DESIGN AND EXPERIMENT OF SPOON-WHEEL PEANUT SEED LOADER BASED ON DISCRETE ELEMENT ANALYSIS
/
基于离散元分析的勺轮式花生排种器设计与试验

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ABSTRACT
In view of the low mechanical sowing rate of peanuts in China, the existing seeders had problems such as insufficient sowing accuracy and slow speed, with the core goal of improving sowing accuracy, a key component of the sowing integrated machine - the spoon-wheel type seed conveyor - was designed. Based on mechanical analysis, the key parameters of the U-shaped groove inclination Angle of the seed spoon being 26° and the side Angle not less than 50° were obtained. The discrete element simulation model of the seed seeder was established by using EDEM software. Taking the rotational speed of the seed seeder, the side Angle of the seed spoon, and the top width of the seed spoon as the experimental factors, and the replay rate and missed broadcast rate as the indicators, single-factor and three-factor three-level orthogonal experiments were carried out, and the parameters were optimized through the response surface method. The results showed that the optimal parameter combination was the side Angle of the seed spoon 54°, the rotational speed of the seed spoon wheel 20r/min, and the width of the top surface of the seed spoon 11.9mm. At this time, the replay rate was 5.19% and the missed broadcast rate was 5.43%, both of which met the requirements of industry standards.

摘要
针对中国花生机械化播种率低、现有播种机存在播种精度不足、速率慢等问题，以提升播种精准度为核心目标，设计一款播种一体机的关键部件——勺轮式排种器。基于力学分析得出种勺 U 型凹槽倾角 26°、侧面角度不小于 50°的关键参数。利用 EDEM 软件建立排种器离散元仿真模型，以排种器转速、种勺侧面角度、种勺顶部宽度为试验因素，重播率和漏播率为指标，开展单因素及三因素三水平正交试验，通过响应面法优化参数。结果表明，最优参数组合为种勺侧面角度 54°、种勺轮转速 20r/min、种勺顶面宽度 11.9mm，此时重播率为 5.19%，漏播率为 5.43%，均满足行业标准要求。

INTRODUCTION
Peanuts are an important oil crop in China, providing a crucial guarantee for the country's economic development and the maintenance of national food and oil security. Currently, the national sown area is approximately 4.6 million hectares, and the total output is about 17 million tons. China has always been the world's largest producer, consumer and exporter of peanuts *(China Statistics Press, 2023; Zhang et al., 2019; Liu et al., 2017)*. At present, the mechanical sowing rate of peanuts in China is only 65.65% *(Shen et al., 2024)*, which restricts the rapid development of the peanut industry.

At present, the integrated sowing machines in China generally have problems such as low working efficiency and low sowing accuracy. Moreover, the deep soil layer and uneven seed distribution caused by many influencing factors of manual planting have affected the growth and yield of peanut plants *(Fu et al., 2024)*.

Wang et al. (2021) designed a mechanical wheat shot seeding and seed distribution device. The coefficient of variation of the uniformity of seed distribution volume is 8.6%, the seed distribution speed is 34.7 m/s, and the average sowing depth is 32 mm, which meets the requirements of wheat sowing operations in North China.

Liu et al. (2021) designed a magnetic finger clamp type seed dispenser. The magnetic finger clamp type seed dispenser, which uses magnetic force to complete the opening and closing of the finger clamp throughout the process, has a seed dispensing qualification rate of 91.7%, a reseeding rate of 6.2%, and a missed seeding rate of 2.1%. *Zhang et al. (2021)* designed and optimized a sliding plate type hole wheel type seed arranger, and carried out single-factor simulation tests and orthogonal simulation tests. The pass rate, replay rate and missed broadcast rate were 89.09%, 3.64% and 7.27% respectively. *Li et al. (2022)* designed a precision seed disperser for narrow-row and densely planted soybeans. They calculated the structural parameters of the seed-holding type holes of the disperser's seed disperser wheel, and the qualification index and coefficient of variation were 90.37% and 12.87%, respectively. *Wang et al. (2024)* designed a spoon-wheel type corn precision seed seeder. Bench verification tests were conducted under vibration conditions, with a pass index exceeding 94.5%, a repeat seeding index less than 4%, a missed seeding index less than 1.5%, and a coefficient of variation less than 25.5%.

