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Design and Parameters Optimization of *Pteris vittata* Automatic Sowing Machine for Phytoremediation

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ABSTRACT

In view of the uneven artificial sowing, low sowing, as well as the fact that the existing seeders cannot meet the sowing requirements of *Pteris vittata*, this paper designed an automatic plug seeder by using the method of spraying and sowing after mixing spores and water. In order to obtain the optimum working parameters of the seeder, response surface method (RSM) was employed to design the experiments and evaluate the results with the purpose of optimizing parameters for improving spraying uniformity. The parameters such as the distance between the nozzle and plug and the nozzle angle and transmission speed were selected, and then the regression equation of spraying uniformity was established. The results showed that the influence of various factors on spraying uniformity coefficient from high to low were nozzle angle, distance between the nozzle and plug and transmission speed. Through the experimental analysis, it can be concluded that when the distance between the nozzle and plug was 11.63 cm, the nozzle angle and the transmission speed were 79.23° and 0.21 m/s, respectively; the seeding uniformity coefficient was the largest, 83.43%. The verification test results indicated that the optimized result was reliable. This study can provide reference for the development of micro seed seeder.

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NOMENCLATURE

ω	Angular velocity of stirring shaft (rad/s)	l	Blade length (mm)
F_n	The reaction force of the mixture to the blade (N)	d	Agitator stirring diameter (mm)
F_f	Friction force (N)	x	The distance between the cross section of the blade and the center of stirring shaft (mm)
F	Centrifugal force (N)	dx	Increments in the x direction
F_z	The supporting force of the stirring shaft to the blade (N)	m	Mass (kg)
G	Blade gravity (N)	g	Gravitational acceleration (m/s^2)
ρ_0	Mixture density (kg/m^3)	CU	Uniform coefficient
v	Linear velocity of blade (m/s)	Δh	Average deviation of water depth (mm)
A_1	Surface area of blade (m^2)	h^-	Average depth of water (mm)
μ	Friction coefficient between mixture and pulp blade	n	Total number of measuring points
ρ_1	Material density of blade (kg/m^3)	h_i	Depth value of the I (mm)
A_2	Cross-sectional area of blade (m^2)	max(t)	Objective function

1. INTRODUCTION

With the mining and smelting of arsenic-bearing metal minerals, the combustion of fossil fuels and the discharge and illegal dumping of industrial wastewater, the concentration of arsenic in soil is increasing, which causes different degrees of soil arsenic pollution all over the world [1, 2]. According to statistics, the average concentration of arsenic in Chinese soil is 11.2 mg/kg, which is about 2 times that of the world average [3].

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Therefore, it is urgent to reduce the concentration of heavy metal arsenic in soil. Ma et al. [4] firstly found the super-accumulating arsenic plant *Pteris vittata* in central Florida in the United States. Chen et al. [5] established the first hyperaccumulative phytoremediation base for soil arsenic pollution in China, and successfully carried out on-site remediation experiments. Phytoremediation technology has the advantages of low cost, low secondary pollution, and the discovery of hyper accumulative plants has set off an upsurge of research on phytoremediation of arsenic pollution in soil.

Plug sowing is a key link in the process of plant cultivation. With the application of industrial seedling technology becoming more and more universal, plug sowing machine has become one of the main equipments of seedling raising [6]. According to the different sowing modes and force of the seed metering devices, the plug seeder is mainly divided into three structures: mechanical type, pneumatic type and magnetic type [7]. However, due to the small size of *Pteris vittata* spores, with an average diameter of 48 μm, the traditional seeder cannot meet the requirements of sowing. At present, the sowing of *Pteris vittata* mainly depends on manual work, with some problems such as high labor intensity, low sowing efficiency and uneven sowing. Therefore, the automatic sowing device for *Pteris vittata* needs to be studied urgently.

In view of the problems in the existing seeders, and combined with the characteristics of *Pteris vittata* spores, a kind of *Pteris vittata* plug automatic seeder was designed in this paper. In order to improve the sowing uniformity of the seeder, comprehensively considering the structural characteristics of the plug automatic seeder, this study selects three key factors: the distance between the nozzle and plug, the nozzle angle and the transmission speed. Taking the spraying uniformity as the test index, the experiment with three factors and three levels was designed, and the influence of test factors on the test index was analyzed by using RSM. This study could provide reference for the design of micro-seed automatic sowing device.

