Discrete Element Parameter Calibration during Cottonseed Crushing Process

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In order to address the current deficit in research on discrete elements within the context of the cotton seed pressing process, a combination of physical tests and simulation experiments were conducted on Xinluzao 84 cottonseed. The Plackett-Burman experimental design was employed to identify the parameters that had a significant impact on the accumulation angle. Subsequently, the Box-Behnken design was employed to establish a second-order regression model for the accumulation angle and the significant parameters. This resulted in the optimal parameter combination for the maximum friction coefficient, minimum sliding friction coefficient and critical shear stress being 0.207, 0.388, and 5×10^6 Pa, respectively. In order to calibrate the cottonseed bonding parameters, a Box-Behnken test was designed based on the results of the cottonseed particle crushing test. The optimal parameter combinations of normal stiffness, tangential stiffness, and bond radius were obtained as 1.25×10^9 N/m², 7.57×10^8 N/m², and 0.727 mm, respectively. The obtained parameters were verified by the simulation of stacking angle and the crushing test simulation. The relative error was 0.84% and 0.46%, respectively. This serves to validate the cottonseed bonding model and simulation parameters, thereby providing a foundation for optimising the core structural parameters of the cottonseed shelling machine.

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INTRODUCTION

Cottonseed meal is a by-product of cottonseed processing, with a low price and high protein content, making it a promising feed resource for development (Tsaliki *et al*. 2003; Jazi *et al*. 2017; Ma *et al*. 2018; Gu *et al*. 2021; Satankar *et al*. 2024). Currently, cottonseed meal is primarily produced through physical processing methods, which involve using a huller to press and separate the cottonseed (China Standard Press 2010). However, the crude fiber content in cottonseed meal is high and the protein content is low due to insufficient shell breaking during cottonseed processing (Wan *et al*. 1998; Zhang *et al*. 2023). In-depth research is needed on the cottonseed crushing process through numerical simulation technology to provide a basis for optimizing the shelling machine.

The discrete element method is a computer numerical simulation method that offers high model fidelity and accurate simulation results (Wang *et al*. 2019; Zhang *et al*. 2022; Yang *et al*. 2023). It has been used to simulate agricultural materials such as soil, grains, and corn (Józef *et al*. 2017; Tian *et al*. 2021; Liu *et al*. 2022; Schramm and Tekeste 2022; Chen *et al*. 2023). Makange *et al*. (2020) developed a soil bonding model to simulate cohesive soil and analysed the soil profile deformation caused by the plow. The simulation results were consistent with the experimental results, demonstrating the accuracy of the soil bonding model. Zhou *et al*. (2024) created a wheat grain model using X-ray microscopy computed tomography and image processing. They calibrated the wheat seed bonding parameters through experiments and obtained the optimal parameter combination. Li *et al*. (2022) developed a discrete element model of corn ears using particle filling and splicing methods. They calibrated the model parameters through simulation experiments to verify its feasibility and accuracy. Hu *et al*. (2022) also developed a model for coated cottonseed using a bonding model. They calibrated the contact parameters through dynamic angle of rest tests. Despite extensive research on agricultural materials, a precise discrete element model for the crushing process of cottonseed materials has not yet been developed.

The EDEM bonding particle model is frequently used to simulate the crushing of agricultural materials (Weerasekara *et al*. 2013; Jou *et al*. 2019; Liu *et al*. 2020; Krok *et al*. 2021; Mu *et al*. 2022; André and Celigueta 2023). The bonding model parameters, which include normal stiffness, tangential stiffness, ultimate normal stress, ultimate tangential stress, bonding radius, and other bonding parameters, in addition to particle contact parameters, are crucial. However, the impact of these parameters on the formation of stacking angles in cottonseed bonding models has been scarcely studied. Accurate cottonseed bonding parameters are necessary for simulating cottonseed crushing experiments. However, calibration work for these parameters has not yet been carried out.

In this work, cottonseed was taken as the research object. The Hertz-Mindlin with Bonding contact model was used. The Plackett-Burman test was employed to ascertain the significance of the discrete meta-parameters of cottonseed, with the objective of identifying the factors that exerted a notable influence on the response values. The optimal range of levels for the significant factors was determined through the application of the steepest-climbing test (an experimental method that can rapidly approximate the optimal region for each significant factor). The parameters affecting the formation of stacking angle (the maximum angle between the surface and the horizontal plane of bulk materials during natural accumulation) in the bonding model were explored by taking the stacking angle as the evaluation index, and the bonding parameters of the cottonseed model were calibrated by using the ultimate crushing force as the evaluation index through the single-particle compression test. The accuracy of the model parameters was verified by the stacking angle simulation test, which provides a basis for the study of cottonseed crushing process. These data will promote the optimal design of cottonseed shelling machine, improvement of cottonseed utilisation rate, and acceleration of cottonseed industrialisation.

EXPERIMENTAL

Determination of Simulation Parameters for Cottonseed

Test materials

The experimental material was Xinluzao 84 cottonseed from the Xinjiang Uygur Autonomous Region. A total of 1000 cottonseeds were selected randomly and divided into 5 groups. The cottonseed density was measured using the drainage method, and the average density was 954 kg/m^3. Additionally, 500 cottonseeds were randomly selected and divided into 5 groups to measure the moisture content using the drying method. The average moisture content of cottonseed, obtained by repeating the process five times, was 8.1%. As the moisture content of cottonseed was relatively low and the interspecific adhesion effect could be ignored, the Hertz-Mindlin (no slip) model was used (Shi *et al.* 2023).

