PARAMETER CALIBRATION AND EXPERIMENT OF DISCRETE ELEMENT SIMULATION OF SPHERICAL-LIKE SOYBEAN BASED ON DEM
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基于DEM 的类球型大豆离散元仿真参数标定与试验

Guangwei CHEN [1], Fuxing LI [1], FaYi QU *[2], Chong Jian ZHANG [1]
[1]Northeast Forestry University, College of Mechanical and Electrical Engineering, Harbin / China;
[2]Northeast Forestry University, Graduate School, Harbin / China.
Tel: +86 15663693373; E-mail: qufae@163.com
DOI：https://doi.org/10.35633/inmateh-74-26

Keywords: *Spherical-like soya bean, Material properties, discrete element simulation, Stacking angle*

ABSTRACT
This paper focuses on the lack of spherical-like soybean simulation parameters when guiding the optimization and design of agricultural machinery and equipment through discrete element simulation. The spheroidal soybean variety SN29 was used as a study subject; the intrinsic properties and physico-mechanical properties of the spherical soybean were determined through actual measurements and the simulation of spherical-like soybean particles with Hertz-Mindlin (no-slip) as the contact model was established. The collision recovery, static, and rolling friction coefficients of the spherical-like soybean and acrylic sheet material were measured by the natural drop and inclined plane methods, combined with discrete element simulation and bench experiments. They were 0.474, 0.496, and 0.0361, respectively. The relative errors between the measured stacking angles and the simulated stacking angles were used as indicators, and the contact parameters between the particles were used as variables for the design of the steepest climb experiment. The collision recovery coefficient, static friction coefficient, and rolling friction coefficient between spherical-like soybean particles were determined to be 0.35, 0.30, and 0.074, respectively, by orthogonal rotational combination experiment and multi-objective optimization. The relative error between the simulated and measured stacking angles was only 1.09%, as verified by the experiment. This proves that the discrete element simulation parameters of the studied spherical-like soybean can reflect its real characteristics and be used as the parameter basis for discrete element simulation.

摘要
*针对类球形大豆在应用离散元仿真指导相关农机设备优化设计时缺乏仿真参数的问题。以类球形大豆品种SN29 为研究对象，通过实际测量和万能试验机，确定了类球形大豆的本征特性与物理力学特性，并建立了以Hertz-Mindlin（no-slip）为接触模型的类球形大豆仿真颗粒模型。通过跌落法和斜面法，结合离散元仿真及台架试验，测得类球形大豆与亚克力板材料的碰撞恢复系数、静摩擦系数和滚动摩擦系数，分别为0.474、0.496 和0.0361。以实测与仿真堆积角的相对误差为指标，颗粒间接触参数为变量，设计了最陡爬坡试验，并通过正交旋转组合试验及多目标优化，确定了类球形大豆颗粒间的碰撞恢复系数、静摩擦系数和滚动摩擦系数，分别为0.35、0.30 和0.074。经试验验证，仿真堆积角与实测堆积角的平均相对误差仅为1.09%。这证明了研究所得的类球形大豆离散元仿真参数*能够反映其真实特性，可作为离散元仿真时的参数依据。

INTRODUCTION
As an essential source of protein, edible oil, and livestock feed, soybean is widely cultivated worldwide and an indispensable crop in agricultural production (*Guo et al., 2023*). As the demand for soybeans continues to grow, it has become crucial to improve the mechanization of the soybean chain (*Shi et al., 2021; Chang et al., 2024*). In the design and optimization of agricultural machinery and equipment, discrete element (DEM) simulation software is often used to simulate the motion state of crops during sowing, harvesting, and clearing; the advantages of this method are that seasonal and experimental conditions do not restrict it, and it has a lower trial-and-error cost compared with actual experiments, which has led to its wide application in the design and optimization of agricultural machinery and equipment (*Zhao et al., 2021; Zhang et al., 2022*).

[1]*GuangWei CHEN Assoc.Prof.; Fuxing LI, Postgraduates.; FaYi QU, Assistant Research Fellow; ChongJian ZHANG, Postgraduates.*

In the process of using discrete element simulation (DEM) to guide the design and optimization of agricultural machinery and equipment, due to the differences in the intrinsic characteristics and physical parameters of different crops, to simulate the actual movement patterns of crops in farm machinery and equipment, exact measurements and other means are usually used to obtain their accurate physical parameters (*Hao et al., 2021*). The relevant parameters' authenticity determines the simulation results' accuracy and reliability (*Xie et al., 2024*). At present, domestic and foreign scholars' studies on the calibration of crop parameters have mainly used actual measurements, cylinder lifting method, inclined surface method and falling method to calibrate the intrinsic characteristics and physical parameters of grain and oil crops and straws, such as white kidney beans, chili peppers, sunflower seeds and alfalfa stems and stalks (*Yang et al., 2024; Chen et al., 2024; Wang et al., 2022; Chen et al., 2023*). However, the calibration of discrete element parameters for spherical-like soybeans grown in Northeast China is still insufficient, resulting in the lack of accurate and effective simulation parameters for spherical-like soybeans when using discrete element simulation to guide the optimization and design of agricultural machinery and equipment, which to a certain extent restricts the optimization and development of the design of farm machinery and equipment for spherical soybean varieties.

In order to determine the physical parameters of the spherical-like soybean, this study obtained the basic material properties of the soya bean and its contact parameters with the acrylic material by combining bench experiments and discrete element simulation experiments. The steepest climb experiment was designed using the interparticle contact parameter as a variable and the minimum error between the measured and simulated stacking angles as an indicator; by designing orthogonal rotational combination experiments with the help of Design Expert 13 software, the optimum contact parameters between the soybean seeds were finally determined through target optimization and validation experiments. The study results can provide accurate, reliable, and reasonable simulation models and parameter support when discrete element simulation guides the design and optimization of agricultural machinery and equipment for spherical soybean varieties.