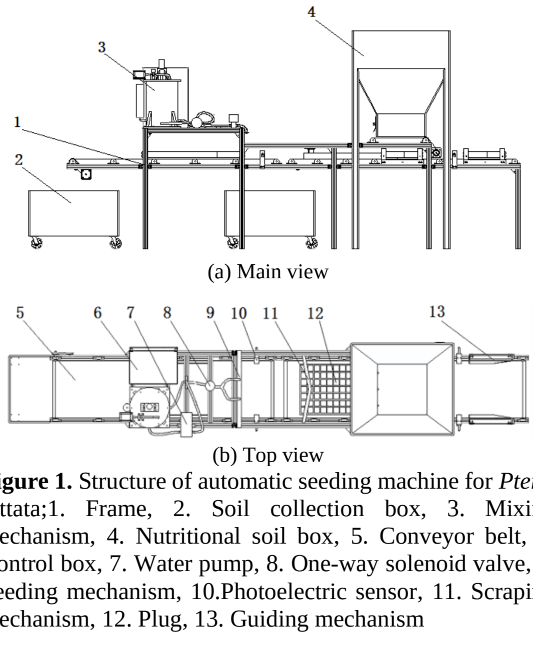
2.GENERAL STRUCTURE AND WORKING PRINCIPLE OF SOWING MACHINE

2. 1. Machine Structure The general structure of the *Pteris vittata* plug automatic seeder is shown in Figure 1. The seeder is mainly composed of a transmission mechanism, a filling mechanism, a soil scraping mechanism, a sowing mechanism, a control box, a mixing mechanism and a soil collection box. A plug guiding mechanism is installed on the frame, so that the plug does not deflect during movement and ensure accurate sowing. Photoelectric sensors are respectively arranged at the sowing mechanism and the filling mechanism to detect the position of the plug. An adjustable baffle is installed at the filling mechanism. The amount of soil can be controlled by adjusting the angle of the baffle.

2. 2. Working Principle The mixing mechanism mixes the spores and water evenly, and the nutritious soil is stored in the soil box. When the photoelectric sensor detects the plug, the upper conveyor belt transports the nutrient soil from the soil box to the plug, and the soil scraping mechanism scrapes away the excess nutrient soil that is then transported to the soil collection box through the conveyor belt. At the same time, the control element in the control box starts the water pump to work, and the conveyor belt drives the plug to move toward the sowing mechanism. When the photoelectric sensor detects the plug, the control element opens the one-way solenoid valve, and the evenly stirred spore mixture is sprayed on the plug through the sprinkler. When the photoelectric sensor detects the plug leaving the induction area, the control element closes the one-way solenoid valve. The system automatically enters the standby mode and waits for the next round of sowing.

3. KEY MECHANISM DESIGN

3. 1. Mixing Mechanism Design The size of *Pteris vittata* spore is relatively small, and the existing hole disk seeder is not suitable for *Pteris vittata* sowing requirements. On the basis of the existing seeder, a mixing mechanism is designed to mix spores and water evenly and then spray sowing, so as to improve the sowing efficiency of *Pteris vittata*.



(a) Main view

(b) Top view

Figure 1. Structure of automatic seeding machine for *Pteris* vittata;1. Frame, 2. Soil collection box, 3. Mixing mechanism, 4. Nutritional soil box, 5. Conveyor belt, 6. Control box, 7. Water pump, 8. One-way solenoid valve, 9. Seeding mechanism, 10.Photoelectric sensor, 11. Scraping mechanism, 12. Plug, 13. Guiding mechanism

The mixing mechanism of *Pteris vittata* spores is shown in Figure 2, which mainly includes motor, stirring tank, baffle, mixing shaft, pulp blade and so on. One end of the stirring shaft is connected with the motor through a coupling, the other end is connected to the bearing that is fixed on the base of the stirring tank. The double-layer four-blade structure is adopted to enhance the turbulence intensity and improve the stirring uniformity in the stirring tank. The placement angle of the blade has a significant effect on the axial velocity and turbulent kinetic energy in the stirring tank. Through the simulation, it is found that the stirring effect is the best when the blade angle is 45° [8]. A backwater mechanism is designed on the outer wall of the stirring tank. After the mixture flows through the outlet, the mixture can flow back into the stirring tank through the return outlet to reduce the pressure of the water pipe during sowing. In order to improve the stirring effect, four baffles are uniformly arranged on the inner wall of the stirring tank.