In recent years, peanut sowing machinery has shown a vigorous development trend both at home and abroad. However, due to significant differences in soil texture and climatic conditions among various regions, in actual agricultural production scenarios, the existing peanut sowing equipment is difficult to achieve high-precision and high-speed *sowing (Yao et al., 2024).* To effectively solve the above-mentioned problems, in order to reduce seed loss and improve their performance *(Bakirov et al., 2025),* a spoon-wheel type seed distributor has been developed with the core goals of improving the accuracy of sowing and increasing the working rate. It can achieve multiple functions such as precise sowing and high-speed sowing, providing a strong technical guarantee for promoting the upgrading of peanut mechanical sowing technology and facilitating the high-quality development of the peanut industry.

MATERIALS AND METHODS

Design of key components and mechanical analysis

The sowing device includes a double-disc furrow opener, a seed box and a seed distributor. Among them, the seed distributor is a key component of the seeder, and its structure is shown in Figure 1. The performance of the work directly affects the quality of sowing *(Gao et al., 2019).*

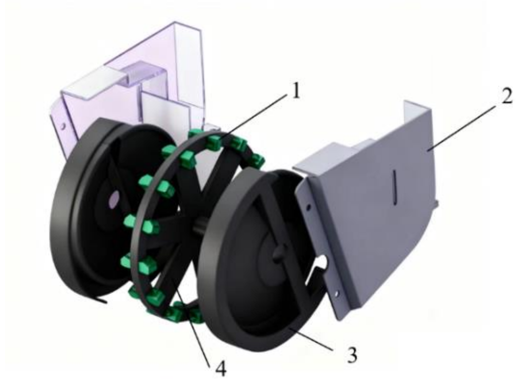


Fig. 1 - Schematic diagram of the seed dispenser structure
1. Seed spoon; 2. Seed storage box; 3. Shell; 4. Spoon wheel plate

The seeds in the seed box enter the seed filling zone of the seed discharger under natural gravity. The seed discharger is a double-seed sowing device. The rotation of the spoon wheel drives the seed spoon to move in a circular motion. After the seed spoon enters the seed filling zone, it takes peanut seeds. When the seed spoon rotates to the seed cleaning zone, the excess peanut seeds will fall back to the seed filling zone under the effect of its own gravity. The seed spoon carries a seed and continues to move circumferentially into the seed holding area. When the seed moves to the seed dropping area, due to the force of gravity, the seed falls off and lands in the seed furrow to achieve sowing.

The spoon wheel and the spoon wheel disc are key components of the seed dispenser *(Huang et al., 2023)*. The structure of the spoon wheel plate is shown in Figure 1. Under certain circumstances, increasing the size of the spoon wheel plate can improve the filling quality by extending the filling time.

According to the references *(Zhang et al., 2025),* the filling time is not affected by the size of the spoon wheel. Therefore, the diameter of the spoon wheel is designed to be 0.29m, and the number of seed spoons is 14, which are evenly distributed on the spoon wheel.

The upper and lower surfaces of the seed spoon are designed to hold large and small seeds respectively, and can be modified by removing it and installing it in reverse. To ensure that peanut seeds are not thrown out or dropped during transportation, the depth of the seed spoon should exceed the maximum diameter of the peanut seeds *(Ding et al., 2008).* The three-dimensional dimensions, 100-seed weight and static friction coefficient of the seeds of the main peanut variety "Luhua" in Shandong region were measured, as shown in Figure 2. 1000 seeds were randomly selected as the experimental samples for weight measurement. Thirty seeds were used as experimental samples for measuring the static friction coefficient between seeds and organic resin and three-dimensional dimensions. The external dimensions of the seeds were measured with a vernier caliper, and the three-dimensional dimensions are shown in Table 1.

