Seed guide path planning and parameter optimization for air-suction carrot seed-metering device

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Abstract: To meet the requirement of "zero speed" for precision sowing, the instantaneous speed of seed falling into the seed bed should be equal to the opposite direction of the forward speed of the machine. Through analyzing the principle of seed guiding process, the main influencing factors affecting the contour curve of the seed tube were determined to plan the seed guiding path and realize zero speed seed delivery. With the help of EDEM simulation software, taking the inclination angle of seed tube end, operating speed of the metering disc, and machine's forward speed as the experimental factors, a single-factor simulation test was conducted with the pass rate, replay rate, and missing seeding rate as experimental indexes. The results of the simulation test showed that the range of inclination angle of the seed tube end was 23°-40°, the range of machine forward speed was 5-9 km/h, and the range of operating speed of the metering disc was 15-40 r/min. The quadratic orthogonal rotation combination test method was carried out using the bench test, and a mathematical regression model was established between experimental factors and experimental indexes to determine the priority order of factors, and the best combination of factors. The test results showed that the pass rate was 93.25%, the replay rate was 2.97% and the missing seeding rate was 3.78% under the condition with the inclination angle of seed tube end of 32.28°, the forward speed of the machine of 6.89 km/h and the operating speed of the metering disc of 28.67 r/min, which can meet the requirements of relevant national standards.

Keywords: carrot, seed-metering device, seed guiding process, mechanism analysis, EDEM software, bench test

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1 Introduction

Carrot seeds are small in size and light in weight, and there are problems such as uneven seed spacing in mechanized seeding[1-5]. In order to improve the uniformity of seed spacing, experts at home and abroad have planted the seed movement track, landing angle and speed, and studied the seed guiding method and structural parameters[6-10]. The outer contour of the seed guide tube of the Maestro SW air-suction precision seeder of the German Horsch company is a smooth curve[11,12]. The section shape of seed guide tube shows a gradual shrinking trend[13]. SpeedTube toothed belt type seed guide device developed by Precision Planting Company of the United States. Enables secondary seeding in the respective area of the toothed belt[14] and ensure the uniformity of seed spacing by adjusting the speed of the conveyor belt. Italian Maschio company developed CHRONO high speed seeding machine, its seed metering device tilted 15°, the seeds leave the seed metering device fall into the seed guide tube will not be friction with the row of seeds tray, to avoid interference in the free fall, at the same time in the guide tube into the positive pressure airflow to improve the speed of seeding so that it is balanced with the speed of the planter, to realize the zero-speed seeding. Germany Amazone company developed the EDX series of high speed precision planter adopts the positive pressure airflow conveying type seed guide mode, in the positive pressure under the action of the blowing force of the seed discharger discharged seed along the inner wall of the seed guide tube quickly slides into the soil to reduce the collision of the seed and the wall of the seed guide tube, the efficiency of the seed guide is high. Domestic scholars have explored the seed delivery methods of corn, soybean and other large grain seeds[15-17]. Li et al.[18,19] studied the problem of different seed dropping positions and lateral seed flying under the condition of high speed operation of corn seeds, and proposed a method of the terminal dial-off and linear seed falling, to achieve uniform seed dropping. Yang et al.[20] developed a new type of seed guide tube suitable for Panax notoginseng planting. By using the methods of image processing and curve fitting, they determined the curve equation of seed motion trajectory and the shape of seed guide tube. The above scholars mainly studied the seed guiding mechanism of large-grain seeds such as corn and soybeans, but did not study the key components of small-grain seeds such as carrots. Therefore, the seed loading and movement state shall be studied to determine the factors affecting the seeding quality and the best parameter combination, which it is of great practical significance to optimize the seed guide structure and working parameters.

2 Materials and methods

2.1 Structure and working principle of seed-metering device

The air-suction precision seed metering device for carrots developed by Qingdao Agricultural University, China (as shown in Figure 1), which can realize negative pressure seed filling, precise seed cleaning and zero pressure seed feeding. When working, the seeds are adsorbed on the rotating seed metering disc, and the redundant seeds are removed by the seed cleaning device, thus achieving single seed sowing; Under the combined action of air

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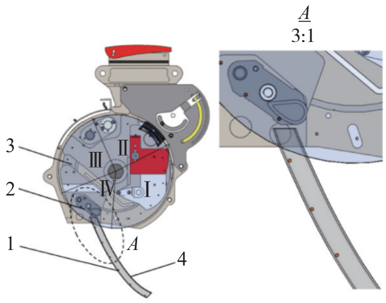
adsorption force, seed gravity, rotational inertia force and collision force of seed scraping parts, the seeds fall into the seed guide tube and complete the fixed-point directional seeding; The falling seeds slide along the surface of the seed guide tube under the action of gravity and friction and fall into the seed ditch. Influenced by factors such as lightweight, small size, large seed falling speed, the seeds are easy to collide with the wall of the seed guide tube and bounce on the ground, affecting the uniformity of seeding[21]. In order to ensure that the seeds slide smoothly in the seed guide tube and avoid the seeds bouncing on the ground, the analytical method is used to study the seed guide process of the seeds, optimize the key parameters of the seeds, and realize the equal spacing seeding of the seeds.