If the speed is too fast, the stirring power increases and the stability of the device becomes worse, which is not conducive to the normal stirring operation. If the speed is too low, the turbulence intensity of the flow field is small, reducing the stirring effect. In the stirring process, when the stirring shaft rotates at its angular speed ω, the force on the blade is shown in Figure 3.

According to the momentum equation of engineering fluid mechanics, the reaction force of the mixture to the blade when the blade is installed at 45° can be deduced [9], that is, the positive pressure is calculated by Equation (1):

$$F_n = \frac{1}{2}\rho_0 v^2 A_1 \tag{1}$$

The friction force on the blade can be calculated through Equation (2):

$$F_f = \mu F_N \tag{2}$$

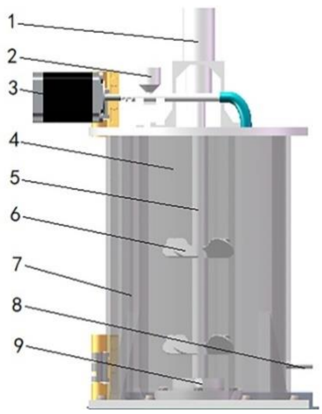


Figure 2. Stirring mechanism; 1. Motor, 2. Feed outlet, 3. Stepper motor, 4. Stirring tank, 5. Stirring shaft, 6. Slurry blade, 7. Baffle, 8. Backwater outlet, 9. Outlet

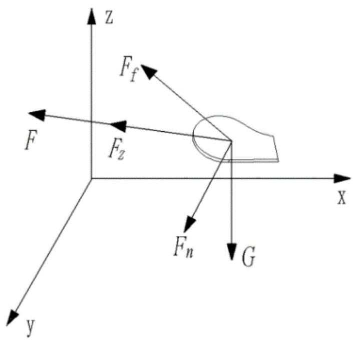


Figure 3. Schematic diagram of blade force analysis

Because of different centrifugal forces in different positions of the blade, the integral method is used to calculate the centrifugal force of the blade by Equation (3).

$$F = \omega^2 \rho_1 A_2 \int_{\frac{d}{2}}^{l+\frac{d}{2}} x\,dx \tag{3}$$

The gravity of the blade cannot be ignored in the stirring process, and according to Equation (4), its gravity can be obtained

$$G = mg \tag{4}$$

3. 2. Control System Design The control system uses ArmSTM32 microcontroller as the main component control circuit, which is mainly used to communicate with the host computer, receive and process sensor data, control the water pressure of the system and adjust the sowing speed.

The system control flow chart is shown in Figure 4. Firstly, the system is powered on and initialized, then the system parameters are set. All of the sensors are started at the same time, and the microcontroller receives and processes the sensor signals. Through the liquid level switch, the water level in the stirring tank can be monitored in real time, and compared with the minimum threshold to determine whether the liquid level is too low, so as to realize the real-time alarm of too low water level.

4. EXPERIMENTAL CONDITIONS AND METHODS

4. 1. Test Purpose In order to improve the sowing uniformity, this paper uses the response surface method to test the working performance of the seeder, analyzes the influence of experimental factors on sowing uniformity, and finds out the optimal combination of parameters to provide guidance for the production of the follow-up prototype.