MATERIALS AND METHODS

Determination of intrinsic properties and discrete element models for spherical-like soybeans

Experiment Material Selection

The representative spherical-like soybean variety SN29 from Suihua, Northeast China, was selected as the experiment material. It was harvested in October 2023, collected from farmers' homes in February 2024, and sealed using ziplock bags after collection to prevent moisture loss.

Hundred-grain weight and triaxial dimensions

Using an electronic balance with an accuracy of 500g ± 0.01g, three groups of materials were randomly selected, and each group was repeated three times, resulting in a consolidated 100-grain weight of 20.84 g. Five hundred soybeans were randomly selected, and using a vernier caliper with an accuracy of 0.01 mm, the geometrical dimensions of their length (L), thickness (T), and width (W) were measured and recorded, and the mean values were obtained to be 7.49 mm, respectively, 7.33 mm and 6.58 mm. The specific measurement positions and tools are shown in Fig. 1.

a-Position of particle triaxial size measurement *b-Digital vernier calipers*

Fig. 1 - Soybean seed geometry measurement positions and tools

In order to provide a basis for establishing the discrete element simulation model, the equivalent diameter and sphericity of soybeans were calculated using Eq. (1) and (2). The combined sphericity was 95.1%, and the combined average diameter was 7.1 mm, resulting in a high overall sphericity. Combining the various data, the histogram of the normal distribution of the equivalent diameters of spherical-like soya-like beans versus the three-axis sizes was plotted using Origin2022, and it can be seen that the various size intervals conformed to the normal distribution, as shown in Fig. 2. In order to avoid repetition or ambiguity, all the descriptions of ‘spherical-like soya beans’ in the following were replaced by ‘soybean’ instead.

$$D_{es} = (L \times T \times W)^{\frac{1}{3}} \tag{1}$$

$$\varepsilon = \frac{D_{es}}{d_s} \times 100 \tag{2}$$

where:

D_{es} is the equivalent diameter, [mm]; L, T, W are the length, width, and thickness, [mm]; ε is the sphericity, [%]; d_s is the diameter of the external ball of the soybean (long axis dimension), [mm].

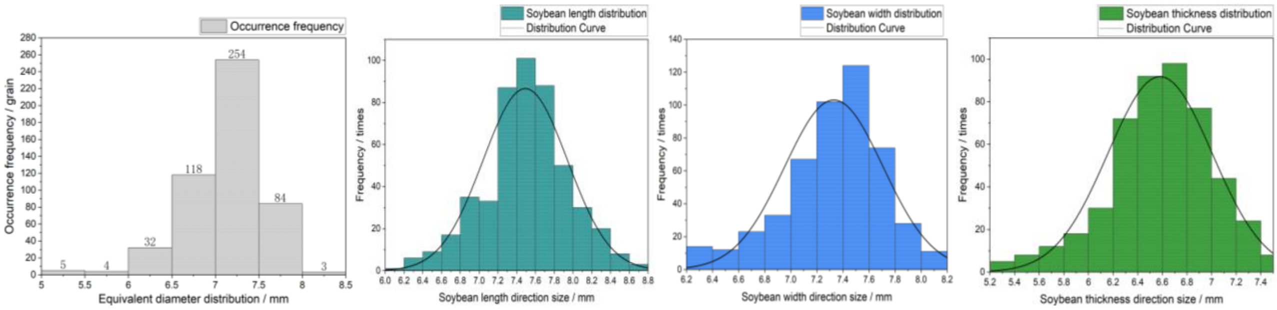
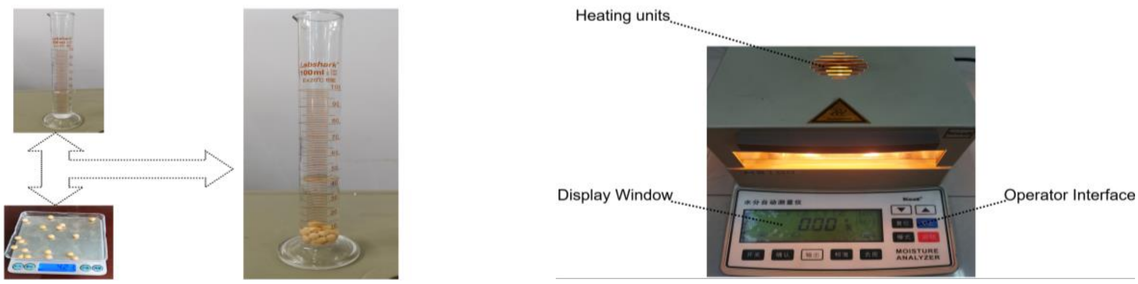


Fig. 2 - Histogram of equivalent diameter and triaxial size distribution of soybean

Moisture content and density

The density of soya beans was measured using the drainage method. The measuring cylinder was filled with a certain volume of pure water, say 40ml (40 cm³), noted as V1. A random portion of soya bean was taken and weighed, noted as M. After putting the soybeans into the measuring cylinder, the combined volume of the two is noted as V2. The density of the soybeans is [M/(V2- V1)] x 1000. After three experimental measurements, the average density of the spherical-like soybeans was 1,252 kg/m³.