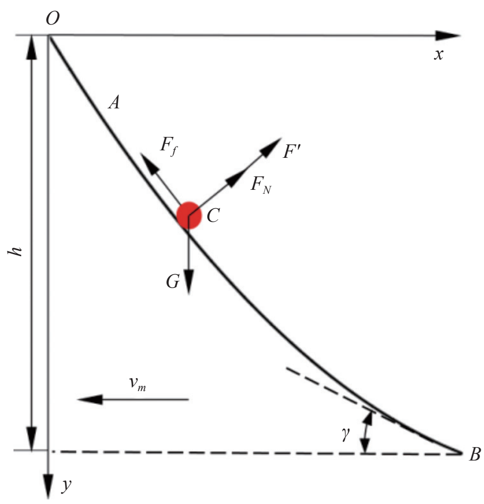
Note: 1.Seed; 2.Seed scraping part; 3.Seed metering plate; 4.Seed delivery tube; Ⅰ Seed filling area; Ⅱ Seed clearing area; Ⅲ Seed carrying area; Ⅳ Seed feeding area.

Figure 1 Structure diagram of seed guide parts of air-suction precision metering device

2.2 Analysis of the seed guide process

The state of motion of the seed in the seed guide mechanism, which determines the state of fall of the seed. In the process of seed falling, the seed fall freely, which is mainly affected by air resistance. Research on the seed guide process to determine stable and reliable seed guide control conditions can improve the seeding effect and operational quality of carrots.

After the seeds fall into the seed tube, take a single seed as the research object to conduct mechanical analysis[22-24], establish a mathematical model, and clarify the control conditions of “zero speed” seed falling (as shown in Figure 2).



Note: F_f is the sliding friction force, N; F_N is the support of the curve to the seed, N; G is the seed gravity, N; F' is the seed centripetal force, N; h is the vertical height of the seed falling, mm; γ is the inclination angle of seed tube end, (°).

Figure 2 Force analysis of seed sliding

The seed is subjected to the supporting force F_N in the seed tube, the seed gravity G, the sliding friction force F_f between the seed and the tube wall and the centripetal force F', from the equilibrium condition of seed C at point B we know that:

$$\begin{cases} ma_c = G\sin\gamma - F_f \\ F_N = G\cos\gamma + \dfrac{mv^2}{r} \\ F_f = \mu F_N \end{cases} \tag{1}$$

where, μ is coefficient of friction between the seed and the wall of the seed guide tube; F_f is sliding friction, N; γ is the inclination angle of seed tube end, that is, the angle of inclination of point B (°).

From Equation (1) it follows that,

$$ma_c = m\frac{\mathrm{d}v}{\mathrm{d}t} = mg\sin\gamma - \mu\left(mg\cos\gamma + \frac{mv^2}{r}\right) \tag{2}$$

If the contour curve equation of seed tube is $y=f(x)$, then

$$\tan\gamma = \frac{dy}{dx} \tag{3}$$

$$\mathrm{d}s = \frac{\mathrm{d}x}{\cos\gamma} = \sqrt{1+\left(\frac{\mathrm{d}y}{\mathrm{d}x}\right)^2}\,\mathrm{d}x \tag{4}$$

From Equations (2)-(4), as:

$$\frac{1}{2}v^2 = g(y-\mu x) - \frac{\mu v^2\sqrt{1+\tan^2\gamma}}{r}x + C \tag{5}$$

If t=0, v=v_0, x=0, y=0, can be obtained $C=\frac{1}{2}v_O^2$, and it can be obtained by Equation (5),

$$v_\mathrm{B} = v = \sqrt{\frac{2g(y-\mu x)+v_0^2}{1+2K\mu x(1+\tan^2\gamma)^{1/2}}} \tag{6}$$

where, $r=\frac{1}{K}$, K is the curvature of the curve; and v_0 is the seed initial speed m/s.

According to Equation (6), the relative velocity of the seed leaving the end of the seed tube is related to the contour curve of the seed tube, the length of the seed tube, the inclination angle of seed tube end γ, friction coefficient between seed and seed tube μ and seed initial speed v_0. Therefore, in order to ensure that the speed of the seed leaving the end of the seed guide tube can offset the forward speed of the machine, it is necessary to plan the seed guide path (seed tube contour curve).

2.3 Seed guide path planning

After the seeds enter the seed tube, they move along the curve of the seed tube, and the speed direction changes constantly. When the horizontal speed of the seed leaving the end of the seed tube is offset by the forward speed, the seed can be dropped at zero speed to ensure the stable landing of the seed. Take the starting position of the seed tube as the coordinate origin O, the opposite direction of the advance speed v_m of the implement is the x-axis, and the vertical falling direction of the seed is the y-axis, and establish a rectangular coordinate system (as shown in Figure 2).

Assume that the contour curve equation of seed tube is $y=ax^2+bx$ (a and b are constants). In the process of seed for sliding from the starting point O (0,0) to seed falling point B (x_B, y_B). Work B done by friction force F_f is,

$$\mathrm{B} = \int F_f dS = \frac{\mu m\left(\sqrt{4ah+b^2}-b\right)}{2a}\left(g+\frac{Kv^2}{\cos\gamma}\right) \tag{7}$$

where, h is the vertical height of seed falling, mm.

