OPTIMAL DESIGN AND SIMULATION OF SANDY LOAM SOIL COVERING DEVICE BASED ON BIONIC SAND CRAB PINCERS
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基于沙蟹螯足仿生的沙壤土覆土装置优化设计与仿真

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ABSTRACT
Aiming at the problems that corn planters are prone to in sandy loam soil conditions, such as uneven soil covering thickness and seed position deviation, which affect the sowing quality, an innovative disk-type soil covering device based on the bionic shape of the claw legs of sand crabs has been optimized and designed. In this study, the contour features of the pincers of sand crabs were extracted using MATLAB software and applied to the tooth profile design of the soil cover plate, aiming to improve their operational performance in sandy loam soil. This study analyzed the operation mechanism of the bionic soil covering device based on the characteristics of sandy loam soil and determined the key parameters affecting the soil covering effect, including the installation deflection angle, installation inclination angle and the distance between the openings at the back of the soil covering tray. Taking the qualified rate of soil cover thickness and the standard deviation of seed lateral displacement as evaluation indicators, and with the help of EDEM discrete element simulation technology, the interaction model of sandy loam - seed - bionic soil cover device was constructed, and the single-factor and Box-Behnken response surface experimental designs were systematically carried out. Through simulation analysis and optimization, the optimal parameter combination of the soil covering device suitable for sandy loam soil was determined as follows: installation deflection angle 21.3°, installation inclination angle 20.1°, and the opening spacing behind the soil covering tray 100.0 mm. It has laid a foundation for the research on improving the uniformity of soil covering and the straightness of seed rows in the soil covering device of sandy loam soil seeders.

摘要
针对沙壤土条件下玉米播种机覆土易出现覆土厚度不均、种子位置偏移等影响播种质量的问题，创新性地优化设计了一种基于沙蟹螯足齿形仿生的盘式覆土装置。本研究利用 MATLAB 软件提取了沙蟹螯足的轮廓特征，将其应用于覆土盘齿形设计，旨在提升其在沙壤土中的作业性能。本研究基于沙壤土特性分析了仿生覆土装置的作业机理，确定了影响覆土效果的关键参数，包括安装偏角、安装倾角和覆土盘后方开口间距。以覆土厚度合格率和种子横向位移标准差作为评价指标，借助 EDEM 离散元仿真技术，构建了沙壤土-种子-仿生覆土装置的互作模型，系统开展了单因素与 Box-Behnken 响应面试验设计。通过仿真分析与优化，确定了适用于沙壤土的覆土装置最优参数组合为：安装偏角 21.3°、安装倾角 20.1°、覆土盘后方开口间距 100.0mm。为研究改善沙壤土播种机覆土装置的覆土均匀性与种行直线度奠定了基础。

INTRODUCTION
Sandy loam is an important type of agricultural soil due to its good air and water permeability *(Wang et al., 2025; Deng et al., 2025)*. However, its loose texture and low cohesion characteristics can easily cause problems such as uneven soil cover thickness and seed positioning deviation in mechanical sowing and soil covering operations, seriously affecting the germination rate of sowing and the uniformity of crop growth *(Wang et al., 2025; Luo et al., 2025)*. Traditional soil covering devices often face challenges such as difficult soil flow control, large disturbance and poor soil covering stability in sandy loam soil, making it difficult to meet the requirements of high-quality sowing. Therefore, optimizing the soil covering device plays a significant role in improving the uniformity of seed soil covering under sandy loam conditions.

In recent years, researchers at home and abroad have conducted extensive studies on soil covering devices on various seeders. The basic structural forms of the soil covering device mainly include three types:

the eight-shaped plate soil covering device, the double disc soil covering device and the extrusion type soil covering and pressing wheel *(Feng et al., 2025; Wu et al., 2024; Liu et al., 2023; Geng et al., 2022; Zhang et al., 2024., Guo, 2019).* Researchers have also conducted research and analysis on the soil covering performance. Lu Qi et al. first constructed a discrete element model of the interaction among soil, seeds and soil covering devices, breaking through the limitations of the traditional "soil-machine" binary simulation and laying the foundation for the parameter optimization of soil covering devices *(Lu et al., 2024).* Liu Fang et al. designed an arc-shaped double-toothed disc soil covering device in response to the fact that traditional scraper or disc soil covering devices are prone to causing fluctuations in soil covering thickness, resulting in exposed seeds or overly deep soil covering, which improved the uniformity of sowing *(Liu et al., 2024).* Inspired by the digging feet of the Oriental mole cricket, Zhang *Zhijun et al. (2018)* designed a bionic soil-breaking disc soil-covering device by measuring key parameters of the insect's toe claws to enhance the soil-breaking performance of a soybean planter. In order to improve the uniformity of seed distribution and the consistency of soil covering thickness, Li Liyan designed a new type of soil covering device with separate discs placed at the front and back. This enables the soil covering volume of two sets of discs to be the same as that of a traditional set of discs, avoiding the drawback of excessive soil covering volume at one time causing significant displacement of seeds *(Li et al., 2017).*