Table 1

Geometric dimensions of peanuts

Indicator	Maximum value (mm)	Minimum value (mm)	Mean value (mm)
Length	22.91	12.36	18.81
Width	12.50	8.18	10.33
Thickness	12.32	8.02	10.19

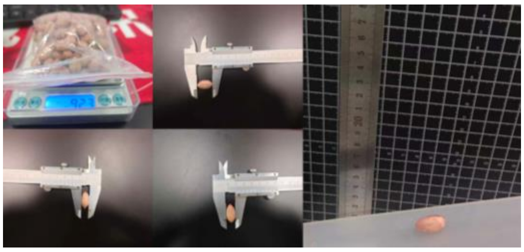


Fig. 2 - Seed physical property test

Its length is concentrated between 17mm and 20mm, and its width is concentrated between 9mm and 11mm. The maximum length is 22.91mm, the maximum width is 12.50mm, the maximum thickness is 12.32mm, the average weight per 100 grains is 90.43g, and the average static friction coefficient with organic resin is 0.47. If the size of the peanut variety to be sown is generally larger than 18mm×11mm×11mm, large-grain seed planes should be used for sowing; otherwise, small-grain seed planes should be used. To ensure that the seeds are fully inside the seed spoon and only one peanut seed is taken each time, the width of both sides is set at 10-14mm, the depth at 8mm, the length of the large seed surface x1 is set at 22mm, and the length of the small seed surface x2 is set at 16mm. The side Angle of the seed spoon is determined after subsequent calculation tests, as shown in Figure 3.

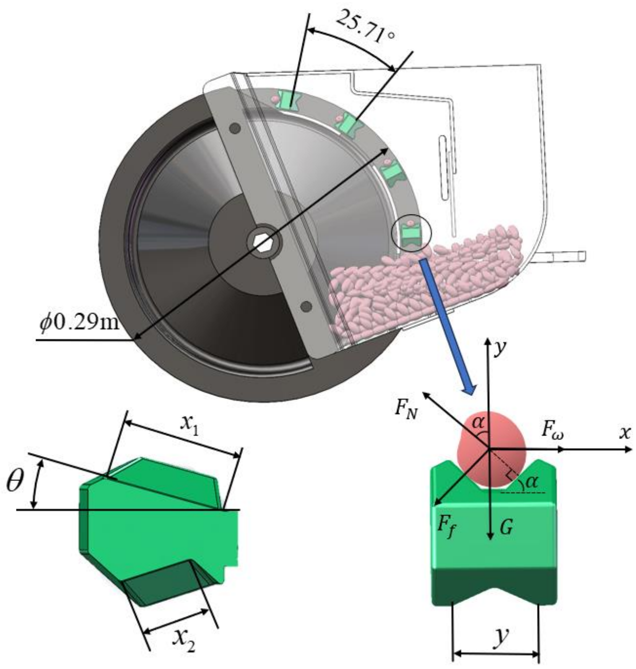


Fig. 3 - Force analysis diagram of seeds at the limit position for filling seeds in the seed spoon

To ensure that the seeds can slide into the seed spoon by their own gravity, the U-shaped groove of the seed spoon is set at a certain Angle. Therefore, the self-gravity of the seeds should be greater than the frictional force between them and the seed spoon, as shown in Equation (1). Calculating θ gives 25.17°, and rounding it to 26°.

$$mg\sin\theta \geq \mu mg\cos\theta \tag{1}$$

where: m-the mass of a single peanut seed, taking m as 0.000904kg; μ - the coefficient of kinetic friction between the seed and the seed spoon; θ - the Angle of the U-shaped groove of a spoon to the horizontal plane, [°].

When the seed filler is filling the seeds, if the side Angle of the seed spoon is too small before the seeds have completely slid into the U-shaped groove of the seed spoon, the centrifugal force acting on the seeds leaving the filling area will cause them to fall off the seed spoon and into the filling area. Therefore, it is necessary to measure the side Angle of the U-shaped groove.

According to the agronomic requirements for planting *(Chen et al., 2025; He Xiaoning et al., 2016)*, the spacing s between peanut plants is 150mm. The maximum forward speed of the machinery is 1.38m/s. The relationship between the forward speed of the machinery and the rotational speed of the seed discharge spoon is as shown in Equation (2).

$$\begin{cases} n = \dfrac{si}{t} \\ v_m = \dfrac{si}{t} \end{cases} \tag{2}$$

where:

n-seed dispenser speed, [m/s]; t-the time it takes for the seed arrangement wheel to complete one full rotation, [s]; s-spacing of peanut planting plants, [m]; i-a number of spoons; v_m-the forward speed of the machinery, [m/s].