The moisture content of the soya beans was determined using the pyrolytic weight principle, using the high-temperature rapid drying unit of the MS100 Halogen Moisture Meter. The masses of the soybeans before and after drying were noted as M1 and M2, respectively, and the moisture content was [(M1-M2)/M1] × 100%. After three measurements, the average value was taken to obtain an average moisture content of 10.93% for the soybeans. The above density and moisture content measurement equipment is shown in Fig. 3.



a-Density Measurement Process *b-MS100 Halogen Moisture Meter*

Fig. 3 - Density and moisture content measuring equipment

Poisson's ratio and modulus of elasticity

Poisson's ratio is a physical quantity that describes the ratio of positive radial strain to positive axial strain of a material in unidirectional tension or compression. It is also known as the transverse deformation coefficient *(Zhang et al., 2024*). Ten soybeans were randomly selected and subjected to Poisson's ratio uniaxial compression experiments using a CTM2500 universal materials experimenting machine. The handle controlled the moving beam to apply the load along the soybean thickness direction at a 5 mm/min descending speed. When the particles made cracking sounds, the pressure was stopped immediately, the moving beam was lifted quickly, and the changes in the soybeans' length and thickness direction dimensions before and after compression were recorded. Substituting the measured data into Eq. (3), the Poisson's ratio of soybeans ranged from 0.17 to 0.35, with an average value of 0.23.

$$\mu = \frac{L_1 - L_2}{W_1 - W_2} = \left| \frac{V_L}{V_W} \right| \tag{3}$$

where: μ is the Poisson's ratio of soybean; L_1 is the length of soybean before compression, [mm]; L_2 is the length of soybean after compression, [mm]; W_1 is the thickness of soybean before compression, [mm]; W_2 is the thickness of soybean seed after compression, [mm]; V_L is the deformation of compression in the direction of the length, [mm]; V_W is the deformation of the direction of the thickness of soybean, [mm].

The modulus of elasticity and shear modulus of soybean refer to the ability of a material to resist deformation when subjected to a force and are essential components of the simulation parameters. Ten soybeans were randomly selected and measured using a universal experimenting machine concerning the ASAE S368.4 DEC2000 (R2008) standard published by the American Society of Agricultural and Biological Engineers (Shirvani M et al., 2014). When the experimenting machine detects that the compression curve exceeds the elastic deformation interval of the soybean, the moving beam will automatically stop the downward pressure and lift upward, outputting the relevant data of the compression experiment and completing the whole measurement process of the modulus of elasticity.

Substituting the obtained values into Eq. (4) and (5), the modulus of elasticity of soybean was calculated as 43.54-109.79 MPa, and the average value was 79.71 MPa. Substituting the values of modulus of elasticity and Poisson's ratio into Eq. (6) gives the range of shear modulus of the soybean as 17.7 to 44.63 MPa with an average value of 32.4 MPa. The described CTM2500 universal materials experimenting machine and its measurement principle are shown in Fig. 4.

$$E = \frac{0.38F(1-\mu^2)}{D^{\frac{3}{2}}}\left[2K\left(\frac{1}{R_1}+\frac{1}{R'_1}\right)^{\frac{1}{3}}\right]^{\frac{3}{2}} \tag{4}$$

where:

$$\begin{cases} R_1 = \left[\left(L/2\right)^2 + \left(W/2\right)^2\right]/W \\ R'_1 = \left[\left(T/2\right)^2 + \left(W/2\right)^2\right]/W \\ \cos\theta = \dfrac{\left(1/R'_1 - 1/R_1\right)}{\left(1/R'_1 + 1/R_1\right)} \end{cases} \tag{5}$$

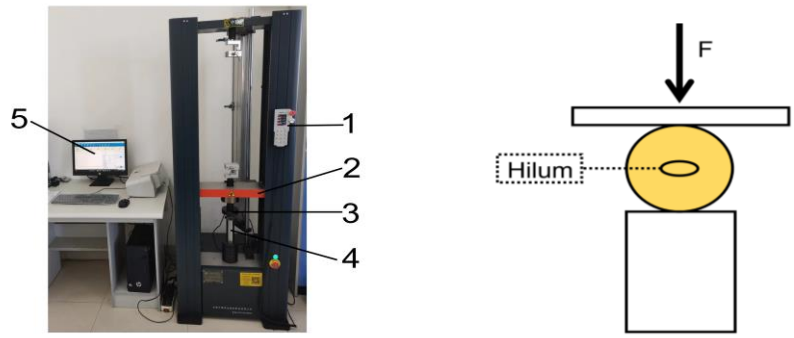
where:

E is the modulus of elasticity of soybean particles, [MPa]; F is the compression load on soybeans, [N]; μ is the Poisson's ratio of soybeans, according to the above calculations it can be known as 0.23; D is the deformation of soybeans, [mm]; R_1 is the radius of curvature of the upper contact surface between soybeans and the circular compression table, [mm]; R'_1 is the radius of curvature of the lower contact surface of the fixed platform of the soybeans and particles, [mm]; K value is an intermediate constant value (calculated using the $cos\theta$ formula in Eq.(6) and obtained after searching in the ASAE S368.4 DEC2000 (R2008) standard).

$$G = E/2(1+\mu) \tag{6}$$

where:

G is the shear modulus of soybean particles, [MPa]; E is the modulus of elasticity of soybean, [MPa]; μ is the Poisson's ratio of soybean.



a-CTM2500 Universal Material Experimenting Machine *b-Experiment principles schematic*

Fig. 4 - Soybean compression experiment equipment and schematic diagram

1.Control Handle; 2. Movable Crossbar; 3. Mobile Pressurized Circular Table; 4. Fixed Material Platform; 5. Computer Control Terminal.

Discrete element modeling of soybean

When the sphericity of the particles is greater than 90%, the single spherical particles that come with the system can be used to build a discrete element simulation model, and this means it can effectively improve the simulation efficiency under the premise of ensuring the reliability of the simulation (*Zhang et al., 2024*). The integrated sphericity of the calibrated soybean was 95.1%, which met the above modeling conditions.

A discrete element simulation model was developed based on a determined equivalent average diameter of 7.1 mm for soybeans. The soybean particle and discrete element simulation model are shown in Fig. 5.

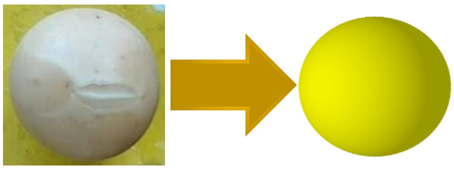


Fig. 5 - Soybean particle and discrete element simulation modeling

Contact Model and Contact Material

Since soybean is a bulk material, particles have no adhesion, and the forces are relatively simple. Therefore, Hertz-Mindlin (no sliding) was chosen as the contact model for the discrete element simulation (*Dun et al., 2022*). When simulating the production process of soybean cleaning or sowing, frequent contact and collisions between particles occur, which is not limited to between soybean particles but also between soybeans and the surrounding wall material. In this paper, acrylic sheets were chosen as the wall material for the study. It has a Poisson's ratio of 0.5, a shear modulus of 1.77 × 108 Pa, and a density of 1180 kg/m^3.

