SIMULATION PARAMETER CALIBRATION AND TEST OF PAK CHOI SEEDS BASED ON DISCRETE ELEMENT METHOD

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基于离散元的小白菜种子仿真参数标定与试验

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ABSTRACT

Physical property parameter measurements and simulation model parameter calibrations of Pak Choi seeds were conducted to address the lack of accurate parameters for discrete elemental seed discharging simulation tests in the seed-metering device. Firstly, physical tests were utilized to determine the basic physical parameters and contact parameters of Pak Choi seeds. The results of these physical tests served as the basis for determining the range of simulation parameters. The Plackett-Burman test was employed to screen out factors that significantly affected the simulated angle of repose from the test parameters, including static friction coefficient between Pak Choi seeds-Pak Choi seeds and rolling friction coefficient between Pak Choi seeds-Pak Choi seeds. The optimal interval of these two factors was determined using the Steepest Climb Test. Subsequently, the regression equation between the significance parameters and the angle of repose was obtained through the Central Composite Designs test, and the best parameter combinations were obtained with the measured stacking angle of 24.3° as the optimisation target value: Pak Choi seeds-Pak Choi seeds static friction coefficient of 0.486, Pak Choi seeds-Pak Choi seeds rolling friction coefficient of 0.104. Finally, simulation and bench comparison tests were carried out for stacking angle and Pak Choi seed discharger performance evaluation. The relative error of the angle of repose was found to be 0.288%, while average relative errors for qualified sowing rate, replanting rate, and missed sowing rate were all less than 5%. These results demonstrate that calibrated Pak Choi seed simulation parameters are reliable and can serve as a reference for design optimization of Pak Choi seed dischargers in academic research writing standards.

摘要

针对小白菜种子在排种器中进行离散元排种仿真模拟试验缺乏准确参数，对小白菜种子进行物性参数测量及仿真模型参数标定。首先，采用物理试验测定小白菜种子的基本物性参数及接触参数，以物理试验结果为基础，确定仿真参数范围，利用Plackett-Burman试验从各组试验参数中筛选出对堆积角影响显著的因素：小白菜种子-小白菜种子静摩擦系数、小白菜种子-小白菜种子滚动摩擦系数，并进一步通过最陡爬坡试验确定两因素最优区间。再通过二次通用旋转组合试验得到显著性参数与堆积角之间得回归方程，并以实测堆积角24.3°为优化目标值获得最佳参数组合：小白菜种子-小白菜种子间静摩擦系数0.486、小白菜种子-小白菜种子间滚动摩擦系数0.104。最后，开展了堆积角对比试验及小白菜排种器的仿真与台架对比试验，得到堆积角的相对误差为0.288%，排种器的合格率、重播率、漏播率的平均相对误差小于5%。由此表明，标定的小白菜种子仿真参数具有可靠性，可为小白菜排种器的设计优化提供参考。

INTRODUCTION

Pak Choi, an annual or biennial plant of the genus Brassica, it is widely loved for its rich nutritional elements and certain medicinal values. In recent years, the planting area of Pak Choi has been increasing year by year in China, the traditional artificial seeding method and the existing seeding equipment have been unable to meet the production needs of Pak Choi, to promote the high efficiency of mechanized Pak Choi seeding device is imminent. The seed-metering device is the core component of seeding machinery *(Wang et al., 2023; Song et al., 2023)*, and the interaction forces between seed populations and between seeds and the discharger are very complex during the working process. To study the mechanical precision seed discharger suitable for sowing Pak Choi seeds, the EDEM software based on the discrete element theory can be used to simulate the seeding process in the seed-metering device and analyze the movement law of Pak Choi seeds in the seed discharger, to provide a reference for the design and optimization of the seed-metering device

(Zeng et al., 2021). Due to the irregular shape of Pak Choi seeds, the direct simulation with the calibrated spherical particle parameters in EDEM software may result in a large error with the physical test results, therefore, discrete element simulation parameters need to be calibrated for Pak Choi seeds.