Inspired by the efficient ability of sand crab claws to manipulate sandy soil, this study designed a disc-type soil covering device based on the bionic shape of its teeth. The contour features of the claw legs of sand crabs were digitally extracted using MATLAB and applied to the tooth shape design to enhance the adaptability to sandy loam soil and operational performance. By analyzing the operation mechanism of the device, it was determined that the installation inclination angle, deflection angle and the distance between the rear openings were the key adjustable parameters. To optimize performance, taking the qualified rate of soil cover thickness and the difference in seed lateral displacement as indicators, an interaction model of sandy loam - seed - device was established using EDEM *(Lu et al., 2023)*, and based on this, single-factor and Box-Behnken response surface tests were carried out to seek the optimal parameter combination to improve the uniformity of soil cover and the accuracy of seed positioning.

MATERIALS AND METHODS

The working principle of the soil covering device

The operation process of the soil covering device (Fig.1) consists of three stages: soil insertion, stabilization operation and soil removal. The device is inserted into the soil at an angle, and its deflection angle drives the toothed cutting edge to push the soil laterally, guiding the soil to converge towards the center line to evenly cover the seed furrows. The thickness of the soil cover is dynamically controlled based on the principle of volume conservation through the deflection angle (to regulate the amount of soil pushed) and the spacing of the rear openings (to regulate the concentration of the soil cover). This process of "tangential soil insertion - directional soil transportation - precise soil covering" adapts to the fluidity of sandy loam soil and builds a stable seed bed for seeds.

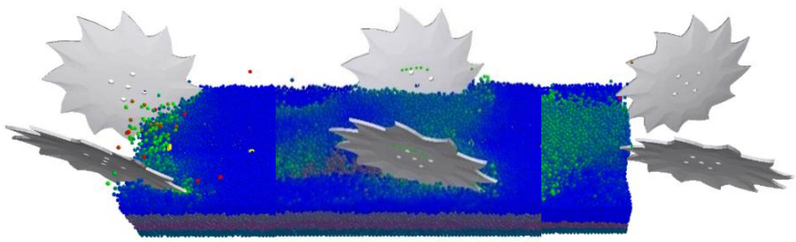


Fig. 1 - Working process of the soil covering device
a) Soil insertion stage; b) Stable operation stage; c) Excavation stage

Tooth profile design of the soil covering device

When the soil covering device is in operation, it mainly achieves soil covering by pushing the soil laterally. However, while its tooth shape pushes away the soil, it is prone to exert lateral forces on the soil and seeds, causing the seeds to shift and thereby disrupting the uniformity of soil coverage and the straightness of the seed rows. To effectively inhibit the lateral sliding of seeds, this study adopted bionics principles and drew on the tooth shape of the claw legs of sand crabs to optimize the design of the soil covering device.

The contour curve of the claw teeth of the sand crab was extracted using MATLAB software, as shown in Fig. 2a. Some of the curves were fitted through MATLAB software, and the fitting process is shown in Fig.2b.

The extracted data coordinates of the outer contour points are imported into the MATLAB curve fitting machine, with the X-axis and Y-axis representing the horizontal and vertical coordinates of the contour points respectively, with the unit being mm. The outer contour curve was fitted using an eighth-degree polynomial function, as shown in Equation (1):

$$y = -1.714x^8 + 2.659x^7 + 8.724x^6 - 13.98x^5 - 12.96x^4 + 25.88x^3 - 6.283x^2 - 17.39x + 756.8 (R^2 = 0.9957) \quad (1)$$

The coefficient of determination $R^2 > 0.99$, indicates that the fitted curve closely matches the actual biometric contour, demonstrating a high level of fitting accuracy.

Studies have shown that the number of notches on the grass-pulling wheel and the notch disc typically ranges from 8 to 15 *(Liu et al., 2024).* Although the uniformity of soil cover is high when the number of teeth is greater than 15, it also leads to increased forward resistance and wear. If the number of teeth is less than 10, uneven soil covering will cause the seed furrows to collapse. Therefore, 12 teeth were selected, and the spacing between the teeth can effectively inhibit the flow of sandy loam soil.