According to Equation (2), The rotational speed of the spoon wheel is consistent with the forward speed of the machinery, $n=v_m$=1.38 m/s=45.6 r/min.

Because peanut seeds grow into strips, it is uncertain what possible posture the peanut seeds may have when taking seeds with a seed spoon. If the seed head or tail touches the seed spoon first, the linear speed of the spoon wheel will have a greater impact on the stability during seed taking. For this purpose, seeds that rotate to the end of the seed filling zone at the maximum rotational speed of the spoon wheel were selected for force analysis. It was assumed that the seeds were at the limit position about to leave the seed spoon, and the force situation at this time is shown in Figure 3. A Cartesian coordinate system is established with the geometric center of the peanut seed as the origin, the horizontal direction as the X-axis direction, and the vertical direction as the Y-axis. Since the seed is at the limit position about to leave the seed spoon, the support force on the seed here is only provided by the right side. Establish the mechanical equilibrium equation:

$$\begin{cases} F_\omega - F_N\sin\alpha - F_f\cos\alpha = 0 \\ F_N\cos\alpha - F_f\sin\alpha - G = 0 \end{cases} \tag{3}$$

where:

F_ω - centrifugal force acting on the seed, [N]; F_N - seed spoon support force on the seed, [N]; F_f-the frictional force acting on the seed, [N], $F_f=\mu F_N$; α - the angle between the side of a spoon and the horizontal direction, [°]; G-the gravitational force acting on the seed, [N], $G=mg$; m - the mass of a single peanut seed, taking m as 0.000904kg.

The relationship between the rotational speed of the seed spoon wheel and the centrifugal force and rotational speed acting on the seed is shown in equations (4) and (5).

$$\omega = \frac{2\pi n}{60} \tag{4}$$

$$F_\omega = \frac{2m\omega^2}{d} \tag{5}$$

where: ω - the rotational speed of the spoon wheel, [rad/s]; d - diameter of the spoon wheel plate, [m].

According to equations (3), (4), and (5), it can be calculated as 49.58°. Therefore, when the spoon wheel rotates at its maximum speed, to ensure that the seeds in the spoon leaving the filling area are not thrown out, the side Angle of the selected spoon should be at least 50°.

Simulation test of main components

Based on the previous measurement and calculation of the three-dimensional dimensions of peanut seed particles, it was learned that the shape of most peanuts is a long strip with a wide middle and narrow ends. Therefore, when modeling, it was regarded as a quasi-cylinder for 3D modeling in SolidWorks, imported into EDEM, filled with particles, and the model of this particle was used as the peanut seed template, as shown in Figure 4*(Baghooee et al., 2025).*

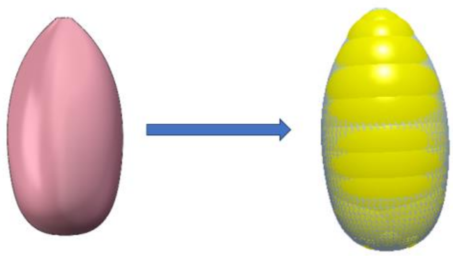


Fig. 4 - Peanut seed model

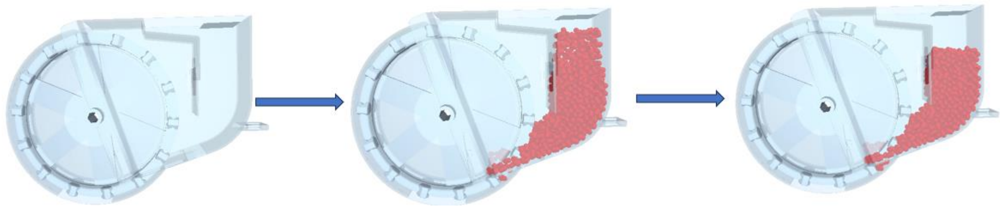
A simplified seed arrangement model was designed using the 3D drawing software SolidWorks and imported into the EDEM software. Based on the measurement of the seed mechanical characteristic parameters of the main peanut variety "Fenghua" in Shandong region, the simulation parameters as shown in Table 2 were obtained.