From the conservation of mechanical energy,

$$v_B^2 - v_0^2 - 2gh = -\frac{\mu\left(\sqrt{4ah+b^2}-b\right)}{a}\left(g+\frac{Kv_B^2}{\cos\gamma}\right) \tag{8}$$

From Equations (6) and (8) it follows that,

$$\frac{\cos\gamma\left[2gx_B+2Kx_Bv_B^2\left(1+\tan\gamma\right)^{1/2}\right]}{g\cos\gamma+Kv_B^2}=\frac{\sqrt{4ah+b^2}-b}{a} \tag{9}$$

If, $\frac{\cos\gamma\left[2gx_B+2Kx_Bv_B^2\left(1+\tan\gamma\right)^{1/2}\right]}{g\cos\gamma+Kv_B^2}=E$, then

$$a=\frac{4hx_B-2Eh}{x_BE^2-2Ex_B^2};\ b=\frac{h-ax_B^2}{x_B} \tag{10}$$

Therefore, the contour curve equation (seed guide path) of the seed tube is,

$$y=\frac{4hx_B-2Eh}{x_BE^2-2Ex_B^2}x^2+\frac{h(E^2-2Ex_B)-(4hx_B-2Eh)x_B}{x_B(E^2-2Ex_B)}x \tag{11}$$

According to Equation (11), the seed falling process is affected by the seed tube contour curve, and is related to the seed falling height h, the inclination angle of seed tube end γ, the initial seed speed v_O (related to the rotation speed n of the seed disc), the curvature K of the curve and the friction coefficient between the seed and the seed guide tube μ and other factors. Because the seed drop height should not be too high and the friction coefficient between the seed materials is less than 1,which have little effect on the equation of the seed trajectory curve and can be neglected. Therefore, the movement track of the seed is mainly related to the inclination angle of seed tube end γ, the operating speed of the metering disc n and the forward speed of the machine v_m.

2.4 One-factor simulation experimental

Coated carrot seeds are small in size and light in weight, and easy to be disturbed by the surrounding environment. By the EDEM simulation software, determine the influence of the inclination angle of seed tube end γ, the operating speed of the metering disc n and the forward speed of the machine v_m on the seed metering uniformity, determine the appropriate parameter range.

2.4.1 Construction of simulation model

In the experiment, coated carrot seed (Mendel II) was taken as the particle model object, the seed discrete element simulation model[25] was established by using the 5-ball combination method. The Hertz-Mindlin (no slip) contact model[26-28] was selected as the contact model. The particle generation mode was dynamic. The total number of particles was 250, and the generation rate was 10/s. The contact parameters and mechanical characteristics parameters are listed in Table 1, and the carrot seed simulation model is shown in Figure 3.

Table 1 Parameters required for discrete element simulation

Parameters	Value
Density of carrot seed/(kg·m^{-3})	1130
Density of ABS/(kg·m^{-3})	1060
Poisson's ratio of carrot seed	0.2
Poisson's ratio of ABS	0.39
Shear modulus of carrot seeds/MPa	6
Shear modulus of ABS/MPa	896
Carrot seed-carrot seed collision recovery coefficient	0.25
Carrot seed-ABS collision recovery coefficient	0.55
Carrot seed-Carrot seed static friction coefficient	0.43
Carrot seed-ABS static friction coefficient	0.45
Carrot seed-Carrot seed rolling friction coefficient	0.08
Carrot seed-ABS rolling friction coefficient	0.06

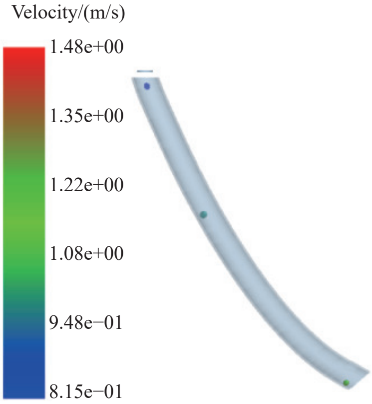


Figure 3 Simulation model of carrot seed guide

2.4.2 One-factor experimental design

The inclination angle of seed tube end γ, the operating speed of the metering disc n and the forward speed of the machine v_m are the core factors affecting the uniformity of seeding. With reference to the standard GB/T 6973-2005, the influence of various factors on the index of grain spacing uniformity (pass rate, repeat rate, missed rate) was studied[29]. The experiment was designed as a 5-level experiment, with each group of experiments repeated 3 times, and the number of seeds counted each time was 250. The calculation method of each index is as follows:

$$A=\frac{n_1}{N}\times 100\% \tag{12}$$

$$D=\frac{n_2}{N}\times 100\% \tag{13}$$

$$M=\frac{n_3}{N}\times 100\% \tag{14}$$

where, A is pass rate, %; D is replay rate, %; M is missed seeding rate, %; n_1 is number of seeds with qualified seed spacing; S is distance between plants, 50-100 mm; n_2 is number of seeds with seed spacing $\leq$ 0.5S; n_3 is number of seeds with seed spacing $\geq$0.5S.

2.5 Parameter optimization test

2.5.1 Test materials and equipment

Taking the coated carrot seed (Mendel II) as the test sample, the JPS-12 test bed of the School of Mechanical and Electrical Engineering of Qingdao Agricultural University was selected. The equipment parameters are: seed bed belt speed 3.6-12 km/h, seed metering shaft speed 10-150 r/min, pneumatic pressure positive pressure 0-35 kPa, negative pressure -28 to 0 kPa (as shown in Figure 4).