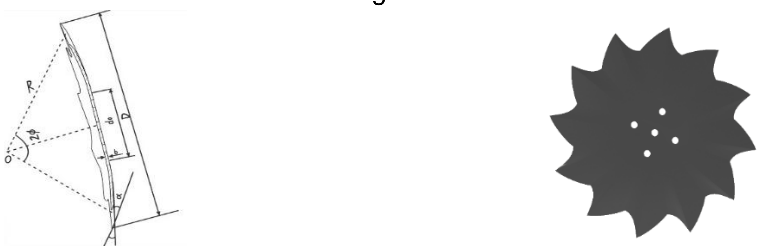
a) *b)*

Fig. 2 - Tooth profile and fitting process diagram

a) Outline of the claw leg teeth of sand crabs; b) Curve fitting process

Diameter design of the soil covering device

Using the fitted equation as a reference, a bionic soil covering device was modeled in SolidWorks 3D software. As the device falls under the category of disc rakes, its key design parameters were calculated based on empirical formulas commonly used for shallow tillage disc rakes *(Lu et al., 2024; Liu et al., 2024)*. The structural schematic of the device is shown in Figure 3.



a) *b)*

Fig. 3 - Schematic diagram of the soil covering device structure

a) Structural parameters of the soil covering device; b) Three-dimensional modeling of the soil covering device

$$D = kH \quad (2)$$

where: D is the diameter of the bionic soil covering device, [mm]; k is diameter to depth ratio coefficient; H is maximum designed depth of penetration into the ground, [mm].

The sowing depth of corn is generally 30 to 50 mm. The soil in this study is sandy loam with poor water retention. Therefore, the sowing depth was taken as 50 mm, and the maximum depth of penetration was 60 mm. The k value of the disc is generally taken as 4 to 6 *(Liu., 2025)*. Thus, the diameter of the bionic soil covering device is ≤ 360 mm.

Considering that sandy loam soil has loose particles, low viscosity and is prone to being scattered during soil covering operations, the diameter should be designed to avoid splashing of sandy loam soil. The formula is:

$$D \geq \frac{v^2}{g tan\varphi} \quad (3)$$

where: v is the operating speed of the seeder, taken as 0.8 to 1.4 m/s; g is acceleration due to gravity, taken as 9.8 m/s; φ is the angle of repose in sandy loam soil, taken as 28° to 32°.

After calculation, it can be found that the critical diameter of the bionic soil covering device for avoiding sandy loam soil splashing is ≥ 346 mm, and the final selected diameter is 360 mm.

Thickness design of the soil covering device

The selection of the thickness of the bionic soil covering device is related to the depth of the device's penetration into the soil and the size of the working load *(Bai., 2019).* It was calculated by the empirical formula: $b = (0.008{\sim}0.012)D$

The thickness b of the bionic soil covering device was calculated to range between 2.88 and 4.32 mm. Given that sandy loam contains a high proportion of hard, abrasive sand particles, excessive wear at the device’s edge can lead to failure. Additionally, a thinner and lighter disc lacks sufficient rigidity, which may increase vibration and negatively impact soil covering uniformity. Therefore, a thickness of b=4 mm was selected for this study.

Design of other structural parameters of the soil covering device

In sandy loam soil, the spherical radius R is the key to regulating the stability and resistance of flow diversion. Reducing the spherical radius R can enhance the directional restraint of the soil, but the frictional resistance increases significantly. Although increasing the spherical radius R reduces resistance, it weakens the accuracy of flow guidance. The design experience formula is:

$$R = \frac{D}{2\sin\phi} \tag{4}$$

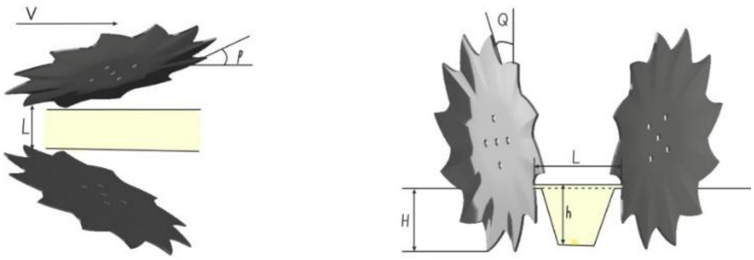
where: ϕ is spherical center angle, taken as 21 to 27 degrees, [°].

After calculation, 396≤R≤502, and finally R=450 mm was selected.

Under the condition of ensuring the strength of the cutting edge and allowing the manufacturing process, the cutting edge angle should be taken as small as possible to reduce the resistance of cutting soil. The common range of cutting edge angles is 14°30' to 22° *(Chinese Academy of Agricultural Mechanization Sciences., 2007)*, so α is taken as 15°.