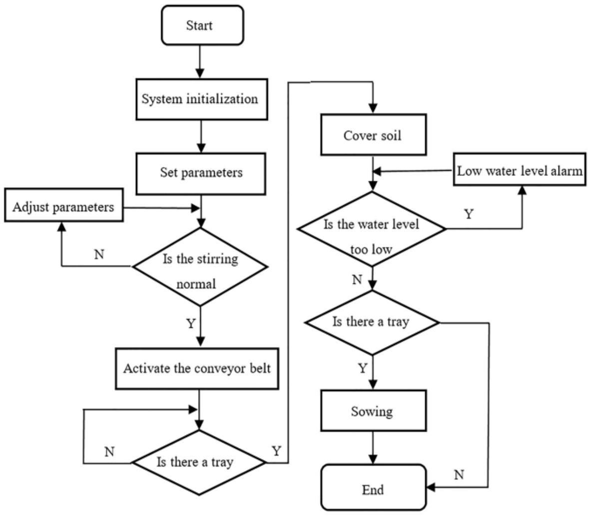


Figure 4. Flow chart of system control

4. 2. Test Indicators The size of *Pteris vittata* spore is small and its density (1.025kg/m^3) is close to that of water when mixed with water. Under the condition of uniform mixing, the uniformity of water spraying can be regarded as the uniformity of sowing. According to the "American Society of Agricultural Engineers Sprinkler Irrigation Distribution Test Standard" [10], the uniformity coefficient is calculated by using Christiansen uniformity [11]. Calculation formula are shown in Equations (5) to (7).

$$\Delta h=\frac{\sum_{i=1}^{n}|h_i-h|}{n} \quad (5)$$

$$\bar{h}=\frac{\sum_{i=1}^{n}h_i}{n} \quad (6)$$

$$CU = \left(1-\frac{\Delta h}{\bar{h}}\right) \times 100\% \quad (7)$$

4. 3. Test Conditions Through the previous simulation test, it is found that the solid-liquid mixing effect is better in the stirring tank when the distance between two blades is 90mm and the stirring speed is 300r/min [12]. On the basis of this research, a uniform sowing experiment was carried out on the *Pteris vittata* plug automatic seeder. The 7 × 15 hole plastic plug was selected. According to the requirements of agricultural sowing, the volume ratio of water and spore is 1:500. During the experiment, the collection bottle was placed in the plug to collect water samples, and the test was carried out under the condition of no wind. The inner diameter of the sprinkler is 1.3 mm and the working pressure range is 100~150kPa.

4. 4. Test Design The distance between nozzle and plug A, nozzle angle B and transmission speed C 3 were selected in the experiment. According to the structure and design parameters of the seeder, the distance between the nozzle and plug was determined to be 10~14 cm, the nozzle angle was 50°~ 80° and the transmission speed was 0.15~0.25m/s. The Box-Behnken Design (BBD) method in Design-Expert10.0 software was used to design the quadratic regression test with 3 factors and 3 levels [13–16]. The coding table of experimental factors is shown in Table 1. A total of 17 groups were carried out, and the design scheme and results are shown in Table 2.

TABLE 1. Coding of factors and levels

Code	Factors		
	A/cm	B/°	C/（m/s）
-1	10	50	0.15
0	12	65	0.2
1	14	80	0.25

TABLE 2. Test results

Number	A/cm	B/°	C/(m/s)	Y/%
1	-1	0	-1	61.71
2	0	-1	1	54.71
3	0	0	0	81.73
4	0	-1	-1	63.92
5	-1	1	0	85.73
6	0	1	1	77.80
7	0	0	0	80.12
8	-1	0	1	62.55
9	1	1	0	74.33
10	0	0	0	80.13
11	0	0	0	76.58
12	-1	-1	0	38.96
13	1	0	1	81.15
14	0	0	0	74.81
15	0	1	-1	82.15
16	1	0	-1	78.08
17	1	-1	0	61.55

5. EXPERIMENTAL RESULTS AND ANALYSIS

5. 1. Establishment of Regression Model and Analysis of Variance

According to the test results in Table 2, a response surface regression equation model was established in DesignExpert10.0 software, which takes the distance between the nozzle and plug, the nozzle angle B and the transmission speed C as the independent variable and the uniformity coefficient Y as the objective function. The results are shown in Equation (8). At the same time, the influence of various experimental factors on the uniformity coefficient is obtained by the analysis of variance; the results of the analysis of variance are shown in Table 3. As can be seen from Table 3, the determination coefficient R^2 of the model is 0.9256, which indicates that the regression equation is in good agreement with the experimental data [17]. The model F=9.68, P=0.0034 < 0.01 shows that there is a significant correlation between the uniformity coefficient and the experimental factors, and the fitting level is good. The misfit P value is 0.0566 > 0.05. It shows that the error between the predicted value and the experimental value is small, so the regression equation model can be used to optimize the relevant parameters of the seeder.