Three axis dimensions and volume distribution

One hundred cottonseeds were randomly selected and measured for their three-axis dimensions using a digital Vernier caliper with an accuracy of 0.02 mm (Dun *et al.* 2022). The dimensions measured were length, width, and thickness, as shown in Fig.1. The statistical results indicated that the average length, width, and thickness of the cottonseeds were 9.32 mm, 5.00 mm, and 4.57 mm, respectively.

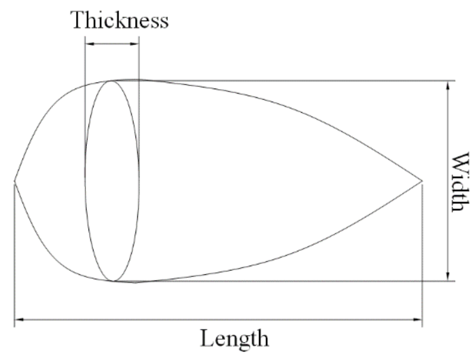


Fig. 1. Three dimensions of cottonseed

After creating a discrete element model using a three-dimensional representation of cottonseed, it is important to determine the distribution pattern of cottonseed volume. The standard deviation of the volume distribution can be calculated from the three-axis dimensions of the cottonseed (Hu *et al.* 2018). The volume of cottonseed was calculated using Eq. 1,

$$V = \frac{\pi B^2 L^2}{6(2L - B)} \tag{1}$$

where V is the volume of cottonseeds (mm^3), L is the length (mm), W is the width (mm), T is the thickness (mm), and $B=(WT)^{1/2}$.

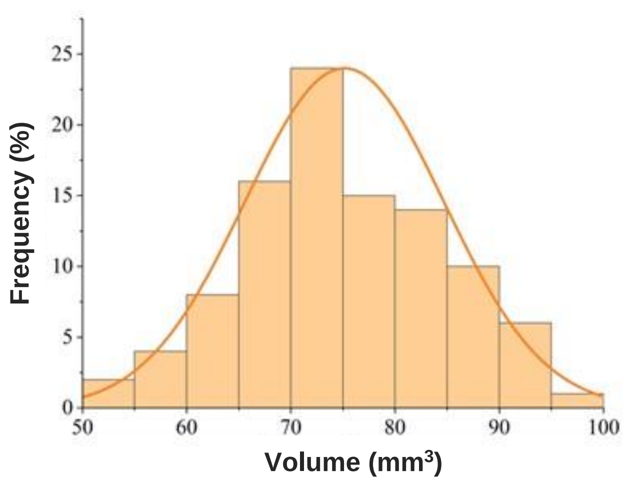


Fig. 2. Volume distribution of cottonseed

Figure 2 shows the volume distribution pattern of cottonseed, which followed a normal distribution with a mean volume of 75.13 ± 9.56 mm^3.

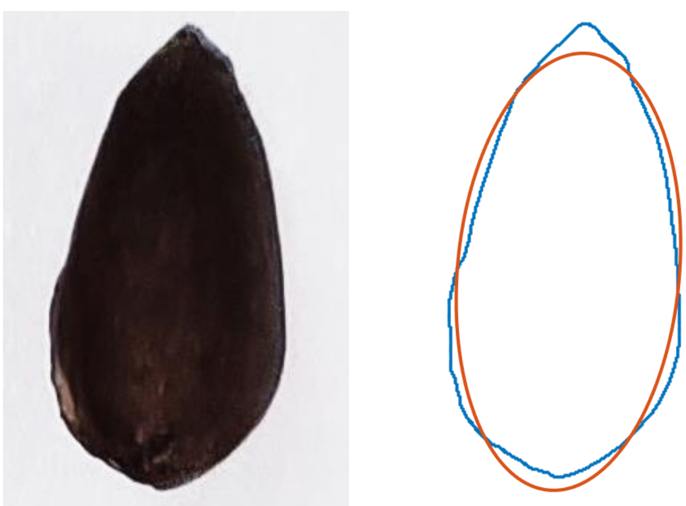
Poisson's Ratio and Shear Modulus

A Vernier caliper was used to measure the lateral and longitudinal lengths of 20 whole cottonseeds. The cottonseeds were placed in the center of the pressure plate on a universal testing platform, which was loaded at a rate of 5 mm/min. The cottonseeds cracked when loaded to 1 to 2 mm. After cracking, the transverse and longitudinal lengths of cottonseeds was measured. The experiment was repeated five times to obtain a Poisson's ratio of 0.19. The elastic model for performing rigid flat extrusion on cottonseed is defined by the ASAE S368.4 DEC2000 (2017) standard, as follows,

$$E = \frac{0.338K^{1.5}F(1-\mu^2)}{D^{1.5}}\left(\frac{1}{R} + \frac{1}{R'}\right) \tag{2}$$

where F is the compressive contact force on the cotton seed (N), D is the cotton seed shape variable (mm), R is the minimum curvature radius at the contact point of the cotton seed (mm), R' is the maximum curvature radius at the contact point of the cotton seed (mm), and K is a coefficient with a dimension of 1.