Calibration of contact parameters between spherical soybeans and acrylic sheets

Collision recovery coefficients

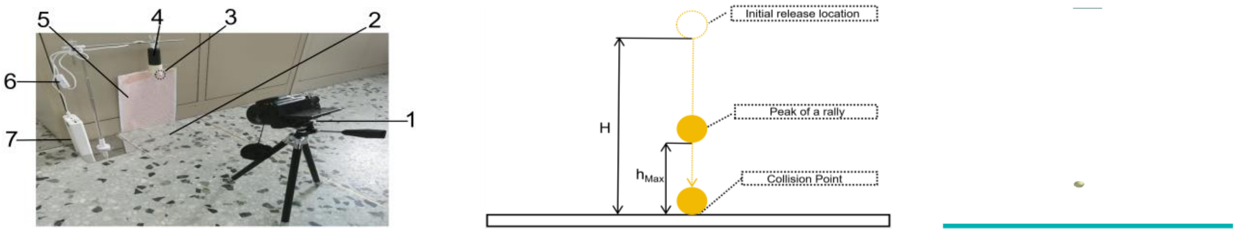
The collision recovery coefficient between soybeans and acrylic sheets was determined using the natural drop method. The experimental equipment required for this method included a high-definition digital camera, grid paper, a vacuum pump, and an acrylic plate. The vacuum pump was switched on to hold the soybean pellets at a height of 250 mm. After the pellets were stabilized, the vacuum pump was switched off and the soybean pellets were subjected to a free-fall motion, with a high-definition digital camera used to record the fall and rebound of the pellets. The recorded video was processed by slow playback and combined with grid paper to measure and record the maximum height of the bouncing of the soybean particles.

Ten soybeans were randomly selected to repeat the above experiment, and the mean value was taken to obtain an average bounce height of 59.93 mm for the soybeans. The measured values were substituted into Eq. (7) to calculate the collision recovery coefficient between the soybeans and the acrylics, which ranged from 0.41 to 0.57.

$$e = \frac{v_1}{v_0} = \frac{\sqrt{2gh_{max}}}{\sqrt{2gH}} = \sqrt{\frac{h_{max}}{H}} \tag{7}$$

where: e is the collision recovery coefficient; V_1 is the pre-collision normal velocity, [m/s]; V_0 is the post-collision normal velocity, [m/s]; h_{max} is the maximum height of bouncing of the soybean after the collision, [mm]; H is the height of the soybean when it is released, [mm].

The static friction coefficient A_2 and rolling friction coefficient A_3 between soybean and acrylic plate, as well as the collision recovery coefficient B1, static friction coefficient B_2, and rolling friction coefficient B3 between soybean particles, do not have a significant effect on the bouncing height of soybeans on the acrylic plate; in order to avoid interference, the simulation experiment can be set to these parameters to 0. Based on the bench experiment, the collision recovery coefficient parameters range between soybeans and the acrylic plate is 0.4 to 0.6, and the setting interval is 0.05. A total of 5 groups of experiments were conducted, each repeated three times, and the average value was taken. The experiment program and results are shown in Table 1. The above bench experiment, principles, and simulations are shown in Fig. 6.



a-Bench experiment *b-Experiment principles schematic* *c-Simulation experiment*

Fig. 6 - Calibration of the collision recovery coefficient between soya beans and acrylic sheets

1. High-Definition Digital Camera; 2. Acrylic Sheet; 3. Soybean Pellet; 4. Vacuum Pump; 5. Grid Paper; 6. Switch; 7 Power Supply.

Table 1

Collision recovery coefficient simulation design of experiments scheme and results

Experiment (group)	e	h_{max} (mm)
1	0.40	46.04
2	0.45	55.63
3	0.50	66.76
4	0.55	79.56
3	0.60	95.04

To demonstrate the relationship between the soybeans' static friction coefficients in Table 2 and the angle of static friction, a quadratic polynomial fit was used to obtain the fitted curves for both, which are shown in Fig. 9. The equation of the fitted curve is given in Eq. (8).

$$h_{max} = 384.28571e^2 - 140.42571e + 40.826 \ (R^2=0.99981) \tag{8}$$

The average value of the maximum bounce coefficient between the soybean and the acrylic plate measured in the bench experiment was 59.93 mm, which was substituted into Eq. (8) to obtain e as 0.474. The value was substituted into the simulation software for validation. The experiment was repeated three times, and the maximum rebound height of the simulation experiment was measured to be 60.83 mm, which had a percentage error of only 1.479 with that of the estimated value of the bench experiment. From this, the collision recovery coefficient e between the soybean and the acrylic plate is 0.474.