Analysis of the Relationship between Installation Parameters and Soil Cover Volume

Based on the principle of volume conservation per unit time, the volume of soil pushed by the soil covering device ≈ the volume of soil covering. The parameter ranges of the installation deflection angle *P*, installation inclination angle *Q* and the distance *L* of the rear opening of the bionic soil covering device were calculated, as shown in Fig. 4



a) ***b)***

Fig. 4 - Schematic diagram of the relationship between the bionic soil covering device and the soil in the seed furrow

$$h \times L \times v = A_d v$$

$$A_d = k \times D \times H \times \sin P \times \cos Q$$

$$h = \frac{25920 \times \sin P \times \cos Q}{L} \geq 50 \tag{5}$$

where: h is requirements for soil cover thickness, h≥50 mm; v is the forward speed of the seeder, v =1.4 m/s; k is soil displacement efficiency coefficient of the soil covering device, k=1.2; A_d is the cross-sectional area of the soil pushed by the soil covering device; L is rear opening spacing, [mm]; D is diameter of the soil covering device, D=360 mm; H is the depth of the soil covering device's penetration into the soil, H=60 mm; Q is installation inclination angle, [°]; P is installation bias angle, [°].

After calculation, it can be determined that the rear opening spacing of the bionic soil covering device is 90 mm <*L*< 125 mm, the installation inclination angle is 15°< Q < 30°, and the installation deflection angle is 17°< P <30°. Due to the high fluidity of sandy loam soil, to avoid uneven soil cover caused by excessive soil dumping, the lower limit of the deflection angle was extended to 10°.

Establishment based on the EDEM simulation model

Based on the research on the qualified rate of soil covering thickness and the standard deviation of lateral displacement of the bionic soil covering device, solid modeling was carried out using SolidWorks 3D software and imported into EDEM in step format to establish a corn seed model and a soil trough model with a length, width and height of 1500×300×180 mm. Considering the soil characteristics of sandy loam, the Hertz-Mindlin (no slip) model in EDEM software was adopted as the contact model *(Hao et al., 2020)*. The simulation model of the sandy loam - seed - bionic soil covering device established is shown in Fig. 5.

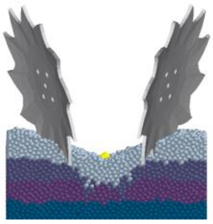
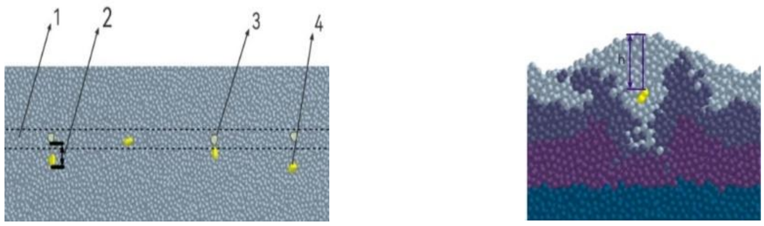


Fig. 5 - Simulation model establishment of soil-seed-soil covering device

The corn seeds are located in the middle of the seed trench, evenly distributed with a total of 8 seeds. Given the small sample size and relatively large error, the number of seeds per replicate was increased to eight. Seeds were sown in the same row for ten consecutive replicates, resulting in a total of eighty seeds. As shown in Fig. 6a, the horizontal offset of the actual position of a single seed after soil covering operation relative to its position before soil covering in the direction perpendicular to the sowing advance is called the lateral displacement S. By statistically analyzing the lateral displacement of the seeds, the standard deviation of the lateral displacement of the seeds was calculated to represent the straightness of the seed rows. The thickness of the soil cover above 80 seeds was measured using the Ruler tool in the post-processing of EDEM, as shown in Figure 6b. A thickness of 40 mm < soil cover thickness h<60 mm is considered qualified, Pass rate $\eta = \frac{\sum_{i=1}^{N} I(h_i)}{N} \times 100\%$ .The basic parameters of discrete element simulation obtained through literature are shown in Table 1 *(Lin et al., 2022; Wang et al., 2017)*.



a) ***b)***

Fig. 6 - Simulation test diagram of soil cover

a) The lateral movement of seeds within the seed furrows; b) Measurement of simulation values of soil cover thickness
1. Seed furrow soil; 2. Lateral displacement of seeds; 3. Seed position before lateral movement;
4. Seeds that move laterally away from the seed furrows

Table 1

Basic parameters of discrete element simulation model

Parameters	Numerical value
Soil density [kg·m^{-3}]	1.39
Soil Poisson's ratio	0.4
Soil shear modulus [Pa]	1.09e+07
Steel density [kg·m^{-3}]	7.85
Steel Poisson's ratio	0.26
Steel shear modulus [Pa]	8.0e+10
Soil - soil recovery coefficient	0.15
Soil-soil static friction coefficient	0.27
Soil-soil kinetic friction coefficient	0.70
Soil-steel plate recovery coefficient	0.50
Soil-steel plate static friction coefficient	0.75
Soil-steel plate kinetic friction coefficient	0.15