The curvature radius of cottonseed was determined through image processing technology, and the image acquisition device included an industrial camera, a circular light source, a bracket, and other parts. The cottonseed was placed on the support plane, and an industrial camera was used for image acquisition. Using Matlab to perform binarization, dilation, corrosion, edge detection, contour extraction, and fitting on images, the resulting cottonseed contour curve and fitting curve are shown in Fig. 3.



a. Cottonseed image **b.** Curve fitting

Fig. 3. Image processing of cottonseed contour

The contour of cottonseed is close to an ellipse, and the general equation for fitting the ellipse based on the least squares method is as follows.

$$Ax^2 + Bxy + Cy^2 + Dx + Ey + F = 0 \tag{3}$$

Taking the derivative of the above equation yields that the curvature radius of $y=f(x)$ at $(x, f(x))$ is:

$$R = \frac{\left(1+f'(x)^2\right)^{1.5}}{|f''(x)|} \tag{4}$$

The cottonseed's minimum and maximum curvature radii were determined using image processing technology. It was then placed axially along the thickness direction in the center of the pressure plate and loaded using a universal testing platform. The loading speed was set at 1 mm/min, with a loading displacement of 2 mm. The experiment was repeated 20 times, resulting in a cottonseed elastic modulus of 13.2 MPa.

Sliding Friction Coefficient and Rolling Friction Coefficient

The coefficient of sliding friction was measured by the inclined plane method. To avoid significant measurement errors due to cottonseed rolling, four cottonseeds were glued together (Wang *et al.* 2022). First, the steel plate of the inclinometer was adjusted to the horizontal. The cottonseed was placed on the steel plate, and the handwheel was turned slowly and evenly, as shown in Fig. 4. The angle between the steel plate and the horizontal plane increased continuously until the cottonseed slid downwards. At this point, the tangent value of the angle between the steel plate and the horizontal plane is the coefficient of sliding friction of the cottonseed. After repeating the experiment 10 times and taking the average value, the coefficient of sliding friction between the cottonseed and the steel plate was obtained as 0.51.

To measure the rolling friction coefficient of cottonseed, a well-shaped cottonseed was placed on a steel plate. With the long axis perpendicular to the direction of inclination of the steel plate, the handwheel was turned slowly and evenly. The angle between the steel plate and the horizontal plane increased continuously until the cottonseed rolled downwards. At this point, the tangent value of the angle between the steel plate and the horizontal plane is the rolling friction coefficient of the cottonseed. After repeating the experiment 10 times and taking the average value, the coefficient of rolling friction between the cottonseed and the steel plate was obtained as 0.21

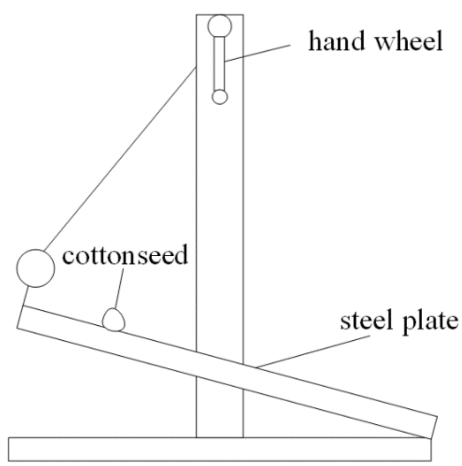


Fig. 4. Inclinometer structure schematic diagram

Collision Recovery Coefficient

The collision recovery coefficient of cottonseed was measured using the free fall collision method. According to Newton's laws of mechanics, the collision recovery coefficient is the ratio of the velocity before and after the cottonseed collision, as follows,

$$e_x = \frac{v_1}{v_0} = \frac{\sqrt{2gh}}{\sqrt{2gH}} = \sqrt{\frac{h}{H}} \quad (5)$$

where v_0 is the velocity before the cottonseed collides with the tested material (m/s), v_1 is the velocity of cottonseed colliding with the tested material (m/s), g is the gravitational acceleration, 9.81 m/s^2, h is the rebound height of cottonseed after collision (m), and H is the height of the cottonseed falling before collision (m).

The cottonseed was released from a height of 150 mm from the steel plate with an initial velocity of zero. After colliding with the steel plate, the cottonseed rebounded. The highest point reached after the rebound was recorded by the camera, and the collision recovery coefficient of the cottonseed was calculated using the formula. After repeating the experiment 10 times and taking the average value, the collision recovery coefficient between cottonseed and steel plate was obtained as 0.46.

Uniaxial Compression Test

Intact cottonseed particles were selected for uniaxial compression tests on a texture analyser. The cottonseed was placed in the centre of the compression platen and loaded at a rate of 1 mm/min, as shown in Fig. 5. The release force was set at 0.3 N until the specimen was damaged. A total of 20 tests were conducted, and the maximum load stress was obtained when the load displacement of the cottonseed particles was 2 mm. Thus, the average ultimate crushing force of the cottonseed was 71.1 N, and the corresponding ultimate crushing displacement was 2 mm.