In recent years, many scholars at home and abroad have studied the calibration of simulation parameters based on discrete elements for agricultural materials such as maize seeds, *Cucurbita ficifolia seeds, Adzuki Bean Seeds, Agropyron seeds, Panax notoginseng Seed sand white radish seed*. *Chen et al., (2018)* used a multi-sphere model (MS) approach to establish a single seed model of maize seeds based on the physical properties of seeds of different shapes, such as horse-tooth and spherical-cone, and verified the feasibility and validity of the particle ensemble of maize seeds and the individual seed particle modelling approach. *Ding et al., (2023)* used response surface method (RSM) and machine learning were utilized for optimization inversion of the parameters, calibration of parameters for discrete element simulation of *Cucurbita ficifolia* seeds was completed. *Liu et al., (2022),* samples were used to determine the DEM parameters of *Adzuki Bean Seeds* using a combination of physical tests and virtual calibration. *Hou et al., (2020),* used a combination of physical and simulation tests to calibrate and align the discrete elemental simulation parameters of *Agropyron seeds*. *Yu et al., (2020)*, used reverse engineering technology to establish a discrete elemental model of Panax quinquefolium seeds in EDEM software based on the bonded particle model and calibrated the optimal contact parameters between Panax quinquefolium seeds and ABS plastics by combining bench tests and simulation tests. *Yan et al. (2022)*, created a discrete elemental model of radius white radish seeds using multiball bonding, and analyzed the optimal ball particle filling radius of white radish seeds by combining the relative error rate of stacking angle with the simulation time. In summary, the discrete element method is widely used in the simulation parameter calibration of agricultural material particles, but there are fewer discrete element simulation parameter calibrations for spherical small-size seeds such as Pak Choi seeds.

In this study, based on the discrete element simulation calibration method for agricultural material particles at home and abroad, the basic physical property parameters and contact parameters of Pak Choi seeds were measured by physical tests, using the simulated angle of repose of Pak Choi seeds as the test index and the physical property parameters as the test factors, the most significant test factors were screened out by the Plackett-Burman test, and the steepest climb test was conducted to select the optimal value region for the screened out significant test factors, then the optimal parameter combination is determined by the secondary generalized rotary combination test, and the determined discrete element simulation calibration parameters are subjected to simulation test to verify the discrepancy with the physical test, to provide a reference for the design and simulation study of the mechanical precision seed-metering device for Pak Choi.

MATERIALS AND METHODS

Determination of material properties of Pak Choi seeds

Measurement of triaxial dimensions and mass

The test selected Jinyu Shenghui four-season Pak Choi seeds widely planted in the northeast region as the object to measure experimental research, to reduce seed error and improve the accuracy of the measurement, from 50 g of Pak Choi seeds randomly selected 100 Pak Choi seeds for measurement, a way to ensure that the measurement of the size and quality of the seed has randomness. The length (L), width (W), and height (H) of each seed were measured and recorded in three directions using the Airex three-button electronic digital vernier calipers (accuracy of 0.01 mm), as shown in Figure 1. UTP-313 electronic balance scale (accuracy of 0.001 g) was used to repeat the measurement of 100 seeds 10 times record the data each time and take the average value.

Fig. 1 - Triaxial dimensional measurement of Pak Choi seed

The data were statistically organized to give a mean value of 1.74 mm with a standard deviation of 0.12 mm for the length of Pak Choi seeds, 1.63 mm with a standard deviation of 0.10 for the width, 1.53 mm with a standard deviation of 0.11 for the height, and a mean value of about 0.0025 g for the seed mass. The length, width, and height size distribution statistics of Pak Choi seeds are shown in Figure 2, all of which are normally distributed, and the overall shape of the seeds is similar to that of a sphere. Based on the seed length, width, and height, the equivalent diameter, sphericity, and volume of the Pak Choi seeds are calculated by applying Equations (1), (2), and (3).