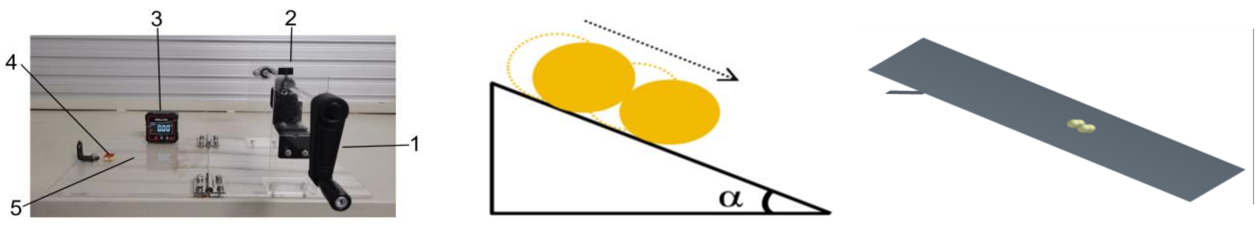
Static friction coefficient

In this experiment, the friction coefficient between soybean particles and acrylic sheets was determined by the inclined plane method with the help of a homemade coefficient of friction experimenting device and high-definition video recording technology. To prevent the rolling of the soybeans, 16 uniformly sized soybeans, four in each group, were selected and glued together following a quadrilateral shape. The equipment was adjusted to a horizontal position for the experiment, and the angle gauge was zeroed. The pellet plate was placed on the device's left plane, the handle was slowly rotated, and a video recording device was used to capture the entire process of the soybean plate from rest to sliding. The video was played slowly to record the angle-measuring device reading as the soybean plate slid. Three trials were repeated for each group of soybean plates, and the average of the angles was taken to give a static friction angle of 26.397° for the soybeans. Substituting the measured angle into Eq. (9), the static friction coefficient between the soybeans and the acrylic plates was found to be 0.38 to 0.56.

$$\mu_s = \frac{F_{smax}}{P} = \frac{mg\sin(\alpha_s)}{mg\cos(\alpha_s)} = \tan\alpha_s \tag{9}$$

where: μ_s is the collision recovery coefficient; F_{smax} is the maximum static frictional resistance between the soybean and the acrylic plate, [N]; P is the positive pressure, the vertically downward force exerted by the soybean particles on the acrylic plate under the action of gravity, [N]; m is the mass of the soybean to have been experimented , [Kg]; and α_s is the static friction angle between the soybean and the acrylic material, [°].

Rolling friction coefficient A_3 between soybean and acrylic plate, as well as the collision recovery coefficient B_1, static friction coefficient B_2, and rolling friction coefficient B_3 between soybean particles, do not have a substantial effect on the angle of static friction α_s between the soybean and the acrylic plate; to avoid interference, the simulation experiment can be set to these parameters to 0. Based on the bench experiment, the static friction parameters range between soybeans and the acrylic plate is 0.35 to 0.6, and the setting interval is 0.05. A total of 6 groups of experiments were conducted, each repeated three times, and the average value was taken. The experiment program and results are shown in Table 2. The above bench experiment, principles, and simulations are shown in Fig. 7.



a Bench experiment *b Experiment principles schematic* *c Simulation experiment*

Fig. 7 - Calibration of the static friction coefficient between soya beans and acrylic sheets
1. Handle; 2. Limit Switch; 3. Angle Gauge; 4. Soybean Plate;5. Acrylic Sheet.

Table 2

Scheme and results of simulation design of experiments for static friction coefficient

Experiment (group)	A_2	α_s [°]
1	0.35	20.22
2	0.40	22.80
3	0.45	24.90
4	0.50	26.16
5	0.55	29.28
6	0.60	31.40

To demonstrate the relationship between the static friction coefficients of the soybeans in Table 2 and the angle of static friction, a quadratic polynomial fit was used to obtain the fitted curves for both, which are shown in Fig.9. The equation of the fitted curve is given in Eq. (10).

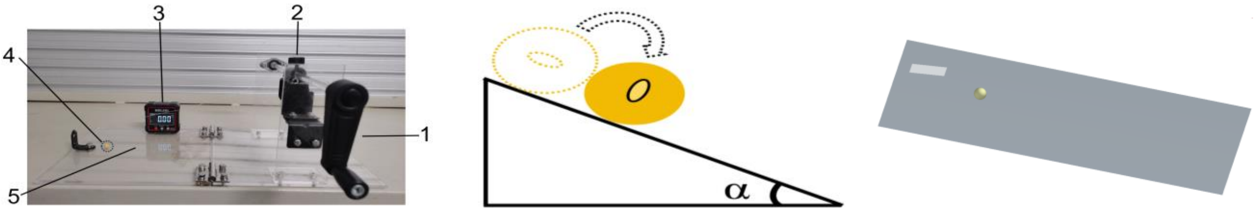
$$\alpha_s = 12.71429{A_2}^2 + 31.69286A_2 + 7.77786 \quad (R^2=0.98647) \tag{10}$$

The average static friction angle between the soybean and the acrylic plate measured in the bench experiment was 26.397°, which was substituted into Eq. (10) to obtain that α_s was 0.474. The value was substituted into the simulation software for validation. The experiment was repeated three times, and the static friction angle α_s of the simulation experiment was measured to be 26.7°, which had a percentage error of only 1.14 compared with that of the estimated value of the bench experiment. From this, the static friction coefficient A_2 between the soybean and the acrylic plate was 0.493.

Rolling friction coefficient

The rolling friction coefficient between the soya bean and the acrylic sheet was still determined using the inclined plane method. Ten uniformly sized soybeans with high sphericity were selected and placed horizontally on the top of the left plane of the friction coefficient experimenting equipment. The handle was slowly rotated, and a high-definition video camera was used to capture the soybean particles from static to rolling. The video was played slowly to record the angle-measuring device reading as the soybean particles rolled. Three trials were repeated for each group of soybean particles, and the average of the angles was taken to give a static friction angle of 2.375° for the soybeans. Substituting the measured angle into $\mu_r = \tan\alpha_r$, the rolling friction coefficient between the soybeans and the acrylic plates was found to be in the range of 0.022-0.063.

Collision recovery coefficient B_1, static friction coefficient B_2, and rolling friction coefficient B_3 between soybean particles have no effect on the rolling friction angle between the soybean and the acrylic plate. To avoid interference, the simulation experiment can be set to these parameters to 0. Based on the bench experiment, the rolling friction coefficient parameters range between soybeans and the acrylic plate is 0.02 to 0.07, and the setting interval is 0.01. A total of 6 groups of experiments were conducted, each repeated three times, and the average value was taken. The experiment program and results are shown in Table 3. The above bench experiment, principles, and simulations are shown in Fig. 8.



a Bench experiment *b Experiment principles schematic* *c Simulation experiment*

Fig. 8 - Calibration of the rolling friction coefficient between soya beans and acrylic sheets
1. Handle; 2. Limit Switch; 3. Angle Gauge; 4. Soybean Pellet; 5. Acrylic Sheet.