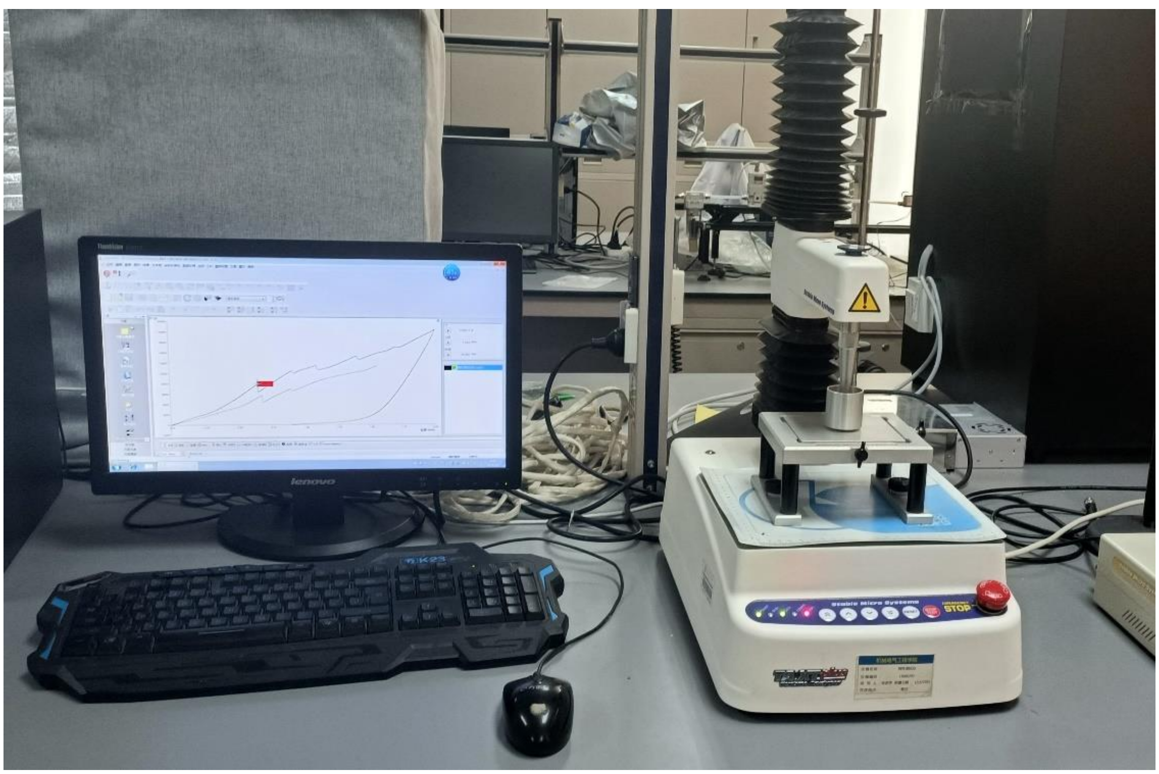


Fig. 5. Cottonseed compression test

RESULTS AND DISCUSSION

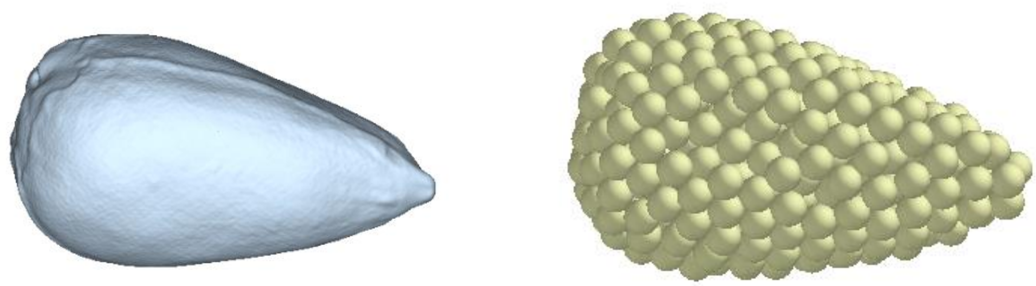
Establishment of Discrete Element Model and Calibration of Contact Parameters

Cottonseed discrete element model

Cotton seeds are irregularly shaped particles. To accurately create a seed contour model to improve calibration accuracy, a Capture MINI scanner was used to scan and obtain cotton seed point cloud data, and a cotton seed contour model was created. Particle templates were imported into EDEM, the templates were filled with particles and a cottonseed bonding model was created.

In the composite model, the material particles are composed of multiple particles. The smaller the particle diameter and the greater the number, the more accurate the simulation model, but the longer the computation time.

Taking into account the accuracy of the model and the computation time, a cottonseed model was created by filling the contour with 440 particles with a radius of 0.35 mm, as shown in Fig. 6. To ensure that the quality of the binding model is equivalent to the actual quality of the cottonseed, the density enhancement method is used. With all other parameters held constant, the density of the particles is increased from 954 to 1063 kg/m^3 (Niu *et al.* 2023).



(a) **(b)**

Fig. 6. Simulation model of corn coated seeds. (a) Contour model; (b) Meta particles

Actual stacking angle test

A steel cylinder with an internal diameter of 50 mm and a height of 150 mm was selected for measurement. The cylinder lift method was used to conduct the stacking angle test on cottonseed. During the test, 100 g of cottonseed was added to the cylinder, which was then uniformly lifted at a speed of 0.05 m/s using a universal testing machine.

The cottonseed fell and formed a conical pile. Figure 7 shows that the images were imported into Matlab software, processed for denoising, greyscale, and binarisation. The image boundaries were then extracted for linear fitting, and the actual stacking angle was determined as the angle between the fitted line and the x-axis. To reduce errors, the actual stacking angle of the cottonseed was measured separately on both sides by taking the average value during the experiment. The average was obtained by repeating the experiment 5 times, resulting in an actual stacking angle of the cottonseed of 24.9°.