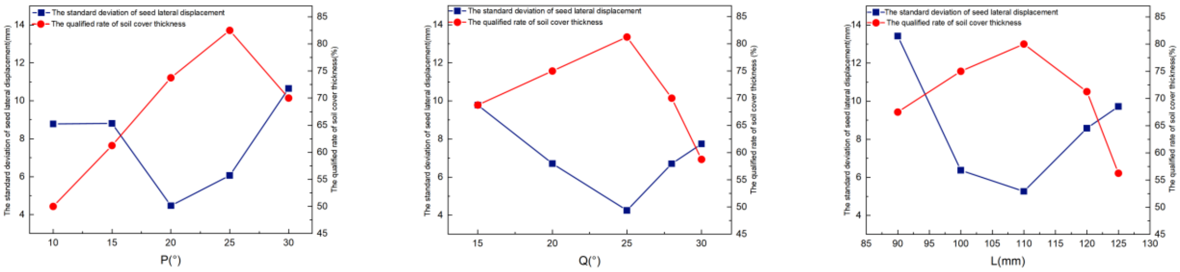
Single-factor trial

Based on the structural design and working principle analysis of the bionic soil covering device, the structural parameters that affect the performance of soil covering operations, namely the installation deflection angle P, installation inclination angle Q, and rear opening spacing L, were selected as the test factors. The influence of each factor on the soil covering thickness and the standard deviation of the seed lateral displacement was analyzed. According to the actual operation of the seeder, the forward speed of the equipment was set at 1.4 m/s. The levels of the single-factor test are shown in Table 2, and the test results are presented in Fig. 7.

Table 2

Single-factor test factor levels for the operation effect of the soil covering device

level	installation deflection angle [°]	installation inclination angle [°]	opening spacing behind the soil covering tray [mm]
1	10	15	90
2	15	20	100
3	20	25	110
4	25	28	120
5	30	30	125



a) *b)* *c)*

Fig. 7 - Results of the single-factor simulation test

To ensure the uniformity of soil covering and the straightness of seed rows, a larger amount of soil covering and a smaller standard deviation of seed lateral displacement are required. As shown in Fig. 7a, the pass rate of soil cover thickness is the highest when the deflection angle is 25°. When the deflection angle is less than 15°, the pass rate is low due to insufficient soil throwing. If the deflection angle is greater than 25°, it will decrease due to excessive scattering and insufficient soil covering at the center. The standard deviation of the lateral displacement of the seeds is the lowest when it is 20°, because the soil reflux path is the optimal. If the deviation angle is too large or too small, the seeds will shift sideways due to the imbalance of soil flow direction. After comprehensive consideration, the recommended installation deflection angle ranges from 15° to 25°.

As shown in Fig. 7b, the qualified rate of soil cover thickness increases slowly with the increase of inclination angle, reaching the peak at 25°. When the inclination angle is less than 20°, the qualified rate is low due to the formation of soil ridges on both sides of the seed furrows and insufficient soil covering in the center. The inclination angle greater than 28° drops due to soil being flung out of the seed furrows and insufficient backfilling. The standard deviation of the lateral displacement of the seeds changes gently between 15° and 25°, and increases significantly between 25° and 30° (if the inclination angle is too high, the soil cover is roughly insufficient, and the seeds exposed on the surface are affected by vibration, resulting in a sudden increase in displacement). To ensure the qualified rate of soil covering and the straightness of the seed rows, the installation inclination angle should be selected between 20° and 28°.

As shown in Fig. 7c, the qualified rate of soil cover thickness increases with the subsequent opening spacing, reaching a maximum at 110 mm. When the spacing is less than 100 mm, the narrow and congested passage leads to discontinuous soil coverage, resulting in a low pass rate. Conversely, if the spacing exceeds 120 mm, the qualified rate decreases due to poor soil concentration and insufficient coverage on both sides of the seed trench. The standard deviation of the lateral displacement of the seeds is the lowest when it is 110 mm (uniform soil coverage ensures balanced force on the seeds). To ensure the stability and continuous uniform soil coverage of the seeds, the spacing of the rear openings should be selected as 100 mm to 110 mm.

RESULTS

Box-Behnken Design Simulation Tests

Based on the single-factor test, taking the installation deflection angle P, inclination angle Q, and rear opening spacing L as factors, and the qualified rate of soil cover thickness and the standard deviation of seed lateral displacement as indicators, a three-factor and three-level Box-Behnken test was conducted to explore the relationship between the key factors and the indicators. The codes of the experimental factors are shown in Table 3, and the protocols and results are presented in Table 4.