$$Y=78.67+5.77A+12.61B-1.21C-8.5AB+0.56AC+1.21BC-6.15A^2-7.38B^2-1.65C^2 \quad (8)$$

TABLE 3. Variance analysis of uniformity coefficient regression equation

Source	Mean square error	F	P	Significance
Model	253.35	9.68	0.0034	Extremely significant
A	266.34	10.17	0.0153	Significant
B	1271.84	48.59	0.0002	Extremely significant
C	11.64	0.44	0.5262	
AB	288.83	11.03	0.0127	Significant
AC	1.24	0.05	0.8337	
BC	5.90	0.23	0.6493	
A^2	159.36	6.09	0.0430	Significant
B^2	229.29	8.76	0.0211	Significant
C^2	11.46	0.44	0.5294	
Residual error	26.18			
Misfit term	50.13	6.10	0.0566	
Pure error	8.22			
R^2				

Table 3 shows that the influence of each parameter on the uniformity coefficient is significant; A, B, AB, A^2, B^2 are significant, among which B is extremely significant, and C, AC, BC, C^2 are not significant. On this basis, in order to establish a simple and optimized regression model, the non-significant parameters are not considered in the model, and the optimized regression model is shown in Equation (9). The P value of the optimized model is less than 0.0001, and the misfit term P value is 0.1428, more than 0.05, indicating that the optimized model has a high degree of fit and can be used to analyze and predict the test results.

$$Y=77.98+5.77A+12.61B-8.5AB-6.24A^2-7.47B^2 \quad (9)$$

The influence of the three factors on the test index can be determined by comparing the size of the P value (the smaller the P value is, the more significant the influence on the index) [18]. Combined with the results of variance analysis, it is concluded that the influence order of each factor on the uniformity coefficient is as follows: nozzle angle > distance between nozzle and plug > transmission speed.

5. 2. Factor Interactive Response Surface Analysis

According to the results of regression equation analysis, DesignExpert10.0 is used to draw the response surface of the interaction of various factors, as shown in Figures 5 to 7. From Figure 5, it can be seen that the interaction between the distance between the nozzle and plug and the nozzle angle has a significant effect on the spraying uniformity. When the transmission speed is 0 level, the uniformity coefficient increases with the increase of the nozzle angle. The reason is that increasing the angle of the nozzle will increase the spraying range, reduce the difference of water distribution between the ends and the middle, and increase the spraying uniformity coefficient, thus improving the sowing uniformity. The uniformity coefficient increases at first and then decreases with the increase of the distance between the nozzle and plug. Because the spraying range becomes narrow when the distance between the nozzle and plug is too small. The difference in the distribution of water between the two ends of the plug and the middle becomes larger, resulting in a decrease in the overall spraying uniformity. When

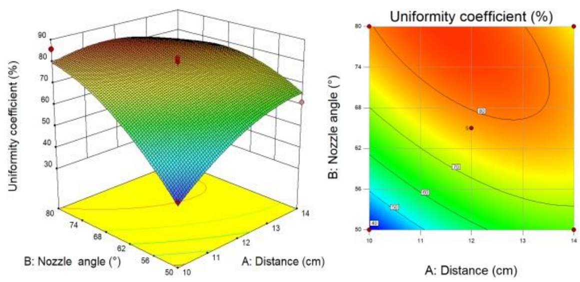


Figure 5. Effect of nozzle angle and distance between nozzle and plug on uniformity coefficient