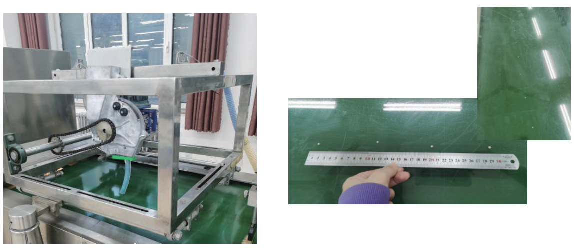


Figure 4 JPS-12 seed-metering performance test bench

2.5.2 Multi-factor experimental design

The inclination angle of seed tube end x_1, the forward speed of the machine x_2 and the operating speed of the metering disc x_3 were selected as the experimental factors, while the pass rate y_1, replay rate y_2 and missing seeding rate y_3 were selected as the experimental indexes to carry out the orthogonal rotation combination test of three factors and five levels. The factor code is listed in Table 2.

Table 2 Experimental factors code

Code	Inclination angle of seed tube end x_1/(°)	Machine forward speed x_2/(km·h^{-1})	Operating speed x_3/(r·min^{-1})
–1.682	23.00	5.00	15.00
–1	26.45	5.81	20.07
0	31.50	7.00	27.50
1	36.55	8.19	34.93
1.682	40.00	9.00	40.00

3 Results and discussion

3.1 Analysis of one-factor simulation experimental result

3.1.1 Influence of inclination angle of seed tube end on seeding uniformity

When the operating speed of the metering disc is 27.5 r/min, and the forward speed of the machine is 7 km/h, the influence of the inclination angle of seed tube end on the pass rate, the replay rate, and the missed seeding rate (as shown in Figure 5).

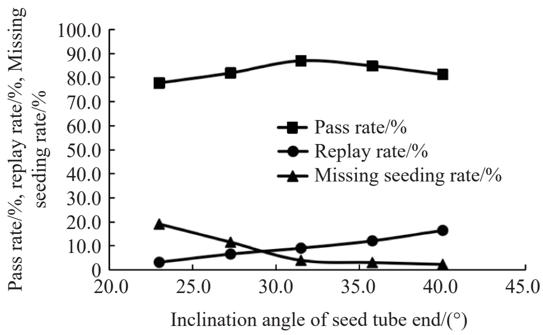


Figure 5 Relation curve between test index and inclination angle of seed tube end

It can be seen from Figure 5 that when the forward speed of the machine and the operating speed of the metering disc are constant, the inclination angle of seed tube end increases, and the pass rate rises first and then falls. The replay rate gradually increased; The missed seeding rate first dropped sharply and then became flat. When the inclination angle of the seed tube end is large, the slope of the curve increases, the time of the seed movement in the seed guide tube is short, the seed pass rate is low, and the replay rate is high. By Design-Expert 12 software, the variance analysis was performed on test results, the variance analysis results are listed in Table 3. The results show that the inclination angle of seed tube end has a significant impact on the pass rate, and has a very significant impact on the replay rate and the missing seeding rate, indicating that the inclination angle of seed tube end is the main factor affecting the experimental performance index, with a significant range of 23°-40°.

Table 3 Variance analysis

Source		Sum of squares	Df	Mean square	F-value	p-value	Significance
Pass rate/%	Intergroup	149.72	4	37.43	12.76	0.0006	Significant
	Within Group	29.33	10	2.93			
	Total	179.04	14				
Replay rate/%	Model	309.35	4	77.34	50.53	<0.0001	Very significant
	Intergroup	15.31	10	1.53			
	Within Group	324.66	14				
Missing seeding rate/%	Intergroup	624.58	4	156.15	102.95	<0.0001	Very significant
	Within Group	15.17	10	1.52			
	Total	639.75	14				

3.1.2 Influence of forward speed of the machine on seeding uniformity

When the operating speed of the metering disc is 27.5 r/min and the inclination angle of the seed tube end is 31.5°, the influence of the machine's forward speed on the pass rate, replay rate and missed seeding rate (as shown in Figure 6).

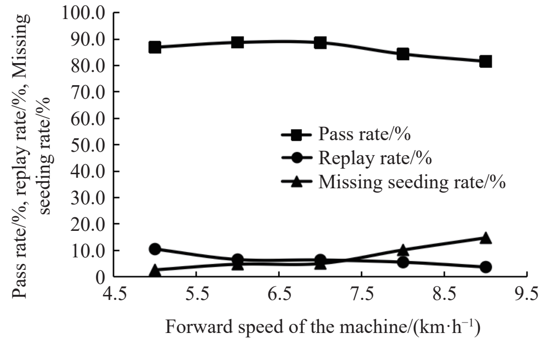


Figure 6 Relation curve between test index and machine forward speed

It can be seen from Figure 6 that when the inclination angle of seed tube end and the operating speed are constant, the forward speed of the machine increases, and the pass rate first slowly rises and then falls. The replay rate gradually decreased; The rate of missed seeding increased gradually. When the machine's forward speed is large, the horizontal part speed of the seed projected into the soil does not offset the forward speed of the machine, and the pass rate shows a decreasing trend. By Design-Expert 12 software, perform variance analysis on test results, the results are listed in Table 4. The results show that the forward speed of the machine has a significant impact on the pass rate, replay rate and missing seeding rate, indicating that the forward speed of the machine is the main factor affecting the experimental performance index, and its significant range is 5-9 km/h.