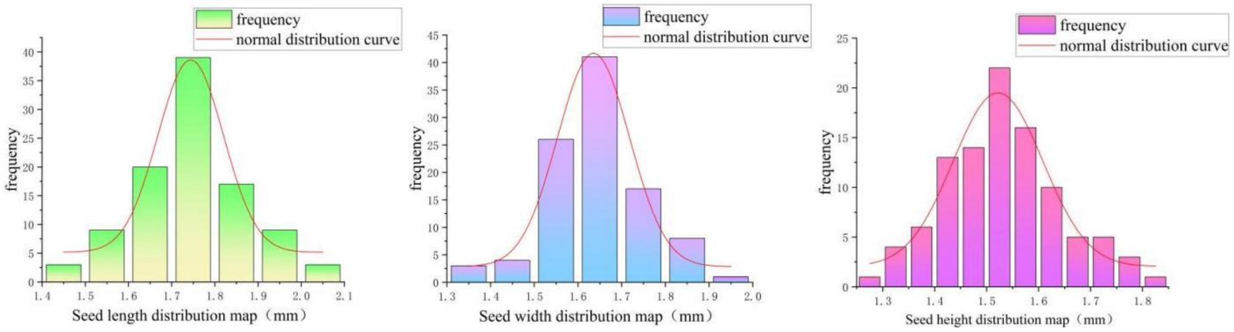
$$D_e = \sqrt[3]{LWH} \tag{1}$$

$$S_P = \frac{D_e}{L} \times 100\% \tag{2}$$

$$V = \frac{4}{3}\pi lwh \tag{3}$$

where: L, W, H is the length, width, height of Pak Choi seeds, mm; D_e is the equivalent diameter of Pak Choi seeds, mm; S_P is the sphericity of Pak Choi seeds, %; V is the volume of Pak Choi seeds, mm^3; l, w, h is the semiaxis of the length, width, and height of Pak Choi seeds, mm.

The equivalent diameter of Pak Choi seeds was calculated to be about 1.63 mm, the sphericity was about 93.7%, and the mean value of the volume was about 2.262 m4m^3.



(a)Seed length distribution map (b) Seed width distribution map (c) Seed height distribution map

Fig. 2 - Seed triaxial size and volume distribution diagram

Density and moisture content measurement

To measure the density of Pak Choi seeds by the immersion method *(Du et al., 2023)*, 10g of Pak Choi seeds were randomly weighed using a UTP-313 electronic balance scale with an accuracy of 0.001 g, 40 ml of pure water was injected into a measuring cylinder with a range of 100 ml, and 10 g of weighed seeds were placed into the measuring cylinder, and the volume of the horizontal plane of the cylinder at this point in time was recorded as V_2. Substituting into Equation (4), the density of the Pak Choi seeds was calculated. Repeat the test 5 times and take the average. Repeat the test 5 times, take the average value of 1.082 g/cm^3 for the density of Pak Choi seeds.

$$p = \frac{m}{V_2 - V_1} \tag{4}$$

where: p is the density of Pak Choi seeds, g/cm^3; m is the addition of the mass of Pak Choi seeds, g; V_1 is the volume of pure water injected into the cylinder, cm^3; V_2 is the volume of the cylinder after the addition of seeds, cm^3.

The drying method was used to measure the water content of Pak Choi seeds, 10 g of Pak Choi seeds were randomly weighed using an electronic balance scale with an accuracy of 0.001 g, placed in a drying oven with the temperature set to 105°C, and dried continuously for 8 hours, and the seeds were cooled in the drying oven and taken out to be weighed again and recorded, substituting the mass of the seeds before drying m_a and the mass of the seeds after drying m_b into the Equation (5) the water content of the seeds was calculated to be 7.82%.

$$M_C = \frac{m_a - m_b}{m_a} \times 100\% \tag{5}$$

where: m_c is the moisture content of Pak Choi seeds, %; m_a is the mass of Pak Choi seeds before drying, g; m_b is the mass of Pak Choi seeds after drying, g.