(a) (b)

Fig. 7. Image processing of repose angle measurement of cottonseed. (a) Original image; (b) Contour extraction and line fitting

Contact Parameter Calibration

When conducting experiments using the discrete element method, it is necessary to calibrate the contact parameters of the cottonseed. The results of the stacking angle test in the discrete element model using the Hertz-Mindlin with Bonding model are affected by the cottonseed interspecies contact parameters and by factors such as normal stiffness, tangential stiffness, critical normal stress, tangential normal stress, and bond radius of the model (Li *et al.* 2022). This study considers the actual stacking angle of cottonseed as the response value. To calibrate the parameters of cottonseed, Design-Expert software was used, employing factor significance screening, steepest climbing, and response surface optimization.

Single particle compression pre experiment

To perform the stacking angle calibration experiment, the range of cottonseed bonding parameters was determined by a single particle compression simulation prior to the experiment, taking into account the influence of bonding parameters on the formation of the cottonseed stacking angle. To simulate compression, the support plate model was imported to EDEM. The particle factory was set to generate a single cottonseed model. After stabilisation, a compression cylinder model was built, as shown in Fig. 8.

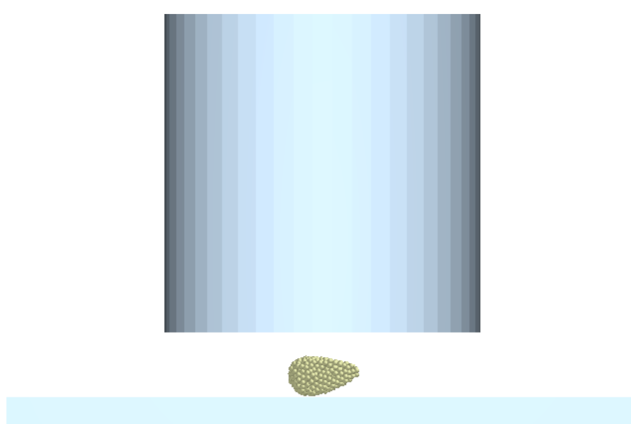


Fig. 8. Cottonseed simulation compression test

The compression cylinder speed was set to 1 mm/s, and the maximum compression distance of particles was 2 mm. The pressure value when the compression cylinder reaches the maximum compression distance of particles was calculated through the EDEM post-processing interface as the maximum crushing force of cottonseed. The range of adhesion parameters obtained from single particle compression tests is shown in Table 1.

Table 1. Cotton Seed Bonding Parameter Range

Parameter	Value range
Normal stiffness (N/m^2)	7×10^8-1.4×10^9
Tangential stiffness (N/m^2)	5×10^8-1×10^9
Normal critical stress (Pa)	3×10^6-6×10^6
Tangential critical stress (Pa)	2×10^6-4×10^6
Bonding radius (mm)	0.4-0.8

Screening for significant factors

To reduce the number of experiments, a Plackett-Burman experimental design was prepared using the DOE module of Design Expert software with cottonseed contact parameters and bonding parameters as factors to determine significant influencing factors. The low and high levels of contact parameters were determined based on the review of relevant literature and preliminary experiments, as shown in Table 2 (Wang *et al.* 2022). Table 3 displays the design and experimental results of Plackett-Burman. Table 4 shows that the angle of accumulation of cottonseed was affected by various factors in the following order: B, A, F, E, H, D, G, and C.

Table 2. Parameter of Plackett-Burman Test

Symbol	Parameter	Low level	High level
A	Cottonseed collision recovery coefficient	0.19	0.38
B	Cottonseed sliding friction coefficient	0.23	0.46
C	Cottonseed rolling friction coefficient	0.13	0.26
D	Normal stiffness (N/m^2)	7×10^8	1.4×10^9
E	Tangential stiffness (N/m^2)	5×10^8	1×10^9
F	Normal critical stress (Pa)	3×10^6	6×10^6
G	Tangential critical stress (Pa)	2×10^6	4×10^6
H	Bonding radius (mm)	0.4	0.8

Table 3. Design and Results of Plackett-Burman Test

Number	A	B	C	D	E	F	G	H	stacking angle θ (°)
1	1	-1	-1	-1	1	1	1	-1	27.01
2	1	-1	1	1	-1	1	-1	-1	23.89
3	-1	1	1	-1	1	-1	-1	-1	22.38
4	1	1	1	-1	1	1	-1	1	20.71
5	-1	1	1	1	-1	1	1	-1	24.23
6	1	1	-1	1	1	-1	1	-1	28.78
7	-1	-1	1	1	1	-1	1	1	20.95
8	-1	1	-1	-1	-1	1	1	1	24.02
9	-1	-1	-1	1	1	1	-1	1	29.16
10	-1	-1	-1	-1	-1	-1	-1	-1	23.63
11	1	1	-1	1	-1	-1	-1	1	20.82
12	1	-1	1	-1	-1	-1	1	1	30.19

Table 4. Analysis of Significance of Parameters in Plackett-Burman Test

Parameter	Effect	Mean square sum	Impact rate	Sort
A	2.41	17.40	13.92	2
B	5.17	80.14	64.12	1
C	0.05	0.01	0.01	8
D	0.22	0.14	0.11	6
E	1.30	5.06	4.05	5
F	-2.32	16.08	12.86	3
G	-0.19	0.11	0.09	7
H	1.22	4.45	3.56	4

Figure 9 indicates that B, A, E, H, D, and C have a positive effect on the stacking angle, while F and G have a negative effect. A, B, and F have a significant effect on the stacking angle with a P-value of less than 0.05. Therefore, A, B, and F are selected for the steepest climb test, while the remaining factors are averaged at high and low levels.