Table 4 Variance analysis

Source		Sum of Squares	Df	Mean Square	F-value	p-value	Significance
Pass rate/%	Intergroup	112.93	4	28.23	8.31	0.0032	Significant
	Within Group	33.95	10	3.4			
	Total	146.88	14				
Replay rate/%	Model	74.37	4	18.59	9.80	0.0017	significant
	Intergroup	18.98	10	1.90			
	Within Group	93.35	14				
Missing seeding rate/%	Intergroup	291.46	4	72.86	15.05	0.0003	significant
	Within Group	48.41	10	4.84			
	Total	339.87	14				

3.1.3 Influence of operating speed of the metering disc on seeding uniformity

When the forward speed of the machine is 7 km/h and the inclination angle of the seed tube end is 31.5°, the influence of the operating speed on the pass rate, replay rate and missed seeding rate (as shown in Figure 7).

It can be seen from Figure 7 that when the inclination angle of seed tube end and the forward speed of the machine are constant, the operating speed gradually increases, and the pass rate first slowly increases and then decreases; The replay rate gradually decreased; The rate of missed seeding increased gradually. When the operating speed is small, the linear speed of the seeding disc is small, the seed filling operation time is relatively long, the centrifugal force on the seed is small, and the seed can slide smoothly and orderly into the seed guide tube from the seed guide mouth, and the pass rate is increasing. When the operating speed is high, the linear speed of the seeding disc is high, the centrifugal force on the seeds is high, the seed dropping speed increases, the number of collisions with the inner wall of the seed guide tube increases, and the pass rate decreases. By Design-Expert 12 software, perform variance analysis on test results, the results are listed in Table 5. The results show that the influence of operating speed of the metering disc on the replay rate is extremely significant, and the influence on the pass rate and the missed seeding rate is significant, indicating that the operating speed of the metering disc is the main factor affecting the experimental performance index, and its significant range is 15-40 r/min.

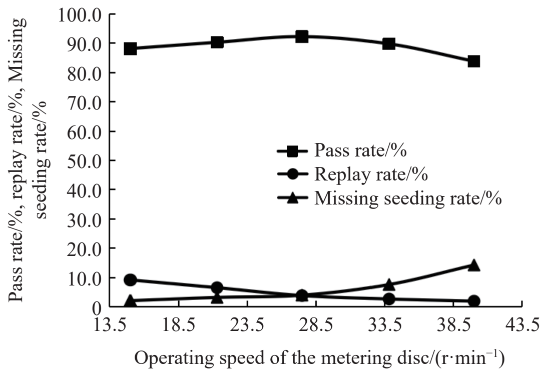


Figure 7 Relation curve between test index and operating speed

Table 5 Variance analysis

Source		Sum of Squares	Df	Mean square	F-value	p-value	Significance
Pass rate/%	Intergroup	120.07	4	30.02	6.19	0.009	Significant
	Within group	48.48	10	4.85			
	Total	168.55	14				
Replay rate/%	Model	107.32	4	26.83	55.05	<0.0001	Very significant
	Intergroup	4.87	10	0.4873			
	Within group	112.19	14				
Missing seeding rate/%	Intergroup	293.48	4	73.37	15.31	0.0003	Significant
	Within group	47.93	10	4.79			
	Total	341.41	14				

3.2 Analysis of multi-factor bench test result

3.2.1 Test results

The inclination angle of seed tube end x_1, the forward speed of the machine x_2 and the operating speed of the metering disc x_3 were selected as the experimental factors, while the pass rate y_1, replay rate y_2 and missing seeding rate y_3 were selected as the experimental indexes to carry out the orthogonal rotation combination test of three factors and five levels. The test scheme and results are listed in Table 6.

Table 6 Experimental design and results

No.	Factor			Test index		
	x_1	x_2	x_3	y_1/%	y_2/%	y_3/%
1	–1	–1	–1	89.38	4.21	6.41
2	1	–1	–1	81.41	6.23	12.36
3	–1	1	–1	86.57	5.83	7.60
4	1	1	–1	82.51	6.13	11.36
5	–1	–1	1	89.48	7.24	3.28
6	1	–1	1	90.11	4.27	5.62
7	–1	1	1	84.27	4.62	11.11
8	1	1	1	86.79	2.31	10.90
9	–1.682	0	0	91.22	4.61	4.17
10	1.682	0	0	86.28	3.11	10.61
11	0	–1.682	0	87.30	8.77	3.93
12	0	1.682	0	84.13	6.42	9.45
13	0	0	–1.682	78.81	5.73	15.46
14	0	0	1.682	84.61	3.85	11.54
15	0	0	0	90.44	4.28	5.28
16	0	0	0	91.61	5.69	2.70
17	0	0	0	89.79	4.11	6.10
18	0	0	0	92.12	3.41	4.47
19	0	0	0	91.40	3.61	4.99
20	0	0	0	90.68	4.43	4.89
21	0	0	0	91.32	3.41	5.27
22	0	0	0	89.71	4.69	5.60
23	0	0	0	91.20	3.88	4.92

3.2.2 Establishment of regression equation and significance test

With the help of Design-Expert 12 software, the results of orthogonal rotation combination test were fitted by multiple regression, and the regression equations of pass rate y_1, replay rate y_2 and missed seeding rate y_3 were obtained. The analysis of variance is listed in Table 7.