Fig. 3 - Moisture content testing device

Poisson's ratio

Poisson's ratio is an elastic constant reflecting the lateral deformation of the material. Due to the small Pak Choi seeds and thin seed coat, the pressure deformation test was used to measure the Poisson's ratio of Pak Choi seeds. 10 Pak Choi seeds were randomly selected, the electronic digital vernier calipers was used for each seed length, thickness was measured and data were recorded. The universal pressure testing machine was used to measure the entire seed along the thickness of the seed to apply pressure, when the surface of the seed ruptured, applying pressure was immediately stopped. The deformation of the seed thickness direction was recorded, the electronic digital vernier calipers was used to measure the deformation of the seed length direction, the Poisson's ratio of Pak Choi seeds was calculated according to the Equation (6). The test was repeated 10 times to take the average value of 0.342 for the Pak Choi seeds Poisson's ratio.

$$u = \left|\frac{g'}{g}\right| = \left|\frac{y_1 - y_2}{b_1 - b_2}\right| \tag{6}$$

where: u is the Poisson's ratio of Pak Choi seeds; g' is the deformation in the length direction of Pak Choi seeds; g is the deformation in the thickness direction of Pak Choi seeds; y_1 is the length of Pak Choi seeds before being pressed, mm; y_2 is the length of Pak Choi seeds after being pressed, mm; b_1 is the thickness of Pak Choi seeds before being pressed, mm; b_2 is the thickness of Pak Choi seeds after being pressed, mm.

Determination of modulus of elasticity and shear modulus

The compression method was used to measure the modulus of elasticity and shear modulus of the seeds, using electronic digital display vernier calipers to randomly measure the thickness of 10 Pak Choi seeds, placing the seeds with the measured thickness horizontally on the pressure tester, applying pressure in the direction of the thickness of the Pak Choi seeds and recording the compression pressure-displacement data of the seeds during compression, and deriving the modulus of elasticity of the Pak Choi seeds according to Equation (7). The modulus of elasticity of Brassica juncea seeds was obtained as 4.56×10^7Pa by repeating the test 10 times and taking the average value.

$$E = \frac{z}{g} \tag{7}$$

where: E is the modulus of elasticity of Pak Choi seeds, Pa; z is the maximum compressive stress, Pa; g is the linear strain of Pak Choi seeds.

The shear modulus of Pak Choi seeds was calculated according to Equation (8), and the shear modulus of Pak Choi seeds was obtained to be 1.66×10^7Pa.

$$C = \frac{E}{2(1+u)} \tag{8}$$

where: C is the shear modulus of Pak Choi seeds, pa; u is the Poisson's ratio of Pak Choi seeds.

Measurement of Static friction coefficient

Measurement of the static friction coefficient between Pak Choi seeds and PLA material was carried out by the inclined plane sliding method *(Xu et al., 2023)*, and the test device used was a homemade static friction angle measuring device made from PLA material, which had a length, width, and height of 150mm×80mm×20mm. In determine the coefficient of static friction between the Pak Choi seeds and the PLA material, because the Pak Choi seeds are bulk materials with small size and easy to tumble. In order to prevent Pak Choi seeds from tumbling, the inclined plane test was carried out by 4 Pak Choi seeds were glued together to form a Pak Choi seeds group, with reference to the relevant literature (*Wang et al., 2022; Zhou et al., 2018*), as shown in Figure 4a. Turning the rocking handle, so that the PLA plate end of the placed seeds is slowly and uniformly elevated,When the seed slides downward on the inclined PLA plate, immediately stop the rotation of the rotor shaft, the inclined PLA plate will be fixed and the use of electronic protractor to measure the angle α between the inclined plane and the horizontal plane, and then use the Equation (9) to calculate the coefficient of static friction between the Pak Choi seeds and the PLA plate.

$$u_g = tan\,\alpha \tag{9}$$

where: u_g is the coefficient of static friction indicated; α is the angle of sliding friction.