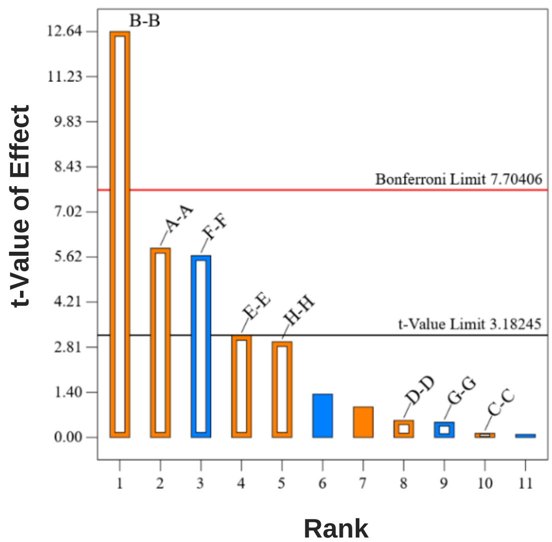


Fig. 9. Response analysis of cottonseed to grain accumulation

Steepest climb test

The steepest climb test represents an experimental method that can rapidly approximate the optimal region for each significant factor. According to the results of the Plackett-Burman test, the initial values of A, B, and F were chosen as 0.1, 0.2, and 2×10^6 Pa, and the step sizes were set as 0.1, 0.1, and 2×10^6 Pa, respectively. Table 5 shows the experimental design and results.

Table 5. Design and Results of Steepest Ascent Test

Number	A	B	F (Pa)	stacking angle θ(°)	Relative error (%)
1	0.1	0.2	2×10^6	18.92	24.02
2	0.2	0.3	4×10^6	21.27	14.48
3	0.3	0.4	6×10^6	26.09	4.78
4	0.4	0.5	8×10^6	30.40	22.09
5	0.5	0.6	1×10^7	36.18	45.30

The error with the actual stacking angle initially decreased and then increased, with the actual stacking angle falling between the 2nd and 3rd order. For response surface analysis, the centre point was chosen as the mean value of the two levels, with the 2nd and 3rd levels being the low and high levels.

Response surface test

Based on the results of the steepest climb test, a three-factor, three-level response surface experimental design was conducted using Design Expert software. Three sets of replications were set up at the central level, and a total of 15 sets of cottonseed stacking angle simulation experiments were conducted. The experimental design and results are shown in Table 6, and the results of the analysis of variance are shown in Table 7.

In the cottonseed stacking angle test, A and B had a significant effect on cottonseed stacking angle, while F had no significant effect on cottonseed stacking angle. In the interaction terms, AB and BF had a very significant effect on cottonseed stacking angle, while AF had no significant effect on cottonseed stacking angle. In the quadratic term, B^2 and F^2 had a very significant effect on cottonseed stacking angle, while A^2 had no significant effect on cottonseed stacking angle. If the P value of the regression model is less than 0.05, the regression model is significant, and the P value of the missing term is greater than 0.05. The missing term was not significant and the regression was judged to be valid.

Table 6. Design and Results of Box-Behnken Test

Number	A	B	F (Pa)	Stacking Angle θ(°)
1	0.25	0.3	4×10^6	23.64
2	0.3	0.4	5×10^6	26.34
3	0.25	0.35	5×10^6	24.97
4	0.25	0.35	5×10^6	25.05
5	0.2	0.35	6×10^6	24.31
6	0.25	0.4	4×10^6	26.97
7	0.25	0.3	6×10^6	24.37
8	0.2	0.35	4×10^6	24.52
9	0.25	0.35	5×10^6	24.81
10	0.3	0.3	5×10^6	25.29
11	0.2	0.4	5×10^6	25.03
12	0.3	0.35	6×10^6	26.78
13	0.2	0.3	5×10^6	21.14
14	0.25	0.4	6×10^6	25.62
15	0.3	0.35	4×10^6	26.83

According to the results of the analysis of variance, the interaction between AB and BF had a significant effect on the accumulation angle of cottonseed. The analysis of variance showed that the interaction between AB and BF had a significant effect on the stacking angle of cottonseed. The response surface was plotted using Design-Expert software under the conditions of F of 6×10^6 Pa and A of 0.2, and the influence of each factor on the stacking angle was further analysed. As shown in Fig. 10, in the AB surface, the response surface curve of A grew faster than that of B, indicating that it had a more significant effect on the stacking angle. In the BF surface, the effect surface curve of B grew faster than that of F, indicating that it had a more significant effect on the stacking angle.