Table 2

Simulation Parameters of the Sowing Device

Project	Parameter	Value
Peanut	Poisonby	0.357
	Shear modulus	2.17
	Density /($kg{\cdot}m^{-3}$)	1250
Seed spoon	Poisonby	0.42
	Shear modulus	1.7
	Density /($kg{\cdot}m^{-3}$)	2700
Peanut - Peanut	Collision recovery coefficient	0.182
	Coefficient of static friction	0.431
	Coefficient of kinetic friction	0.0782
Peanut - seed spoon	Collision recovery coefficient	0.612
	Coefficient of static friction	0.473
	Coefficient of kinetic friction	0.0931

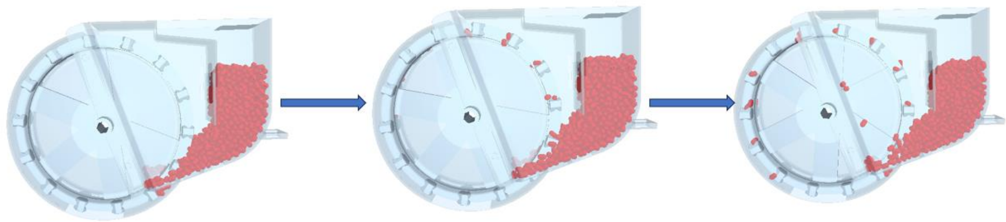
The operation quality of the seed sorter is closely related to the rotational speed of the seed wheel. To study its optimal value, a single-factor experiment with the reseeding rate and missed seeding rate as indicators is now conducted. To ensure the continuity of the simulation process, the fixed time step was set to 6×10^{-6}s through the EDEM software, the grid size was 2.5 times the minimum particle radius, and the total simulation duration was set to 10s. The required seed particles were generated in the first 1s, and seed arrangement was carried out in the last 9s. Establish a pellet factory for 1,000 peanut seeds with an initial speed of 3m/s and generate them at a rate of 2000 per second, ensuring that the generation is completed within 0.5 seconds and they are compacted by their own gravity within 1 second, as shown in Figure 5.



(a) t=0s (b) t=0.5s (c) t=1s

Fig. 5 - Schematic diagram of the particle generation process

Starting from t=1s, seed arrangement is carried out. The speed of the seed arrangement wheel is set to start moving at a speed of 30 r/min, as shown in Figure 6. At t=2s, the seed spoon that took the peanut seed from the first capsule entered the seed delivery area to prepare for the seed discharge. By t=3s, the seed had already been discharged through the gap at the bottom.



(a) t=1s (b) t=2s (c) t=3s

Fig. 6 - Schematic diagram of the seed arrangement work process

Test Results and Analysis

The operation quality of the seed discharger is closely related to the rotational speed of the seed discharger wheel. To explore the optimal value of this parameter, a single-factor experiment was carried out with the replay rate and missed broadcast rate as indicators. The simulation test was carried out by using the fixed variable method. Among them, the quantification is the top width of the seed spoon and the side Angle of the seed spoon, which are respectively set at 12mm and 55°.

The simulation test results are shown in Figure 7. With the increase of the speed of the seed arranger, the rate of missed sowing shows a gradually increasing trend, while the rate of repeated sowing shows a gradually decreasing trend. According to the industry standard NY/ T1143-2006 "Technical Specification for Quality Evaluation of Seeders" *(Technical Specification for Quality Evaluation of Seeders, 2006),* the main performance indicators of the precision seed dispenser include a reseeding rate of no more than 15% and a missed seeding rate of no more than 8%. Therefore, when the rotational speed of the seed dispenser is between 15 and 40r/min, the seeding quality of the seed dispenser meets the requirements. And a multi-factor test was conducted at a rotational speed of 20-40r/min, which had both a low missed broadcast rate and a low replay rate.