The static friction coefficient of between Pak Choi seeds was also determined by the inclined plane method, in order to more accurately measure the coefficient of static friction between Pak Choi seeds, the test seeds were made into seed boards with adhesive and pasted on the test plane of measuring device, so that the cabbage seeds could be arranged as closely as possible, as shown in Figure 4b. Place the Pak Choi seeds group on the Seed board, slowly turn the Rocking handle until the Pak Choi seeds group appears to slide on the seed board, stop rotating and record the inclined plane angle at this time. The experiments were repeated for 10 times in each group, and the average value was obtained. The average value of static friction coefficient between Pak Choi seeds and PLA material was 0.46, and the average value of static friction coefficient between Pak Choi seeds was 0.52.

a) measuring device *b) Pak Choi Seeds board* *c) Test Schematic Diagram*

Fig. 4 - Test for determination of static friction coefficient between seeds

1. PLA plate; 2. Rocking handle; 3. Pak Choi seeds group; 4. Rack

Measurement of rolling friction coefficient

The rolling friction coefficient between Pak Choi seeds and PLA material as well as between Pak Choi seeds was determined using the inclined rolling method. The test setup for determining the rolling friction coefficient between seeds and PLA material consisted of two plates made of PLA material, with one of the plates inclined at 30°. The Pak Choi seed is placed at a fixed height b = 0.075 m, θ = 30° inclined plate, the Pak Choi seed is released with an initial speed of 0, the seed rolls along the inclined plate to the PLA horizontal panel and comes to rest. The rolling distance T of the Pak Choi seed on the PLA horizontal panel is measured and recorded, the schematic diagram is shown in Figure 5, the rolling friction coefficient between Pak Choi seeds and PLA material can be obtained by applying equation (10). Determination of the rolling friction coefficient between Pak Choi seeds and Pak Choi seeds test method is the same as above, the test device will be replaced by two PLA boards for two pieces of Pak Choi seeds plate.

The average coefficient of rolling friction between Pak Choi seeds and PLA material as well as the Pak Choi seeds was 0.163 and 0.098, respectively, after 10 times repeated tests.

$$mg \cdot sin\theta \times b = u_s mg(cos\theta \times b + T) \tag{10}$$

where: u_s is the rolling friction coefficient; m is the mass of Pak Choi seeds, kg; g is the gravitational acceleration of the seeds, m; α is the inclination angle of the inclined plane, m/s^2; b is the rolling length of the inclined plane, m; T is the rolling length of the horizontal plane, m.

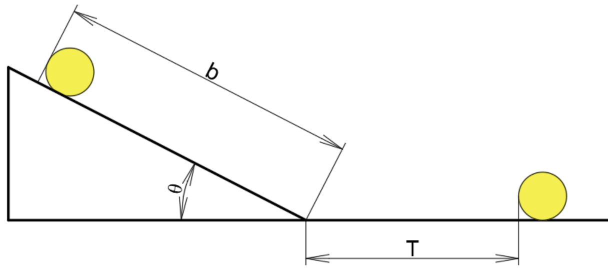


Fig. 5 - Schematic diagram of inclined plane rolling friction test measurement

Determination of Collision Recovery Coefficient

The collision recovery coefficient is the ratio of the normal relative separation velocity to the normal relative approach velocity at the contact point of the two objects before and after the collision *(Xie et al., 2022)*, which is an important parameter for EDEM software simulation and has a relatively large impact on the qualification rate of the seed-metering device. The collision bounce test was used to determine the collision recovery coefficients between Pak Choi seeds and PLA materials and between Pak Choi seeds, the test setup has a computer, scale, coordinate grid paper, PLA board, high-speed camera, the PLA board was placed horizontally on the desktop, and the coordinate grid paper was pasted on the wall using tape to make a backdrop, as shown in Figure 6.

Fig. 6 - Collision restitution coefficient measurement test

1. Computer; 2. Scale; 3. Grid paper; 4. PLA material; 5. High-speed photography camera.

In the Pcc3.7 software, the number of frames is set to 2500 frames, and a seed is released from the height of H_r=250mm to fall freely, and the high-speed camera is controlled to record the whole motion process of the seed falling on the PLA plate and rebounding, and the principle is shown in Figure 7. The maximum rebound height h_r of the collision of the Pak Choi seeds on the PLA plate reflected in the coordinate grid paper was intercepted and the data were recorded. Applying Equation (11), the coefficient of recovery of collision between Chinese Pak Choi seeds and PLA material was calculated.