Table 7 Variance analysis of qualified rate, replay rate and missing rate

Soruce	Pass rate y_1/%				Replay rate y_2/%				Missing seeding rate y_3/%			
	Sum of square	Df	F-value	p-value	Sum of square	Df	F-value	p-value	Sum of square	Df	F-value	p-value
Model	293.76	9	34.61	<0.0001	42.78	9	10.72	0.0001	258.59	9	35.08	<0.0001
x_1	21.63	1	22.94	0.0004	2.20	1	4.96	0.0442	37.63	1	45.95	<0.000
x_2	17.75	1	18.82	0.0008	3.60	1	8.12	0.0137	37.34	1	45.60	<0.000
x_3	30.88	1	32.74	<0.000	3.37	1	8.38	0.0125	13.17	1	16.08	0.0015
x_1x_2	4.21	1	4.46	0.0547	0.1404	1	0.3168	0.5831	2.81	1	3.43	0.0869
x_1x_3	28.80	1	30.54	<0.000	7.22	1	16.28	0.0014	7.18	1	8.77	0.0110
x_2x_3	5.81	1	6.16	0.0275	4.65	1	10.49	0.0065	20.87	1	25.48	0.0002
x_1^2	4.07	1	4.31	0.0583	0.5663	1	1.28	0.2789	7.67	1	9.36	0.0091
x_2^2	39.61	1	42.00	<0.000	20.35	1	45.90	<0.0001	3.18	1	3.88	0.0706
x_3^2	142.51	1	151.10	<0.000	0.3115	1	0.7026	0.4171	129.50	1	158.12	<0.000
Residual	12.26	13			5.76	13			1065	13		
Lack of Fit	6.85	5	2.02	0.1792	1.55	5	0.5871	0.7111	3.40	5	0.7518	0.6075
Pure Error	5.41	8			4.22	8			7.24	8		
Sum	306.02	22			48.54	22			269.23	22		

(1) Pass rate y_1

It can be seen from Table 7 that the fitting model of the pass rate is p<0.001, the model is extremely significant, and the lack of fit item p=0.1792, which is not significant, indicating that the quadratic relationship between the pass rate and the test factors is significant. Among them, the interaction term x_1x_2 of the1inclination angle of seed tube end and machine's forward speed, the squared term x_1^2 of the inclination angle of the seed tube end are both greater than 0.05, which has no significant impact on the pass rate. The other items are significant or extremely significant. The regression model after removing the insignificant factors is:

$$y_1 = 36.51 - 1.23x_1 + 13.50x_2 + 2.56x_3 + 0.0504x_1x_3 - 0.0962x_2x_3 - 1.11x_2^2 - 0.0540x_3^2 \quad (15)$$

Through analysis, it can be concluded that the primary and secondary order of the factors affecting the pass rate is the operating speed of the metering disc, the inclination angle of the seed tube end and the forward speed of the machine.

(2) Replay rate y_2

It can be seen from Table 7 that the fitting model of the replay rate is p=0.001, the model is significant, and the lack of fit item p=0.7111, which is not significant, indicating that the quadratic relationship between the replay rate and the test factors is significant. Among them, the interaction term x_1x_2 of the inclination angle of seed tube end and machine's forward speed, the squared term x_1^2 of the inclination angle of seed tube end and the squared term x_3^2 of the operating speed of the metering disc are both greater than 0.05, which has no significant impact on the replay rate. The other items are significant or extremely significant. The regression model after removing the insignificant factors is:

$$y_2 = 2.03 + 1.24x_1 - 8.56x_2 + 1.19x_3 - 0.0253x_1x_3 - 0.0860x_2x_3 + 0.7992x_2^2 \quad (16)$$

Through analysis, it can be concluded that the primary and secondary order of the factors affecting the replay rate is the operating speed of the metering disc, the forward speed of the machine and the inclination angle of the seed tube end.

(3) Missing seeding rate y_3

It can be seen from Table 7 that the fitting model of the missing seeding rate is p<0.001, the model is extremely significant, and the lack of fit item p=0.6075, which is not significant, indicating that the quadratic relationship between the missing seeding rate and the test factors is significant. Among them, the interaction term x_1x_2 of the inclination angle of seed tube end and machine's forward speed, the squared term x_2^2 of the forward speed of the machine are both greater than 0.05, which has no significant impact on the missing seeding rate. The other items are significant or extremely significant. The regression model after removing the insignificant factors is:

$$y_3 = 61.45 - 0.0040x_1 - 4.94x_2 - 3.44x_3 - 0.0252x_1x_3 + 0.1822x_2x_3 + 0.0272x_1^2 + 0.0514x_3^2 \quad (17)$$