Table 3

Scheme and results of dynamic friction coefficient simulation design of experiments

Experiment (group)	A_3	α [°]
1	0.02	1.38
2	0.03	2.28
3	0.04	2.46
4	0.05	3.12
5	0.06	3.66
6	0.07	4.26

To demonstrate the relationship between the rolling friction coefficients of the soybeans in Table 3 and the rolling friction angle, a quadratic polynomial fit was used to obtain the fitted curves for both, which are shown in Fig. 9. The equation of the fitted curve is given in Eq. (11).

$$\alpha_r = -10.71429{A_3}^2 + 55.82143A_3 + 0.37286 \;\; (R^2=0.97259) \tag{11}$$

The average value of the rolling friction angle between the soybean and the acrylic plate measured in the bench experiment was 2.375, which was substituted into Eq. (11) to obtain that α_r was 0.0361. The value was substituted into the simulation software for validation.

The experiment was repeated three times, and the friction angle α of the simulation experiment was measured to be 2.34°, which had a percentage error of only 1.47 with that of the estimated value of the bench experiment. From this, the rolling friction coefficient A_3 between the soybean and the acrylic plate was 0.0361.

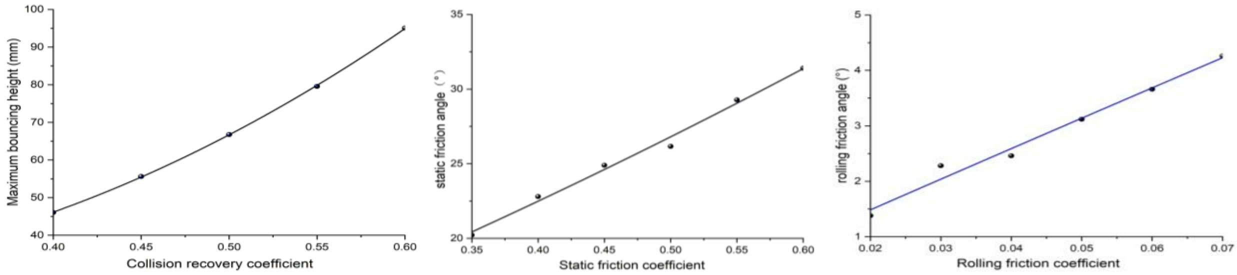


Fig. 9 - Fitted calibration curves for parametric relationships between spheroidal-like soybeans and acrylic plates

RESULTS

Calibration of inter-seed contact parameters in spherical-like soybeans

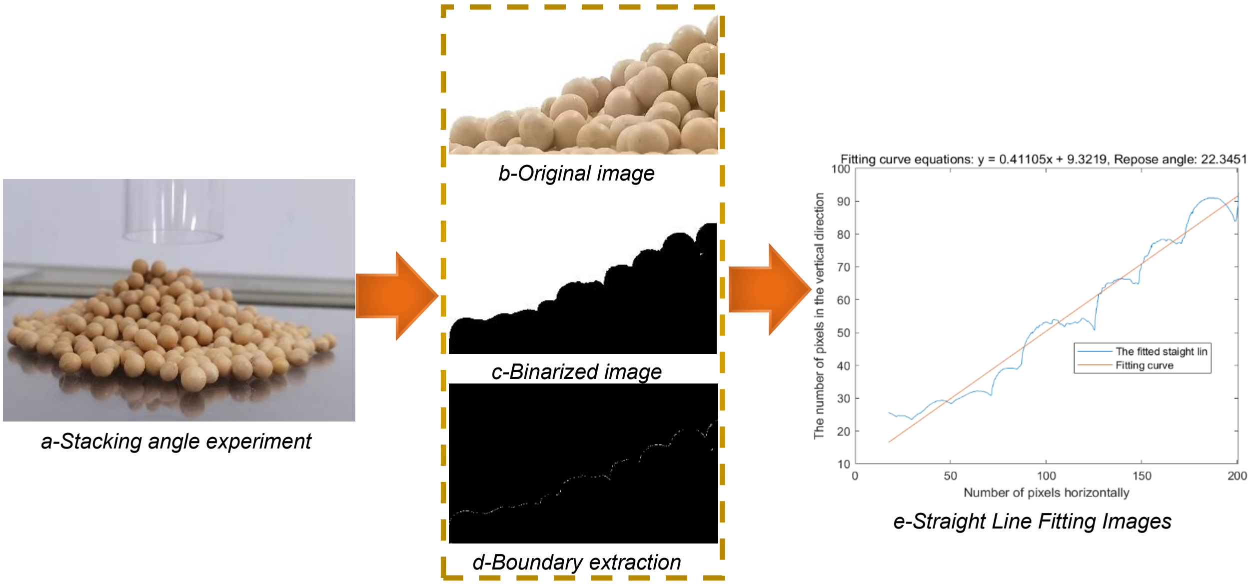
Selection of calibration method

Although the main body of the soybean particles has spherical characteristics, the shape and thickness are not the same; in the determination of the contact parameters between the particles, there may be obstruction, collision, bouncing, and other interferences, resulting in significant differences in the determination of the parameters, which, to a certain extent, will affect the accuracy of the measurement results *(Zhang et al., 2022)*. It was found that the collision recovery coefficient, the static friction coefficient, and the rolling friction coefficient all affect the stacking angle during the falling and molding process. Therefore, this study used a combination of stacking angle simulation experiments and bench experiments to determine the optimal parameter interval for soybean interparticle contact parameters by performing the steepest climb experiment with the contact parameters between particles as variables and the relative errors between measured and simulated stacking angles as indicators. With the help of Design Export 13 software, a regression orthogonal combination experiment was designed to determine the optimal contact parameters between spherical soybean particles through analysis of variance (ANOVA) and objective optimization.