To determine the coefficient of recovery of collision between Pak Choi seeds, the PLA material plate was replaced with a Pak Choi seed plate placed horizontally on the tabletop, and the test method was the same as above. The test was repeated 10 times to obtain the average rebound height of Pak Choi seeds on PLA material at h=56 mm and on Pak Choi seed plates at h=22 mm, the collision recovery coefficient between the Pak Choi seeds and PLA material as well as the Pak Choi seeds 0.473, 0.297.

$$e = \frac{v_t}{v_0} = \sqrt{\frac{h_r}{H_r}} \tag{11}$$

where:

e is the collision recovery coefficient; v_t is the normal relative approach velocity before the collision, m/s; v_0 is the normal relative separation velocity after the collision, m/s; h_r is the maximum height of the seed rebound, mm; H_r is the initial height of the seed drop, m.

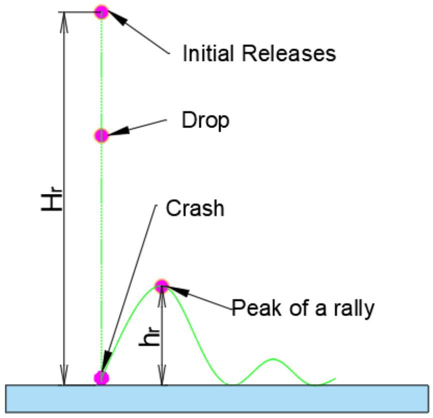


Fig. 7 - Schematic diagram of the collision recovery coefficient determination test

Material angle of repose Test

The material angle of repose reflects the friction characteristics and scattering performance between seeds and seeds, which is related to the physical properties of the contact materials and seeds, and its calibration can effectively reflect the reasonableness and reliability of the seed friction characteristics parameters. This test uses the funnel method to measure the material pile *(Liu et al., 2020; Gong et al., 2021)*, and the test device uses a homemade angle of repose tester. Use the baffle plate to block the lower drop port, pour 15g of Pak Choi seeds into the upper funnel at a uniform speed, open the baffle plate quickly, the seeds fall freely and form a seed pile on the bottom disk, and wait until the seed pile is completely stationary, use an electronic protractor to measure the angle between the right half of the taper and the base plate, as shown in Figure 8. At the same time, in order to reduce the error that exists in the human measurement of the angle of repose, an image processing method was used to analyze the test photos, the frontal image of the seed pile was captured with a high-definition camera, and the image of the right side of the seed pile was grayscale processing, binarization processing, the extraction of the image boundary pixel points and the boundary pixel points were fitted by MATLAB, and the angle of the fitted straight line with the horizontal plane is the physical angle of repose of the Pak Choi seeds, as shown in Figure 9. The test was repeated 10 times to take its average value, and the angle of repose was obtained as 24.3°.

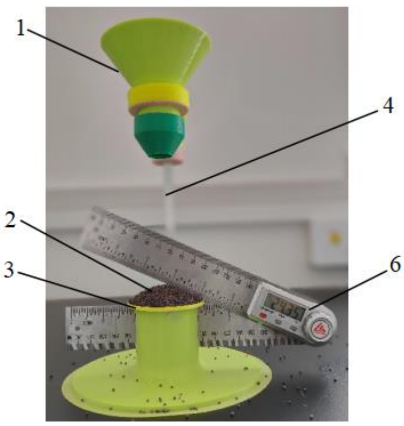
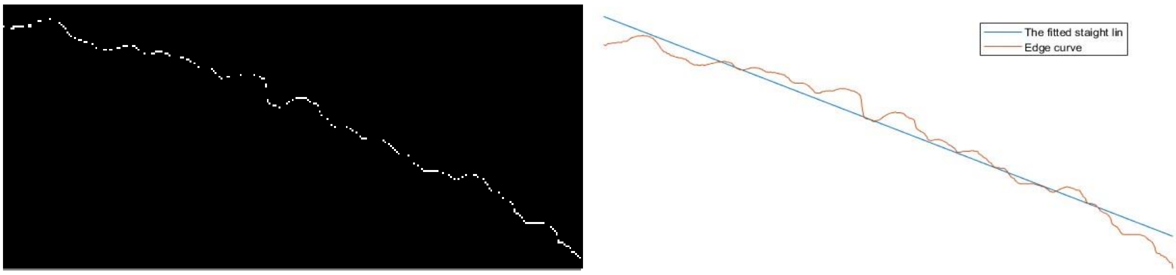