Table 7. ANOVA of Quadratic of Box-Behnken Test

Source of variance	Mean square	Degree of freedom	Sum of squares	F-value	P-value
model	30.41	9	3.38	140.69	< 0.0001
A	13.11	1	13.11	545.83	< 0.0001
B	11.33	1	11.33	471.77	< 0.0001
F	0.0968	1	0.0968	4.03	0.1009
AB	2.02	1	2.02	83.97	0.0003
AF	0.0064	1	0.0064	0.2665	0.6277
BF	1.08	1	1.08	45.04	0.0011
A^2	0.0010	1	0.0010	0.0427	0.8444
B^2	0.8389	1	0.8389	34.94	0.0020
F^2	1.72	1	1.72	71.80	0.0004
Residual	0.1201	5	0.0240		
Lack of Fit	0.0902	3	0.0301	2.01	0.3489
Pure Error	0.0299	2	0.0149		
Cor Total	30.53	14			

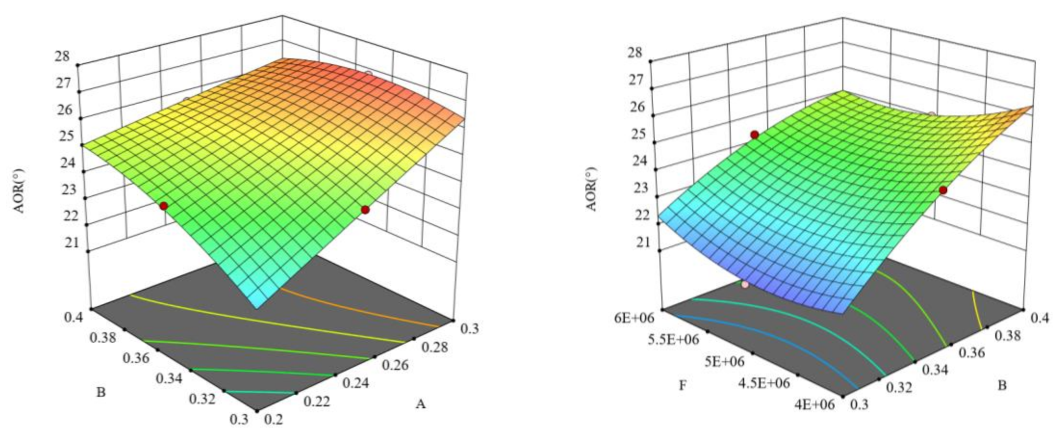


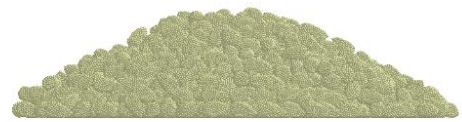
Fig.10. Response analysis of cottonseed to grain accumulation

To determine the optimal combination of parameters for each factor, it is necessary to minimise the range of constraint conditions as much as possible. Since the actual stacking angle of cottonseed was 24.9°, the stacking angles of Group 3 and Group 11 experiments were closest to the actual values, and F is 5 × 10^6 Pa for both experiments. Therefore, the constraint range was set as follows.

$$\begin{cases} \theta = 24.92\,° \\ 0.2 \le A \le 0.25 \\ 0.35 \le B \le 0.4 \\ F = 5 \times 10^6\ Pa \end{cases} \tag{6}$$

Using Design-Expert software for optimization, the cottonseed stacking angle was 24.9° when A, B, and F were 0.207, 0.388, and 5×10^6 Pa, respectively. The stacking angle was simulated and verified using the optimal parameter combination obtained, and the experiment was replicated 5 times. As shown in Fig. 11, the average value of the simulated stacking angle was 25.1°, with a relative error of 0.84%, which is relatively small compared to the actual stacking angle. This indicates that the simulation results under the optimal parameter combination are accurate and reliable, and can be used for subsequent simulation experiments.

a. Actual stacking angle



b. Simulation stacking angle

Fig. 11. Comparison of actual and simulated cottonseed stacking angles

Cotton Seed Crushing Test and Bonding Parameter Calibration

After obtaining the contact parameter values of cottonseed, the combination of bonding parameters in the cottonseed model was determined by a single particle compression crushing test, using particle crushing force as the evaluation index. After consulting the relevant literature, it was found that the material particles produced by the bonding model had a significant effect on their crushing force due to the bonding parameters D, E and H, while the effects of F and G on the crushing force can be ignored (Niu *et al.* 2022). Therefore, according to the parameter range in Table 5, a cottonseed crushing test was conducted and a three-factor, three-level response surface experimental design was carried out using Design Expert software. The central level repeated measures experiment was conducted three times, and a total of 15 sets of experiments were conducted.

Table 8. Design and Results of Box-Behnken Test

Number	D (N/m^2)	E (N/m^2)	H (mm)	Crushing force (N)
1	1.05×10^9	5×10^8	0.8	71.3
2	1.05×10^9	7.5×10^8	0.6	64.9
3	1.05×10^9	7.5×10^8	0.6	65.9
4	1.05×10^9	7.5×10^8	0.6	65.3
5	1.4×10^9	7.5×10^8	0.8	74.1
6	7×10^8	7.5×10^8	0.8	68.6
7	1.4×10^9	1×10^9	0.6	66.9
8	7×10^8	1×10^9	0.6	65.7
9	1.05×10^9	5×10^8	0.4	50.6
10	7×10^8	5×10^8	0.6	60.1
11	7×10^8	7.5×10^8	0.4	48.3
12	1.4×10^9	5×10^8	0.6	61.8
13	1.05×10^9	1×10^9	0.8	76.4
14	1.05×10^9	1×10^9	0.4	57.1
15	1.4×10^9	7.5×10^8	0.4	51.7