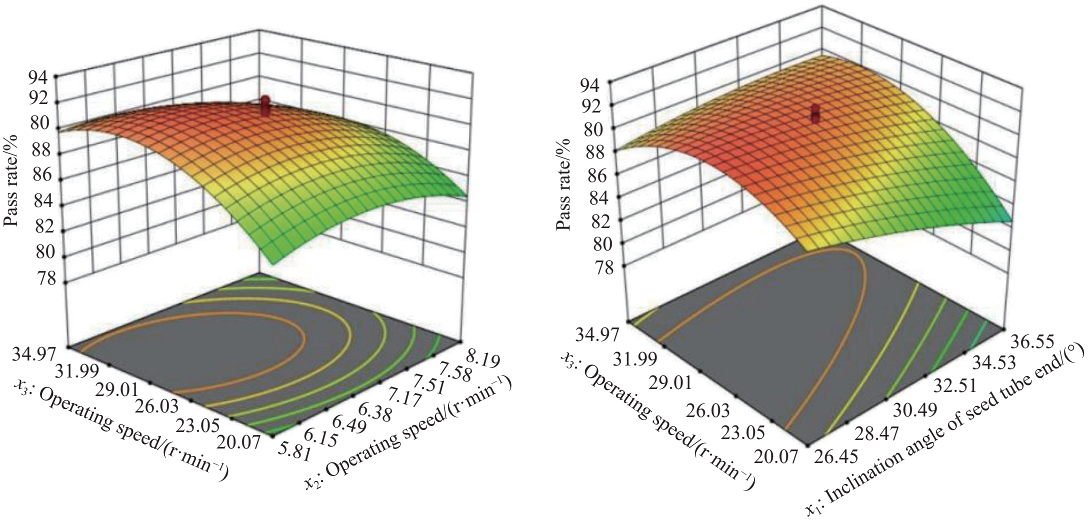
Through analysis, it can be concluded that the primary and secondary order of the factors affecting the replay rate is the inclination angle of the seed tube end, the forward speed of the machine and the operating speed of the metering disc.

3.2.3 Response surface analysis of various factors to performance indicators

Use the dimension reduction method to adjust any one of the test factors, such as the inclination angle of seed tube end, the operating speed of the seed metering disc and machine's forward speed, to zero level[30], and draw the response surface diagram of the influence of the interaction items on the pass rate, the replay rate and the missed seeding rate (as shown in Figures 8-10).

(1) Response surface analysis of two-factor interaction on pass rate

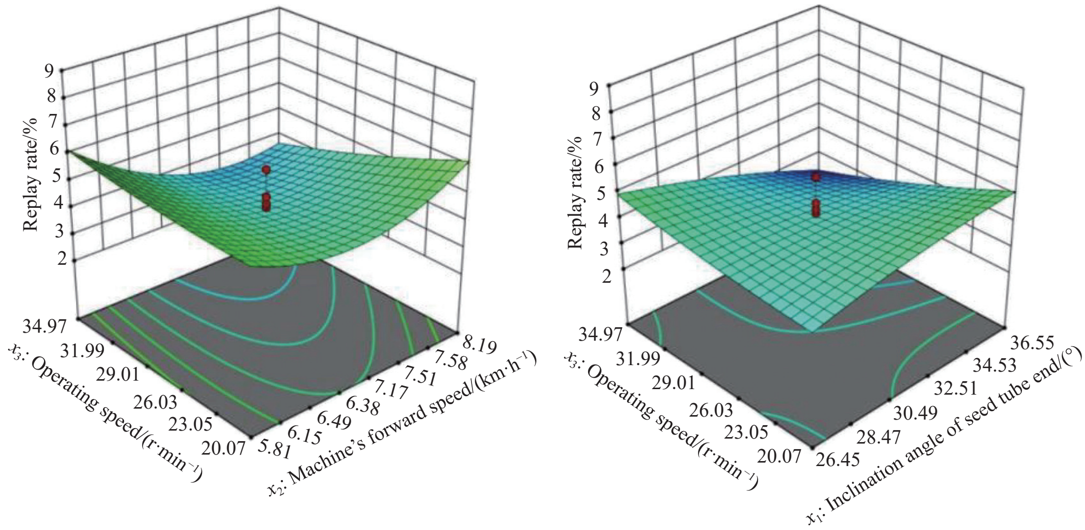
Figure 8a shows the corresponding curved surface of the interaction between the operating speed and the forward speed of the machine and the pass rate when the inclination angle of the seed tube end is 31.5°. It can be seen from the figure that at the same operating speed, the pass rate first increases and then decreases with the increase of the forward speed of the machine; With the same forward speed of the machine, the operating speed increases, and the pass rate first rises and then decreases, and the trend is flat. Figure 8b shows the corresponding curved surface of the interaction between the operating speed and the inclination angle of seed tube end and the pass rate when the forward speed of the machine is 7 km/h. It can be seen from the figure that at the same operating speed, the pass rate gradually decreases with the increase of the inclination angle of seed tube end; With the same inclination angle of seed tube end, the operating speed increases, and the pass rate increases first and then decreases.