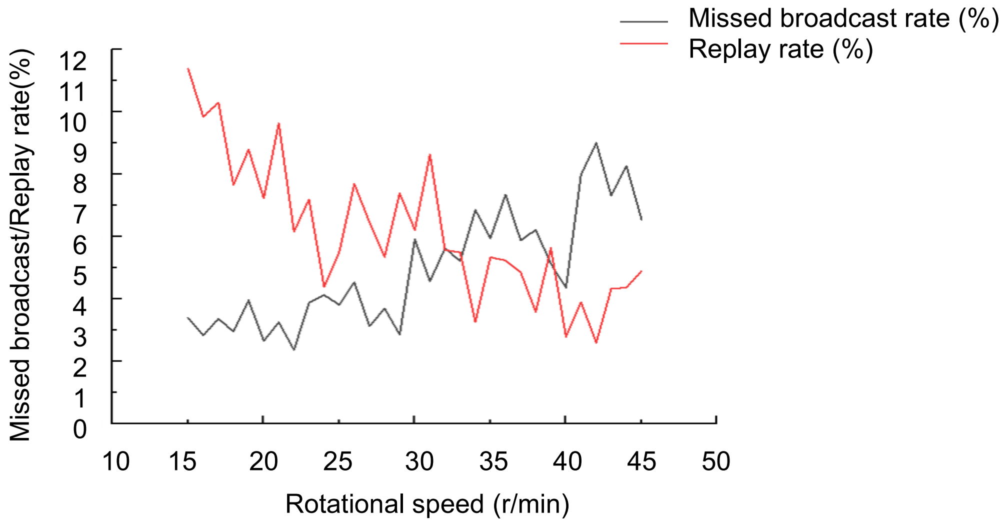


Fig. 7 - The influence of the speed of the seed distributor on the quality of sowing

Based on the analysis of the working process of the seed dispenser, the test takes the rotational speed of the seed dispenser (X_1), the side Angle of the seed spoon (X_2), and the top width of the seed spoon (X_3) as the test factors. Taking the replay rate and missed broadcast rate as experimental indicators, the three-factor and three-level orthogonal test method was adopted to arrange the experiments. The factor codes are shown in Table 3, and the test schemes and results are shown in Table 4. The response surface analysis method was used to study and analyze the influence laws of the correlation and interaction effects of each factor *(Xu Zhuxin et al., 2012)*.

Table 3

Test factor coding table

Encodings	Considerations		
	X_1/(°)	X_2/ (r/min)	X_3/(mm)
-1	50	20	10
0	55	30	12
1	60	40	14

Table 4

Test plan and results

Test serial number	Plan			Replay rate (%)	Missed broadcast rate (%)
	Speed	Angle	Width		
1	0	1	-1	5.4	5.38
2	0	0	0	6.19	5.58
3	0	0	0	6.02	5.42
4	0	0	0	6.11	5.77
5	0	0	0	5.88	5.97
6	0	0	0	6.45	5.59
7	1	0	-1	8.59	5.42
8	1	-1	0	9.4	5.78
9	-1	1	0	5.12	7.56
10	1	1	0	7.38	5.15
11	-1	0	-1	5.69	9.16
12	1	0	1	8.95	5.17
13	-1	-1	0	6.23	10.39
14	0	-1	-1	8.39	8.9
15	0	1	1	6.38	5.22
16	0	-1	1	7.86	5.78
17	-1	0	1	6.79	6.6

The test results were subjected to secondary regression analysis using the Design Expert13.0.1.0 software, and multiple regression fitting was performed to obtain the regression equations of the replay rate Y_1 and the missed broadcast rate Y_2, and significance tests were conducted. The results of the analysis of variance for the experimental indicators are shown in Table 5. The standard deviations and confidence intervals of the test results are shown in Table 6.

As can be seen from Tables 5, the P-values of both regression models are less than 0.0001, and the test results of the unfitting terms are both insignificant, which are P=0.1791 and P=0.1152 respectively. This indicates that the regression models are significant and the regression equations are meaningful. The experiment found that the side Angle X_1 of the seed spoon and the rotational speed X_2 of the seed spoon wheel had extremely significant effects on both the replay rate and the missed rate. The top width X_3 of the seed spoon had a significant influence. After eliminating the insignificant factors, the regression equations for the replay rate Y_1 and the missed rate Y_2 were obtained as equations (6) and (7) *(Chen et al., 2016):*

$$Y_1 = 6.13 + 1.31X_1 + 0.95X_2 + 0.23X_3 - 0.37X_2X_3 + 0.7X_1^2 + 0.98X_3^2 \quad (6)$$

$$Y_2 = 5.67 - 1.52X_1 + 0.94X_2 - 0.76X_3 - 0.55X_1X_2 + 0.57X_1X_3 - 0.74X_2X_3 + 0.91X_1^2 + 0.64X_2^2 \quad (7)$$