Analysis of variance was performed on the experimental results, and the P-value of the model was less than 0.05. The model determination coefficient R^2 was 0.9936, and the corrected determination coefficient R^2_{adj} was 0.9821. The model fit was good. According to Table 9, in the cottonseed crush test, D, E, and H had a significant effect on the cottonseed crushing force, while E and H had no significant effect on the cottonseed crushing force; in the interaction terms, the effects of DE, DH and EH on the cottonseed crushing force were not significant; in the quadratic term, D^2 and H^2 have a significant effect on the cottonseed crushing force, while E^2 has no significant effect on the cottonseed crushing force.

Table 9. ANOVA of Quadratic of Box-Behnken test

Source of variance	Mean square	Degree of freedom	Sum of squares	F-value	P-value
model	974.12	9	108.24	86.46	< 0.0001
D	17.40	1	17.40	13.90	0.0136
E	62.16	1	62.16	49.66	0.0009
H	854.91	1	854.91	682.93	< 0.0001
DE	0.0625	1	0.0625	0.0499	0.8320
DH	1.10	1	1.10	0.8807	0.3911
EH	0.4900	1	0.4900	0.3914	0.5590
D^2	19.39	1	19.39	15.49	0.0110
E^2	2.88	1	2.88	2.30	0.1897
H^2	15.77	1	15.77	12.60	0.0164
Residual	6.26	5	1.25		
Lack of Fit	5.51	3	1.84	4.92	0.1735
Pure Error	0.7467	2	0.3733		
Cor Total	980.38	14			

The optimisation solution was carried out with the actual crushing force of 71.1 N as the objective, and the values of D, E and H were obtained to be 1.25×10^9 N/m^2, 7.57×10^8 N/m^2, 0.727 mm. As shown in Fig. 12, the average cottonseed crushing force obtained from 5 experiments was 70.8 N, and the relative error with the actual crushing force of 71.1 N was 0.46%. The simulation results had a small error with the experimental results, indicating that the particle adhesion parameters are reliable.

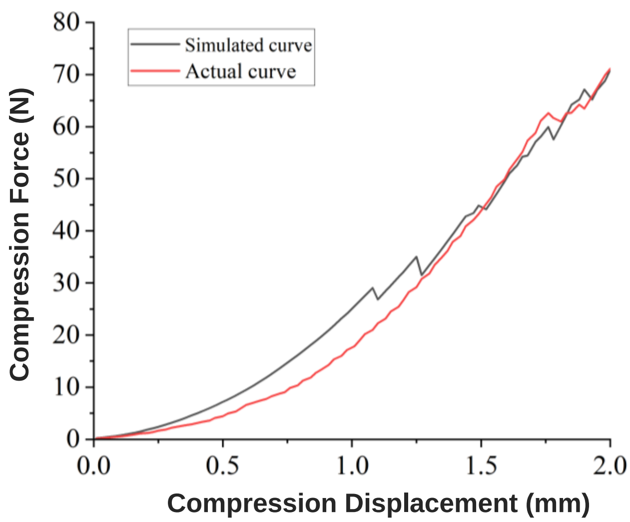


Fig. 12. Comparison of compression force compression displacement curves

CONCLUSIONS

This article has presented a simulation of the compression process of cottonseed with representative size and moisture content, which may be regarded as a reference value. However, it should be noted that the moisture content of cottonseeds can vary significantly in actual working conditions. Mohammad and Mehari (2020) have identified differences in parameters such as density and collision coefficient, which suggests that further analysis is required to understand the influence of moisture content on the cottonseed pressing process. Additionally, it is important to recognise that in processing equipment, cottonseed compression is not limited to single particle compression, but involves the compression and crushing of a large number of particles simultaneously. This highlights the need for further research to improve the model. Conclusions are as follows:

1. A discrete element particle model of Xinluzao 84 cottonseed was established based on reverse engineering technology. By combining physical and simulation experiments, the optimal parameter combination of the cottonseed binding model was obtained using experimental optimisation design methods. The simulation results were verified by stacking angle tests and particle crushing tests.
2. The Poisson's ratio, shear modulus, stacking angle and average crushing force of cottonseed after hulling in Beiquan Town, Shihezi City, Xinjiang Uygur Autonomous Region were 0.19, 13.2 MPa, 24.92° and 71.13 N, respectively; the collision recovery coefficient, static friction coefficient and rolling friction coefficient between cottonseed and steel plate were 0.46, 0.51 and 0.21, respectively.
3. The Plackett-Burman experiment was used to screen the parameters in the cottonseed-steel plate adhesion model that have a significant effect on the stacking angle. The optimal parameter combinations for cottonseed collision recovery coefficient A, cottonseed sliding friction coefficient B and normal critical stress F were calibrated to be 0.207, 0.388 and 5×10^6 Pa, respectively.
4. Through the simulation test of single particle compression of cottonseed, the normal stiffness D, tangential stiffness E, and bond radius H were calibrated to be 1.25×10^9 N/m^2, 7.57×10^8 N/m^2, and 0.727 mm, respectively. The relative error between the simulation test and the physical test crushing force under the optimal bonding parameter combination was 0.46%.

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