a. x_2x_3 Interactive

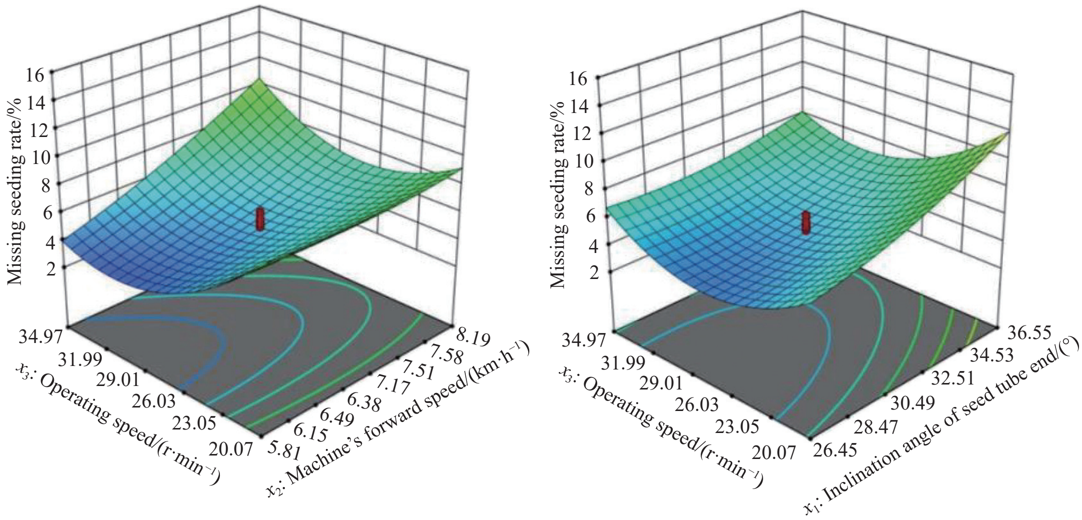
b. x_1x_3 Interactive

Figure 8 Effects of interactive factors on pass rate.



a. x_2x_3 Interactive b. x_1x_3 Interactive

Figure 9 Effects of interactive factors on replay rate



a. x_2x_3 Interactive b. x_1x_3 Interactive

Figure 10 Effects of interactive factors on missing seeding rate

(2) Response surface analysis of two-factor interaction on replay rate

Figure 9a shows the corresponding curved surface of the interaction between the operating speed and the forward speed of the machine and the replay rate when the inclination angle of the seed tube end is 31.5°. It can be seen from the figure that under the condition of the same forward speed of the machine, the operating speed increases and the replay rate gradually increases; At the same operating speed, the replay rate tends to first decrease and then increase with the increase of machine forward speed. Figure 9b shows the corresponding curved surface of the interaction between the operating speed and the inclination angle of seed tube end and the replay rate when the forward speed of the machine is 7 km/h. It can be seen from the figure that at the same operating speed, the replay rate gradually increases with the increase of the inclination angle of seed tube end; With the same inclination angle of seed tube end, the operating speed increases, and the replay rate gradually increases and the trend is flat.

(3) Response surface analysis of two-factor interaction on missing seeding rate

Figure 10a shows the corresponding curved surface of the interaction between the operating speed and the forward speed of the machine and the missing seeding rate when the inclination angle of the seed tube end is 31.5°. It can be seen from the figure that under the same operating speed, the missed seeding rate gradually increases with the increase of the machine's forward speed; With the same forward speed of the machine, the operating speed increases, and the rate of missed seeding decreases first and then increases. Figure 10b shows the corresponding curved surface of the interaction between the operating speed and the inclination angle of seed tube end and the missing seeding rate when the forward speed of the machine is 7 km/h. It can be seen from the figure that under the same operating speed, the rate of missing seeding increases gradually with the increase of the inclination angle of seed tube end; With the same inclination angle of seed tube end, the operating speed increases, and the rate of missing seeding decreases first and then increases.

3.3 Optimal parameter combinations

In order to obtain the best combination of test parameters, the performance indicators are optimized based on the multi-objective parameter optimization module in the Design-Expert 12 software. Optimization conditions of the objective function and various factors are:

$$\begin{cases} y_1 \geq 90\% \\ y_2 \leq 5\% \\ y_3 \leq 5\% \\ 23^\circ \leq x_1 \leq 40^\circ \\ 5\ \mathrm{km/h} \leq x_2 \leq 9\ \mathrm{km/h} \\ 15\ \mathrm{r/min} \leq x_3 \leq 40\ \mathrm{r/min} \end{cases} \tag{18}$$

The best combination of the test parameters is obtained as follows: the inclination angle of the seed tube end is 32.28°, the forward speed of the machine is 6.89 km/h, and the operating speed is 28.67 r/min; The predicted value of the objective function is 90.98% of the pass rate, 4.08% of the replay rate, and 4.94% of the missing seeding rate. In order to verify the reliability of the optimization results, the best parameter combination was tested and verified. The results showed that the pass rate was 93.25%, the replay rate was 2.97%, and the missing seeding rate was 3.78%.The test is demonstrated that under the best combination of parameters, the pass rate, replay rate and missing seeding rate can meet the design requirements.

4 Conclusions

(1) The process of seed guide was analyzed, and the main influencing factors of seed guide path were determined as follows: the inclination angle of seed tube end γ, the operating speed of the metering disc n, the forward speed of the machine v_m.

(2) With the help of EDEM software, study the influence of the inclination angle of seed tube end γ, the operating speed of the metering disc n and the forward speed of the machine v_m on the pass rate, replay rate and missing seeding rate, and determine the appropriate range of key factors: The inclination angle of seed tube end is 23°-40°, the forward speed of the machine is 5-9 km/h, the operating speed of the metering disc is 15-40 r/min.

(3) By the quadratic orthogonal rotation combination test method, the regression model between the inclination angle of seed tube end, the forward speed of the machine, the operating speed of the metering disc and the pass rate, the replay rate, and the missing seeding rate was established, and the primary and secondary order of the factors and their influence on the index were determined.

(4) Optimize the test indexes and determine the best combination of factors. When the inclination angle of seed tube end is 32.28°, the forward speed of the machine is 6.89 km/h, the operating speed of the metering disc is 28.67 r/min, the pass rate is 93.25%, the replay rate is 2.97%, and the missing seeding rate is 3.78%, which meets the requirements of relevant national standards.

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