Table 3

Factor coding for multi-factor test on the operation effect of the soil covering device

Encodings	Factors		
	P [°]	Q [°]	L [mm]
-1	15	20	100
0	20	25	110
1	25	28	120

Table 4

Experimental Scheme and Results

Serial Number	Factors			Standard deviation of seed lateral displacement [mm]	The qualification rate of soil cover thickness [%]
	P[°]	Q[°]	L[mm]		
1	15	20	110	6.71	68.75
2	25	20	110	2.63	85.00
3	15	28	110	3.61	80.00
4	25	28	110	5.06	75.00
5	15	24	100	3.98	76.25
6	25	24	100	2.13	86.00
7	15	24	120	4.39	80.00
8	25	24	120	4.68	85.00
9	20	20	100	3.87	82.50
10	20	28	100	4.73	78.75
11	20	20	120	7.21	82.50
12	20	28	120	4.78	85.00
13	20	24	110	4.21	77.50
14	20	24	110	3.85	78.75
15	20	24	110	3.91	78.75
16	20	24	110	4.05	77.50
17	20	24	110	3.45	75.00

Table 5

Analysis of variance in the simulation test of standard deviation of seed lateral displacement

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model	24.24	9	2.69	31.90	$<$0.0001
P	2.19	1	2.19	25.99	0.0014
Q	0.6272	1	0.6272	7.43	0.0295
L	5.04	1	5.04	59.70	0.0001
PQ	7.65	1	7.65	90.55	$<$0.0001
PL	1.14	1	1.14	13.56	0.0078
QL	2.71	1	2.71	32.05	0.0008
P^2	0.5827	1	0.5827	6.90	0.0341
Q^2	4.05	1	4.05	47.95	0.0002
L^2	0.3138	1	0.3138	3.72	0.0952

Source	Sum of Squares	df	Mean Square	F-value	P-value
Residual	0.5910	7	0.0844	-	-
Lack of Fit	0.2675	3	0.0892	1.10	0.4455
Pure Error	0.3235	4	0.0809	-	-
Cor Total	24.83	16	-	-	-

Table 6

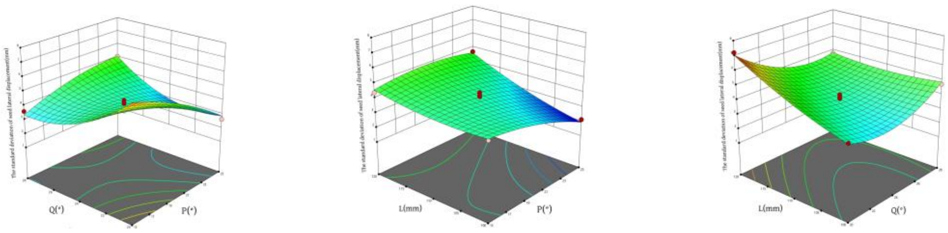
Analysis of variance in the simulation test of the qualified rate of soil cover thickness

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model	314.56	9	34.95	18.51	0.0004
P	84.50	1	84.50	44.75	0.0003
Q	0.00	1	0.00	0.00	1.00
L	10.13	1	10.13	5.36	0.0537
PQ	112.89	1	112.89	59.78	0.0001
PL	5.64	1	5.64	2.99	0.1276
QL	9.77	1	9.77	5.17	0.0571
P^2	0.4975	1	0.4975	0.2635	0.6235
Q^2	0.0041	1	0.0041	0.0022	0.9641
L^2	91.29	1	91.29	48.34	0.0002
Residual	13.22	7	1.89	-	-
Lack of Fit	3.84	3	1.28	0.5467	0.6764
Pure Error	9.37	4	2.34	-	-
Cor Total	327.78	16	-	-	-

As can be seen from Table 4, when the installation deflection angle P=25°, the installation inclination angle Q=24°, and the rear opening spacing L=100 mm, the minimum standard deviation of the seed lateral displacement is 2.13 mm, and the maximum qualified rate of the soil cover thickness is 86%.The results of the analysis of variance (see Tables 5 and 6) indicate that the installation deflection angle P, inclination angle Q, and rear opening spacing L have extremely significant effects on the standard deviation *(Z)* of the seed lateral displacement and the qualification rate *(F)* of the soil cover thickness, and the regression equations of Z, F with P, Q, and L have been established. Based on the analysis of the influence of the interaction of P, Q and on Z and F by Design-Expert, the response surfaces are shown in Fig. 8 and 9.

