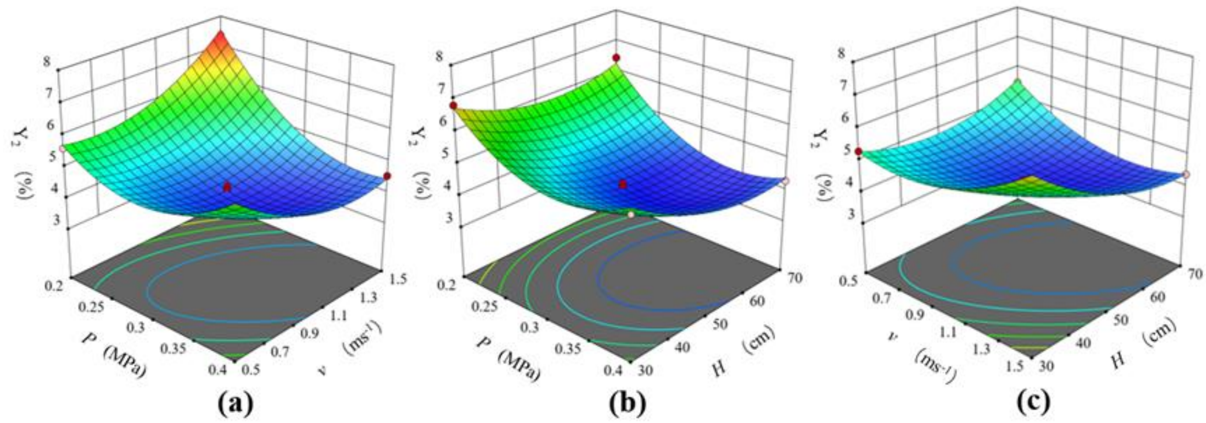

Figure 3. Response surface of interaction effect on variation coefficient of droplet deposition

3.4 Optimal Operating Parameters and Model Validation of Sprayer

In order to determine the optimum operating parameters of the self-propelled spray bar sprayer, the model was processed and analysed using Desgin-Expert software to obtain the values of spray pressure, forward speed and working height at the time when the maximum mean value of droplet deposition per unit area and the minimum coefficient of variation of droplet deposition were satisfied. Analysis results: in the pressure of 0.291MPa, forward speed of 0.5m / s, nozzle working height of 42.185cm when the droplet deposition per unit area mean value of 3.418μL/cm^2, the coefficient of variation of 4.852%, at this time for the optimal combination of operating parameters of the sprayer. In order to verify the reliability of the model, the optimal combination of factors was verified in the test, and the test was repeated three times, and the test verification is shown in Table 5, with e as the error in the table.

Table 5. Test verification table

	P/MPa	v/ms^{-1}	H/cm	Y_1/μLcm^{-2}			Y_2/%		
				experimental	anticipate	e_1/%	experimental	anticipate	e_2/%
1	0.3	0.5	42	3.084	3.418	-9.77	4.439	4.852	-8.51
2	0.3	0.5	42	3.269	3.418	-4.36	5.147	4.852	6.08
3	0.3	0.5	42	3.732	3.418	9.18	5.289	4.852	9

As can be seen from Table 5, the prediction errors of the experimental results and model predictions of the mean value of droplet deposition per unit area and the coefficient of variation of droplet deposition are within 10%, and the difference between the predicted values and the actual measured values is not large, with a high degree of agreement, indicating that the model prediction effect is reliable.

4. Conclusions

The mean value of droplet deposition per unit area on the blade was significantly affected by spray pressure, spray height, and travelling speed of the spray bar, and the factors were ranked in descending order of their significance on the mean value of droplet deposition per unit area as spray pressure, spray height, and travelling speed of the spray bar.

The coefficient of variation of droplet deposition was significantly affected by spray pressure and working height. The level of significance of the effect of each factor on the coefficient of variation of droplet deposition was ranked from largest to smallest as spray pressure, working height, travelling speed. The coefficient of variation of droplet deposition decreases with the increase of spray pressure, increases with the increase of forward speed, and decreases with the increase of working height in the level range of each factor, but the coefficient of variation increases again after exceeding a certain height.

According to the model, the maximum mean value of droplet deposition per unit area and the minimum coefficient of variation of droplet deposition are proposed as the working parameters of the spray bar sprayer: pressure 0.3MPa, travelling speed of the spray bar 0.5 m/s, spraying height 42cm, which can achieve the optimal matching of droplet deposition and uniformity of the self-propelled spray bar sprayer.

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