Fig. 8 - Angle of repose determination test

1. Funnel; 2. Pak Choi seeds; 3. Brackets; 3. Base support; 5. Digital Angle Measuring Ruler

a. The right half image of the seeds pile

b. Binary image



c. Edge detection image *d. Linear fit chart*

Fig. 8 - Image processing of Pak Choi seeds pile

Discrete element modelling and simulation parameter calibration

<u>Pak Choi seeds simulation modeling</u>

To make the simulation model of seeds closer to the size and shape of the actual seeds, the basic physical properties data of Pak Choi seeds were obtained through the preliminary physical test measurements, using SolidWorks 3D modeling software, according to the shape of the seeds as well as the average of the three-axis dimensions of the modeling, the 3D model of the seeds was saved as an stl file format, and the seed model was imported into the EDEM software, the discrete element simulation model of Pak Choi seed was established by using the method of spherical particle polymerization filling model, shown in Figure 10.

Fig. 10 - Pak Choi seeds granules and their discrete element models

<u>Material angle of repose simulation test</u>

The angle of repose simulation test was carried out using EDEM software, as shown in Figure 11, and the contact parameters between seed populations and between seeds and PLA materials were set up in EDEM software by combining the pre-measured data on the physical properties of Pak Choi seeds. Since the surface of Pak Choi seeds is smooth and has no adhesion, the Hertz-Mindlin no-contact model was chosen for the simulation contact model. At the same time, the same geometric model of the measuring device as the bench test measuring device was imported into the EDEM software, and the material was set to PLA material. A virtual plane was established above the funnel to generate a total amount of 30g seed model, and the generation time was set to 1 second. To ensure the continuity of the simulation test, the time step was set to $3.44244e\times10^{-6}$ s, the total simulation time was 6s, and the virtual simulation test was the same as the bench test.

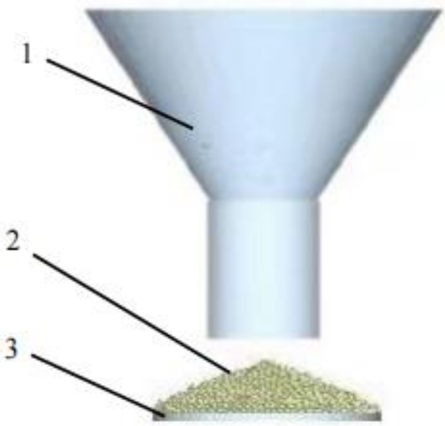


Fig. 11 - Angle of repose simulation test

1. Funnel; 2. Pak Choi seeds; 3. Chassis.

RESULTS

Plackett-Burman Test

Design-Expert 10.0 software was applied to carry out the Plackett-Burman experimental design to screen out the experimental factors that had significant effects on the seed angle of repose of Pak Choi using the seed angle of repose of Pak Choi as the experimental index *(Bai et al., 2022)*.

A-H is taken to indicate the actual test factors, respectively, and +1 indicates a high level and -1 indicates a low level in each test factor. Based on the measured values of the previous physical tests, the range of values of each test factor was determined as shown in Table 1.

The experimental design scheme is shown in Table 2, and a total of 12 groups of tests were designed, and the angle of repose of each group of tests was simulated by EDEM software.