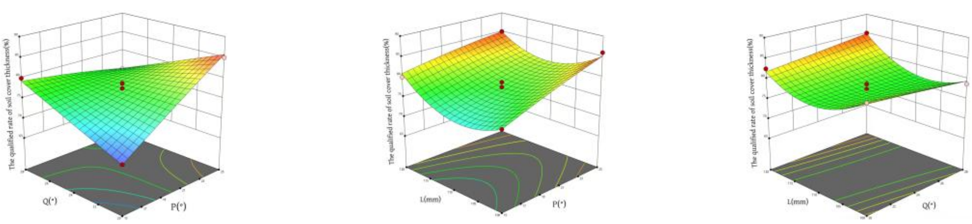
$$Z = +3.89 - 0.5237P - 0.2800Q + 0.7938L + 1.38PQ + 0.5350PL - 0.8225QL - 0.3720P^2 + 0.9805Q^2 + 0.2730L^2 \quad (6)$$

$$F = +77.50 + 3.25P + 1.12L - 5.31PQ - 1.19PL + 1.56QL - 0.3438P^2 + 0.0313Q^2 + 4.66L^2 \quad (7)$$



a) b) c)

Fig. 8 - Response surface illustrating the interaction effects of various factors on the standard deviation of seed lateral displacement



a) b) c)

Fig. 9 - Response surface illustrating the interaction effects of various factors on the qualification rate of soil cover thickness

Experiments show that P, Q and L all affect Z and F. To obtain the optimal parameters of the device, the Design-Expert optimization module was utilized for optimization.

The objective function and constraint conditions are:
$$\begin{cases} min\,Z\,(P,Q,L) \\ max\,F\,(P,Q,L) \\ 20^\circ \le P \le 25^\circ \\ 20^\circ \le Q \le 28^\circ \\ 100\text{mm} \le L \le 120\text{mm} \end{cases}$$

The optimal parameter combination that satisfies the constraint conditions was obtained as follows: when the installation deflection angle is 21.3°, the installation inclination angle is 20.1°, and the installation spacing is 100.0 mm, the standard deviation of the seed lateral displacement is 3.1 mm, and the qualified rate of the soil cover thickness is 85.0%.

CONCLUSIONS

1. Considering the characteristics of sandy loam soil and soil covering requirements, a bionic soil covering device was optimized. Using MATLAB, the claw profile of the sand crab was fitted (R^2 > 0.99) to realize continuous operations of "tangential soil entry–directional transport–precise covering," which enhanced soil adaptability while ensuring uniform covering thickness and the straightness of the seed rows.

2. Theoretical analysis defined the test factor ranges, and single-factor simulations via the discrete element method were conducted. Installation deflection angle *(P)*, inclination angle *(Q)*, and rear opening spacing *(L)* were selected as variables, while the standard deviation of seed lateral displacement *(Z)* and soil covering qualification rate *(F)* served as evaluation indices. A regression model between *(P, Q, L)* and *(Z, F)* was developed using Box-Behnken design. The optimal parameter set was determined as P = 21.3°, Q = 20.1°, and L = 100.0 mm.

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REFERENCES

[1] Bai L. (2019). Design and Experiment of Seed Fertilizer Distribution Device Based on Active Soil Covering (基于主动覆土的种肥分施装置设计与试验). *Northwest A&F University,* Shanxi/China.

[2] Chinese Academy of Agricultural Mechanization Sciences. (2007). Agricultural Machinery Design (Volume 1) (农业机械设计(上册)). *China Agricultural Science and Technology Press,* Beijing/China.

[3] Deng C., Feng J., Wang J., Li H., Qiao H. (2025). Effects of Soil Factors on emergence and emergence of Goji berry red gall Mosquito (土壤因子对枸杞红瘿蚊出土羽化的影响). *Journal of Environmental Entomology,* Vol. 47, no. 2, pp. 483-490, Guangdong/China.

[4] Feng B., Sun W., Xin S., Wang G., Lv W. (2025). Optimization Design and Experiment of Soil-Covering Device for Astragalus Mulching Transplanting Machine. *Agriculture,* Vol. 15, no. 7, pp. 769-769, US.

[5] Geng Y., Wang X., Zhong X., Zhang X., Chen K., Wei Z., Lu X., Cheng X., Wei M. (2022). Design and Optimization of a Soil-Covering Device for a Corn No-Till Planter. *Agriculture,* Vol. 12, no. 8, pp. 1218-1218, USA.

[6] Guo H. (2019). Research on Evaluation of Corn Sowing Quality and Soil Covering and Pressing Device (玉米播种质量评价与覆土镇压装置研究). *Jilin University,* Jilin/China.