Measured and simulated calibration of stacking angle

Material stacking angle is an essential parameter for measuring powder or granular materials' flow and friction characteristics. The angle of accumulation of soya beans was determined experimentally using the cylinder lifting method. The experiment device consists of a bottomless cylinder and a support plate. According to the regulations, the inner diameter of the acrylic cylinder should be at least 4 to 5 times the diameter of the soybean, and the height should be three times the inner diameter. (*Xu et al., 2023*). Therefore, the cylinder size used for the experiment was 40[mm]×120[mm], and the support plate was 200[mm]×200[mm]×5[mm], both made of acrylic.

A bottomless cylinder filled with soybeans is slowly and uniformly lifted so the soybeans will slowly fall due to gravity, into the acrylic plate to form a pile; at this time the acrylic plate and the soybean pile are formed by the angle of inclination that is the stacking angle. When the cylinder is fully lifted and the stack is shaped to be stationary, the front and side images of the stacked corner are taken in a horizontal position using a high-definition camera. The stacking angle picture is binarized using Matlab software and combined with the least squares method through edge detection to extract the contour curve for fitting. The tangent value of the slope of the fitted curve is the stacking angle. Repeating three experiments to take the average value, the soybean stacking angle was 22.50 degrees. The determination process is shown in Fig.10.



a-Stacking angle experiment; b-Original image; c-Binarized image; d-Boundary extraction; e-Straight Line Fitting Images

Fig. 10 - Bench experiment stacking angle measurement procedure

For the stack angle simulation experiment, the experiment setup was modeled at a 1:1 scale and imported into the Discrete Element Simulation software. The soybean interparticle contact parameters, B_1, B_2, and B_3, used in the simulation were determined as ranges of values based on the General Elemental Materials Database (GEMM) module under the Bulk Materials tab of the Discrete Element Simulation Software, as well as on recently published literature (*Sun et al., 2021; Qu et al., 2024; Dun et al., 2024*). Specifically, B_1: 0.15 to 0.75, B_2: 0.2 to 0.50, and B_3: 0.02 to 0.20. Poisson's ratio, shear modulus, and the contact parameters e, A_2, and A_3 between the soybean and the acrylic sheet material were taken from the above measurements. To facilitate observation and measurement, the appearance of the soybean pile was processed, and then the angle tool that comes with the software was used to measure from the x, y, -x, and -y directions and take the average value; the measurement process is shown in Fig. 11.

a-Measurement of simulated stacking angle; b-Measuring Direction of Simulation

Fig. 11 - Measurement of simulated stacking angle

Steepest ascent experiment

To determine the optimal parameter interval for soybean interparticle contact parameters, the steepest climb experiment was designed using the soybean inter-grain contact parameters B_1, B_2 and B_3 as the experiment factors, and the relative error of stacking angle between the bench experiment and the simulation experiment as the experiment indexes, in conjunction with the range of values of the soybean inter-grain contact parameters obtained as mentioned above. The experiment program and results are shown in Table 4, and the relative error calculation formula is shown in Eq. (12). The experiment results show a tendency for the error to decrease and then increase. According to the magnitude of the error value, The third set of data has the smallest error value, so it can be used as a level 0 test factor for the quadratic orthogonal rotational combination test, while the second and fourth sets of data are used as factor-1 and level 1 test factors, respectively.

$$\delta = \frac{|\theta' - \theta|}{\theta} \tag{12}$$

where:

δ is the relative error of stacking angle;
θ' is the simulated stacking angle, [°];
θ is the measured stacking angle, [°].

Table 4

Steepest ascent experiment and results

Code	Experiment factors			Experiment results	
	Collision recovery coefficient B_1	Static friction coefficient B_2	Rolling friction coefficient B_3	Repose angle θ'[°]	Relative error δ [%]
1	0.15	0.20	0.02	9.25	58.89
2	0.25	0.25	0.05	19.03	15.42
3	0.35	0.30	0.08	23.10	2.67
4	0.45	0.35	0.11	25.59	13.73
5	0.55	0.40	0.14	31.74	41.06
6	0.65	0.45	0.17	35.40	57.33
7	0.75	0.50	0.20	36.66	62.93

Central-Composite experimental design and results analysis

To clarify the optimal combination of the inter-particle contact parameters B_1, B_2, and B_3, a quadratic orthogonal rotational combination experiment was designed using Design Export 13 software, with the range of values of the parameters determined by the steepest ascent experiment as the factors and the simulated stacking angle as the experiment index. The simulation factor level table is shown in Table 5, and the Experiment plan and results are shown in Table 6.

Table 5

Factor level table

Level	Experiment factors		
	Collision recovery coefficient B_1	Static friction coefficient B_2	Rolling friction coefficient B_3
-1.682	0.18	0.22	0.03
-1	0.25	0.25	0.05
0	0.35	0.30	0.08
1	0.45	0.35	0.11
1.682	0.52	0.38	0.13

Table 6

Experiment plan and results table

Code	Experiment factors			Repose angle θ'[°]	Code	Experiment factors			Repose angle θ'[°]
	B_1	B_2	B_3			B_1	B_2	B_3	
1	0.25	0.25	0.05	19.03	11	0.35	0.22	0.08	24.13
2	0.45	0.25	0.05	18.54	12	0.35	0.38	0.08	25.15
3	0.25	0.35	0.05	21.52	13	0.35	0.3	0.03	17.95
4	0.45	0.35	0.05	21.09	14	0.35	0.3	0.13	26.75
5	0.25	0.25	0.11	25.78	15	0.35	0.3	0.08	22.45
6	0.45	0.25	0.11	24.77	16	0.35	0.3	0.08	23.18
7	0.25	0.35	0.11	26.98	17	0.35	0.3	0.08	22.97
8	0.45	0.35	0.11	25.05	18	0.35	0.3	0.08	22.40
9	0.18	0.3	0.08	22.68	19	0.35	0.3	0.08	23.64
10	0.52	0.3	0.08	21.32	20	0.35	0.3	0.08	23.34

The results of the data in Table 6 were analyzed by ANOVA and multiple regression fitting, and the results of the ANOVA are shown in Table 7. The regression equation for the angle of accumulation of soybeans is Eq. (13). From the ANOVA results in Table 7, it can be seen that the model has an extremely significant effect on the stacking angle ($p<0.01$), and the out-of-fit term ($p>0.05$) is not significant, which means that the model has a better fit in this data range. The effect of B_1, B_2, B_3, B_2^2 on stacking angle was highly significant ($p<0.01$), B_2B_3, B_1^2 on stacking angle was significant ($0.01<p<0.05$), and the effect of B_1B_2, B_1B_3, B_3^2 was not significant ($p>0.05$).