Table 5

Analysis of variance for replay rate

Source	Replay rate					Missed broadcast rate				
	Sum of Squares	DF	Mean square	F-value	P-value	Sum of Squares	DF	Mean square	F-value	P-value
Model	26.88	9	2.99	38	< 0.0001	40.6	9	4.51	46.41	< 0.0001
X_1	13.76	1	13.76	175.04	< 0.0001	18.57	1	18.57	191.1	< 0.0001
X_2	7.22	1	7.22	91.88	< 0.0001	7.11	1	7.11	73.11	< 0.0001
X_3	0.456	1	0.456	5.8	0.0468	4.64	1	4.64	47.7	0.0002
X_1X_2	0.207	1	0.207	2.63	0.1486	1.21	1	1.21	12.45	0.0096
X_1X_3	0.1369	1	0.1369	1.74	0.2284	1.33	1	1.33	13.72	0.0076
X_2X_3	0.57	1	0.57	7.25	0.0309	2.19	1	2.19	22.54	0.0021
X_1^2	2.06	1	2.06	26.25	0.0014	3.49	1	3.49	35.93	0.0005
X_2^2	0.1727	1	0.1727	2.2	0.1818	1.74	1	1.74	17.92	0.0039
X_3^2	1.92	1	1.92	24.41	0.0017	0.0005	1	0.0005	0.005	0.9456
Residual	0.5501	7	0.0786			0.6804	7	0.0972		
Incoherent	0.3691	3	0.123	2.72	0.1791	0.5035	3	0.1678	3.79	0.1152
Inaccuracies	0.181	4	0.0453			0.1769	4	0.0442		
Aggregate	27.43	16	29.7395			41.28	16	45.099		

The response surface analysis of the test results was conducted through the Design-Expert13.0.1.0 software. The standard deviations and confidence intervals of the two test indicators are shown in Table 6. The influence laws of each test factor on the missed playback rate and replay rate are shown in Figure 8 and Figure 9.

Table 6

Standard deviation and confidence interval of the test results

Project	Std Dev	95% CI low	95% CI high	99% CI low	99% CI high
Replay rate	0.280	4.77%	5.61%	3.56%	6.82%
Missed broadcast rate	0.311	4.96%	5.89%	3.61%	7.24%