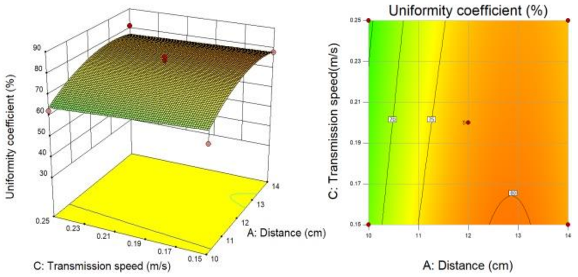


Figure 6. Effect of transmission speed and distance between nozzle and plug on uniformity coefficient

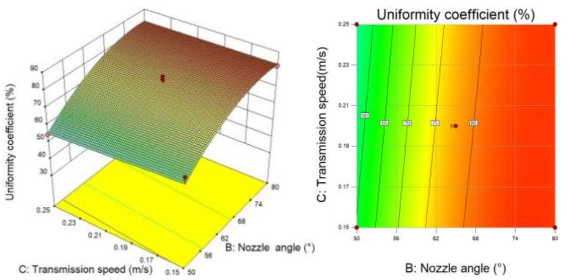


Figure 7. Effect of transmission speed and nozzle angle on uniformity coefficient

the distance between the nozzle and plug is too large, the spraying operation is unstable due to the atomization phenomenon of the nozzle, so the spraying uniformity is reduced. This phenomenon is similar to the results of previous study [19]. Through the result analysis, we know that when the distance between the nozzle and plug is 10 cm and the nozzle angle is 80°, the spraying uniformity coefficient is the highest.

From Figure 6, it can be seen that when the nozzle angle is 0 level, the uniformity coefficient does not change significantly with the increase of transmission speed. Since increasing the transmission speed will reduce the amount of water per time sprayed in the plug, it will not change the spraying range. Meanwhile, the uniformity of water at both ends and in the middle of the plug remains unchanged, so it has little effect on the uniformity coefficient. The uniformity coefficient increases at first and then decreases with the increase of the distance between the nozzle and plug, so it can be concluded that the influence of the distance between the nozzle and the plug on the uniformity coefficient is greater than that of the transmission speed. From Figure 5, when the distance between the nozzle and plug is 12cm and the transmission speed is 0.20m/s, the spraying uniformity coefficient is the highest.

From Figure 7, it can be seen that the effect of the nozzle angle on the uniformity coefficient is greater than that of the transmission speed. The uniformity coefficient increases with the increase of the nozzle angle, but changes little with the increase of the transmission speed. When the nozzle angle is 80° and the transmission speed is 0.15m/s, the spraying uniformity coefficient is the largest.

Combined with Figure 5-Figure 7, by comparing and analyzing the bending degree of the surface, we can get the influence of the nozzle angle, and the distance between the nozzle and plug on the uniformity coefficient is greater than that of the transmission speed.

5. 3. Parameters Optimization and Experimental Verification The uniformity coefficient is an important index for spraying. In order to make the best working effect of the seeder, the larger the uniformity coefficient is, the better it must be in the test range. The DesignExpert10.0 software is used to optimize the parameters, and the objective function and variable interval are shown in Equation (10).

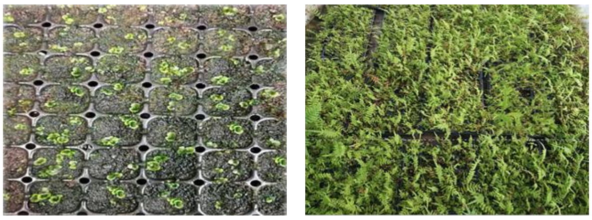
$$\begin{cases} max(t) = Y(A,B,C) \\ 10cm < A < 14cm \\ 50° \leq B \leq 80° \\ 0.15m/s \leq C \leq 0.25m/s \\ 60\% \leq Y \leq 100\% \end{cases} \quad (10)$$

The optimization results are shown in Table 4. As can be seen from Table 4, the best test conditions for theoretical optimization are as follows: the distance between the nozzle and plug is 11.63cm, the nozzle angle is 79.23°, the transmission speed is 0.21 m/s, and the theoretical sowing uniformity coefficient is 83.43%. In order to verify the accuracy of the optimized parameters, experiments are carried out using the above parameters. Considering the convenience of nozzle processing and device adjustment, the distance between nozzle and plug is 11.60 cm, the nozzle angle is 80°, and the transmission speed is 0.20 m/s. Under this parameter combination, three consequitive experiments are carried out, and the average value is taken as the final verification result. The experiment shows that the sowing uniformity coefficient is 80.70%, and the relative error with the theoretical optimization value is less than 4%, indicating that the established optimization model is reliable. The optimization results meet the seeder requirements [20].