[7] Hao J., Long S., Li J., Ma Z., Zhao X. (2020). Particle scale effect of discrete element model for fluidity of sandy loam soil in Yam Planting field(麻山药种植田沙壤土流动性离散元模型颗粒放尺效应). *Transactions of the Chinese Society of Agricultural Engineering,* Vol.36, no. 21, pp. 56-64, Beijing/China.

[8] Li L. (2017). Experimental Study and Simulation Analysis of Front and Rear Disc-type Soil Cover (前后分置圆盘式覆土器的试验研究与仿真分析). *Jilin Agricultural University,* Jilin/China.

[9] Lin H., Wang Q., Liao P., Zheng W., He J. (2022). Calibration of discrete element simulation parameters for the interaction between tobacco-planted sandy loam and soil contact components (植烟沙壤土与触土部件相互作用的离散元仿真参数标定). *Journal of Chinese Agricultural Mechanization,* Vol. 43, no. 5, pp. 196-203, Jiangsu/China.

[10] Liu F., Gao X., Jia X., Huang Y., Zhang C. (2024). Design and Experiment of Archimedean Helical Arc-shaped Double-Toothed Disc Soil Covering Device for High-Speed Precision Seeder (高速精量播种机阿基米德螺线型弧面双齿盘覆土装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery,* Vol. 55, no. 6, pp. 91-100+120, Beijing/China.

[11] Liu G. (2025). Corn Conservation Tillage and Full-process Mechanized Planting Technology (玉米保护性耕作及全程机械化种植技术). *Seed Science and Technology,* Vol. 43, no. 11, pp. 87-89, Shanxi/China.

[12] Liu Q., Sun W., Wang H., Meng Y. (2023). Design and Field Test of a Leaping Type Soil-Covering Device on Plastic Film. *Agriculture,* Vol. 13, no.9, US.

[13] Lu Q., Liu F., Liu L., Liu Z., Liu Y. (2023). Establishment and Verification of Discrete Element Model of soil-seed-soil Covering Device Interaction in Seed furrows (种沟土壤-种子-覆土装置互作离散元模型建立与验证). *Transactions of the Chinese Society for Agricultural Machinery,* Vol. 54, no. 10, pp. 46-57, Beijing/China.

[14] Lu Q., Liu L., Liu Z., Jin W. (2024). Design and Experiment of Star-toothed Spherical Disc Soil Covering Device for Seeder (播种机星齿球面盘式覆土装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery,* Vol. 55, no. 4, pp. 23-31+73, Beijing/China.

[15] Luo M., Guan Z., Yan Y., Chai Y., Liu J. (2025). Analysis of the Differences in Growth and Quality of Qinggan Leek in Simulated Rhizosphere Habitat(模拟根际生境下青甘韭生长与品质的差异分析). *Plateau Agriculture,* Vol. 9, no. 1, pp. 65-72+132, Xizang/China.

[16] Wang J., Liu R., Guo Z., Wang S., Gao W. (2025). Root Morphology and tensile characteristics of different varieties of quinoa in the northern foot of Yinshan Mountain, Inner Mongolia (内蒙古阴山北麓地区不同品系藜麦根系形态和抗拉特性). *Jiangsu Agricultural Sciences,* Vol. 53, no.2, pp. 61-67, Jiangsu/China.

[17] Wang T., Shang Z., Zhang G., Tao C., Guo R. (2025). Effects of Soil pH of Different Types of Tobacco Planting on Soil Nutrient Availability (不同类型植烟土壤酸碱度对土壤养分有效性的影响). *Central South Agricultural Science and Technology,* Vol., 46, no. 4, pp. 29-32+51, Hubei/China.

[18] Wang X., Hu H., Wang Q., Li H., He J. (2017). Parameter Calibration Method for Soil Model Based on Discrete Elements (基于离散元的土壤模型参数标定方法). *Transactions of the Chinese Society for Agricultural Machinery,* Vol., 48, no. 12, pp. 78-85, Beijing/China.

[19] Wu X., Jiang Z., Zhang L., Hu X., Li W. (2024). Optimization Design and Experimentation of a Soil Covering Device for a Tree Planting Machine. *Agriculture,* Vol. 14, no.3, US.

[20] Zhang F., Wu M., Li A., Wei Q., Zheng Z. (2024). Design and Experiment of Transverse Interlaced Transplanting Device for Polygonatum odoratum Root Seedlings (黄精块根苗横向交错移栽装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery,* Vol. 55, no. S1, pp. 186-196, Beijing/China.

[21] Zhang Z., Sun X., Jin Z., Bing Z., Sun J. (2018). Design and Experiment of Bionic Soil Covering Device for Soybean Planter Crushing (大豆播种机破碎式仿生覆土装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery,* Vol. 49, no. 2, pp. 34-40+73, Beijing/China.