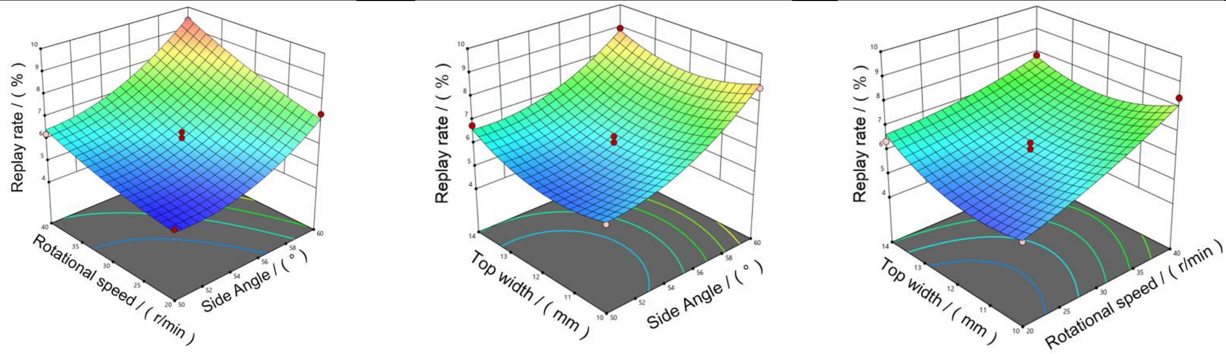


Fig. 8 - The response surface of factor interaction to replay rate

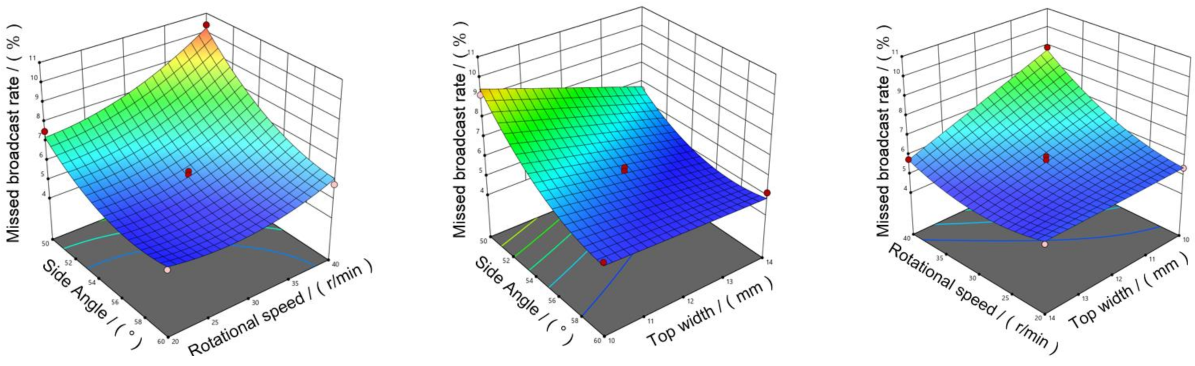


Fig. 9 - The response surface of factor interaction to missed broadcast rate

As can be seen from Figure 8, when the side Angle is 51.68°, the rotational speed is 20.39r/min, and the width is 11.30mm, the minimum replay rate is 5.12%. The replay rate increases with the increase of the side Angle and rotational speed, while the wider the top surface, the higher the replay rate shows a trend of first decreasing and then increasing.

As can be seen from Figure 9, when the side Angle is 58.01°, the rotational speed is 30.12r/min, and the width is 12.30mm, the minimum missed broadcast rate is 5.02%. The missed broadcast rate decreases with the increase of the side Angle and the top width, and gradually increases with the increase of the rotational speed.

The parameter optimization module of Design-Expert13.0.1.0 software was adopted to optimize and solve the target parameters. The values of the side Angle of the seed spoon, the rotational speed of the seed spoon wheel, and the top width of the seed spoon were selected to obtain the optimal values of the replay rate and the missed broadcast rate. Based on the boundaries of the experimental factors and in combination with the analysis results of the relevant models, the optimization solution constraints are obtained as shown in Equation (8):

$$\begin{cases} \min Y_1(X_1, X_2, X_3) \\ s.t. \begin{cases} 50° \le X_1 \le 60° \\ 20r/\min \le X_2 \le 40r/\min \\ 10mm \le X_3 \le 14mm \end{cases} \\ \min Y_2(X_1, X_2, X_3) \end{cases} \tag{8}$$

Through optimization and solution, when the side Angle of the seed spoon is 54°, the rotational speed of the seed spoon wheel is 20r/min, and the width of the top surface of the seed spoon is 11.9mm, it is the optimal combination parameter, with a replay rate of 5.19% and a missed broadcast rate of 5.43%. Compared with traditional seed scheduling devices, the maximum speed has increased by 13%, the rebroadcast rate has decreased by 3.98%, and the missed broadcast rate has dropped by 2.86%.

CONCLUSIONS

We designed a spoon-wheel peanut seed loader by using the peanut sowing mechanics model and EDEM simulation. In the multi-factor experiments after EDEM simulation, it was obtained that the side Angle of the seed spoon and the rotational speed of the seed arrangement wheel have extremely significant effects on the replay rate and missed broadcast rate, and the top width of the seed spoon has a significant effect. Among the three interactions, the interaction between the rotational speed of the seed spoon wheel and the top width has the most prominent impact on the missed broadcast rate. After optimization through the Design-Expert software, the optimal parameters were determined as the side Angle of the seed spoon 54°, the rotational speed of the seed arranging wheel 20r/min, and the width of the top surface of the seed spoon 11.9mm. At this time, the replay rate was 5.19% and the missed broadcast rate was 5.43%. Finally, this research laid a foundation for the further development of peanut seed cultivation, achieving precise, accurate and high-speed sowing of peanuts and improving operational efficiency.

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