5. 4. Seedling Experiment The experiment of raising seedlings in the plug is carried out under the optimal parameter combination of the seeder, and the growth of plug seedlings are shown in Figure 8. From Figure 8, it can be seen that *Pteris vittata* grows well, and the distribution of seedlings is more uniform.

TABLE 4. Comparison of optimized results with experimental values

Items	distance between nozzle and plug/cm	nozzle angle /°	transmission speed /m/s	uniformity coefficient /%
Prediction	11.63	79.23	0.21	83.43
Test	11.60	80	0.20	80.70



(a) *Pteris vittata* seedlings (b) Grown-up *Pteris vittata*

Figure 8. Cultivation of *Pteris vittata* in a greenhouse

6. CONCLUSION

In this study, RSM was used to analyze the influence of experimental factors on sowing uniformity of the sowing machine. Based on the findings and results, the following conclusions can be drawn:

1) In view of the fact that the current seeder cannot meet the sowing requirements of small seeds, a kind of *Pteris vittata* plug automatic seeder was designed by using the method of mixing spores and water. The seeder realized the functions of filling, scraping and sowing.

2) According to the Box-Benhnken center combination method, the orthogonal regression experiment of three factors and three levels was designed and carried out. Through the response surface analysis test, it is concluded that the influence of various factors on the spraying uniformity coefficient is in the following order: the nozzle angle, the distance between the nozzle and the plug and the transmission speed.

3) The parameters are optimized through factor interaction test analysis, and the optimization results are as follows: when the distance between nozzle and plug is 11.63 cm, the nozzle angle is 79.23°, and the transmission speed is 0.21 m/s, the sowing uniformity coefficient of theoretical response value is 83.43%. Through the verification test, it is concluded that the average spraying uniformity coefficient is 80.70%, which meets the operation requirements of the *Pteris vittata* automatic seeder. This study provides a basis for the study of micro seed sowing devices.

7. ACKNOWLEDGEMENT

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Persian Abstract

چکیده

با توجه به کاشت مصنوعی ناهموار، کاشت کم، و همچنین این واقعیت که نهال‌های موجود نمی‌توانند شرایط کاشت *Pteris vittata* را برآورده کنند، این مقاله با استفاده از روش پاشش و کاشت مخلوط اسپورها و آب، بذرپاش اتوماتیک پلاگین را طراحی کرده است. برای به دست آوردن پارامترهای بهینه کاشت بذر، از روش سطح پاسخ (RSM) برای طراحی آزمایشات و ارزیابی نتایج با هدف بهینه‌سازی پارامترها برای بهبود یک‌نواختی اسپری استفاده شد. پارامترهایی مانند فاصله‌ی بین نازل و پلاگین و زاویه‌ی نازل و سرعت انتقال انتخاب شد و سپس معادله رگرسیون یک‌نواخت پاششی برقرار گردید. نتایج نشان داد که تأثیر عوامل مختلف بر ضریب یک‌نواختی پاشش به‌ترتیب نزولی عبارتند از: زاویه‌ی نازل، فاصله‌ی بین نازل و پلاگین و سرعت انتقال. با تحلیل تجربی می‌توان نتیجه گرفت که اگر فاصله‌ی نازل و پلاگین ۱۱/۶۳ سانتی‌متر، زاویه‌ی نازل ۷۹/۲۳ درجه و سرعت انتقال ۰/۲۱ متر بر ثانیه باشد، ضریب یک‌نواختی بذر بیشینه و ۸۳/۴۳ درصد خواهد بود. نتایج آزمون تأیید نشان داد که نتیجه‌ی بهینه‌شده قابل اعتماد است. این مطالعه می‌تواند مرجعی برای ساخت بذرپاش بذرهای خرد (میکرونی) باشد.