The coefficient of determination R^2=0.9807 and the corrected coefficient of determination R^2adj=0.9632, which is close to 1, and the standard deviation is 2.12%, which is a small difference, meaning that the model can be used to accurately respond to the real situation of the stacking angle and its prediction.

$$\theta' = 23.01 - 0.4479B_1 + 0.6213B_2 + 2.73B_3 - 0.1075B_1B_2 - 0.2525B_1B_3 - 0.4450B_2B_3 - 0.3880{B_1}^2 + 0.5875{B_2}^2 - 0.2973{B_3}^2 \quad (13)$$

Table 7

Variance analysis of regression equation

Source of variation	Sum of Squares	Degree of Freedom	Mean Square	F Value	P Value
Model	119.56	9	13.28	56.32	< 0.0001**
B_1	2.76	1	2.76	11.72	0.0065**
B_2	5.07	1	5.07	21.47	0.0009**
B_3	101.36	1	101.36	429.67	< 0.0001**
B_1B_2	0.0924	1	0.0924	0.3919	0.5453
B_1B_3	0.5100	1	0.5100	2.16	0.1722
B_2B_3	1.58	1	1.58	6.72	0.0269*
${B_1}^2$	2.26	1	2.26	9.56	0.0114*
${B_2}^2$	4.27	1	4.27	18.08	0.0017**
${B_3}^2$	1.10	1	1.10	4.65	0.0565
Residual	2.36	10	0.2359		
Lack of fit	1.14	5	0.2276	0.9321	0.5298
Pure error	1.22	5	0.2442		
Sum	121.92	19			

Note: 0.01<p<0.05 (significant effect, *); p<0.01 (highly significant effect, **)

Combination of Optimal Parameters and Verification of Stacking Angle

The objective optimization module of Design-Expert 13 software was applied to optimally solve the regression model Eq. (14) with the inter-soybean contact parameter interval as the optimization variable and the objective of minimizing the relative error value of the measured stacking angle and the simulated stacking angle. The objective and constraint equation conditions are shown below.

$$\begin{cases} \min\theta'(B_1, B_2, B_3) \\ s.t.\begin{cases} 0.18 \le B_1 \le 0.52 \\ 0.22 \le B_2 \le 0.38 \\ 0.03 \le B_3 \le 0.13 \end{cases} \end{cases} \tag{14}$$

Based on the above constraints and objectives, the collision recovery coefficient B_1 of the spherical-like soya bean is obtained as 0.35, the static friction factor B_2 is 0.3, and the rolling friction factor B_3 is 0.074.

To check whether the obtained soybean contact parameters B_1, B_2, and B_3 are accurate and reliable, the optimized optimal parameter combinations are verified for the stacking angle. The experiment was repeated five times, and the average value of the simulated stacking angle was 22.26°, with an average relative error of only 1.09% from the bench experiment stacking angle of 22.5°, which is in high agreement and proves that the simulation parameters and results obtained are authentic and valid. Stacking angle test simulations, as shown in Figure 12, and a summary of the results of the above simulations are shown in Table 8.

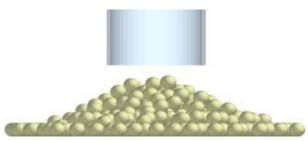


Fig. 12 - Experimental simulation of stacking angle

Table 8

Analysis of the simulation experiment

Code	Repose angle θ'[°]	Relative error δ [%]
1	22.16	1.64
2	22.38	0.53
3	22.45	0.22
4	22.23	1.20
5	22.08	1.86

CONCLUSIONS

（1）Aiming at the lack of simulation parameters for spherical soybeans in the application of discrete element simulation to guide the optimization and design of agricultural machinery and equipment, this paper calibrates the parameters of spherical soybean variety SN29. The intrinsic properties of the material were determined by means of actual measurements, and a simulated particle model with a particle size of 7.1 mm was established based on the measured parameters.

（2）The collision recovery coefficients, Static friction coefficient, and rolling friction coefficient between the spherical soybean and the acrylic sheet were measured using the natural fall method and the inclined plane method through a combination of bench experiments and simulation experiments and were 0.474, 0.496 and 0.0361, respectively.

（3）The frontal and lateral stacking angles between the spheroidal soybeans and the acrylic panels were measured by the cylinder lift method in combination with a high-definition video camera and Matlab software, and the combined stacking angle was calculated to be 22.5°. The steepest climb experiment was designed to determine the optimum range of contact parameters between spherical-like soybean particles. With the help of Design-Expert 13 software, the parameter ranges obtained from the steepest climb experiment were used as variables. The simulated stacking angle was used as an index to design a three-factor, five-level quadratic orthogonal rotary combination experiment, and the results were optimized and analyzed and the ANOVA table and regression equation of the influencing factors and stacking angle were obtained. Through further optimization of the solution, the spherical-like optimal collision recovery coefficient between soybean particles was 0.35, the static friction coefficient was 0.3, and the rolling friction coefficient was 0.074.

（4）For the optimal parameter combinations obtained, the stacking angle verification experiments were carried out, and the relative error between the simulated stacking angle and the measured stacking angle was only 1.09 %. It shows that the calibration parameters have high credibility, which can provide a parameter basis for the design optimization and discrete element simulation of spherical soybean agricultural equipment.

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