Table 1

Plackett-Burman test parameter table

Serial number	Experimental factors	Low level (-1)	High Level（+1）
A	Poisson's ratio of Pak Choi seeds	0.24	0.53
B	Shear modulus of Pak Choi seeds / Pa	1.2×10^7	3.8×10^7
C	Pak Choi seeds - Pak Choi seeds collision recovery coefficient	0.24	0.56
D	Pak Choi seeds - Pak Choi seeds rolling friction coefficient	0.083	1.24
E	Pak Choi seeds - Pak Choi seeds static friction coefficient	0.36	0.71
F	Pak Choi seeds - PLA plastic collision recovery coefficient	0.45	0.88
G	Pak Choi seeds - PLA plastic rolling friction coefficient	1.43	1.92
H	Pak Choi seeds - PLA plastic static friction coefficient	0.28	0.53

Table 2

Packett-Burman test protocol and results

Serial number	A	B	C	D	E	F	G	H	Angle of repose / °
1	1	1	-1	1	1	1	-1	-1	26.65
2	-1	1	1	-1	1	1	1	-1	25.97
3	1	-1	1	1	-1	1	1	1	28.12
4	-1	1	-1	1	1	-1	1	1	27.76
5	-1	-1	1	-1	1	1	-1	1	22.46
6	-1	-1	-1	1	-1	1	1	-1	27.22
7	1	-1	-1	-1	1	-1	1	1	22.52
8	1	1	-1	-1	-1	1	-1	1	14.48
9	1	1	1	-1	-1	-1	1	-1	18.97
10	-1	1	1	1	-1	-1	-1	1	24.86
11	1	-1	1	1	1	-1	-1	-1	31.92
12	-1	-1	-1	-1	-1	-1	-1	-1	17.56

The analysis of variance (ANOVA) of the test results was performed by Design-Expert software to obtain the significance results of each test parameter on the angle of repose of the test indexes, as shown in Table 3. In the ANOVA table, the p-value is used to assess the extent to which each test factor affects the test metrics, i.e., to measure whether the effects of different test factors on the results are statistically significant.

As can be seen from Table 3, the P-value of the rolling friction coefficient (D) and the static friction coefficient (E) of Pak Choi seeds - Pak Choi seeds is less than 0.01, indicating that the effect on the angle of seed stacking is highly significant, and the P-value of the collision recovery coefficient (C) of Pak Choi seeds - Pak Choi seeds is less than 0.05 on the angle of repose is significant, while the other test factors are greater than 0.5, and the effect on the angle of repose is not significant.

Table 3

Significance analysis of test parameters

Source	Sum of squares	Degree of freedom	Mean square	F number	P value
Model	273.82	8	34.23	25.81	0.0110*
A	0.84	1	0.84	0.63	0.4849
B	10.29	1	10.29	7.76	0.0687
C	21.63	1	21.63	16.31	0.0273*
D	165.54	1	165.54	124.84	0.0015**
E	56.64	1	56.64	42.71	0.0073**
F	0.14	1	0.14	0.11	0.7642
G	13.29	1	13.29	10.02	0.0506
H	5.45	1	5.45	4.11	0.1356

*Note: ** indicates highly significant effect ($p<0.01$), * indicates significant effect ($0.01<p<0.05$).*

Steepest Climb Test

The steepest climb test was conducted based on the highly significant parameters of rolling friction coefficient between Pak Choi seeds-Pak Choi seeds (D) and static friction coefficient between Pak Choi seeds-Pak Choi seeds (E) screened by the Plackett-Burman test as a quick way to determine the optimal region of each significant factor relative to the test index. The relative error between the actual angle of repose and the simulated angle of repose was used as the test index, and D and E were used as the test factors. In the EDEM software angle of repose simulation experiments, the rolling friction coefficient between Pak Choi seeds-Pak Choi seeds was selected as 0.083-0.124, the static friction coefficient between Pak Choi seeds-Pak Choi seeds was selected as 0.36-0.72, and all other non-significant factors were used as the average values of physical tests. The results of the steepest climb test design are shown in Table 4. The results show that the relative error of the 3 sets of simulation tests is minimized, which shows that the optimal interval is near the 3 sets of tests. Therefore, the Pak Choi seeds-Pak Choi seeds static friction coefficients of 0.43-0.57 and the Pak Choi seeds-Pak Choi seeds rolling friction coefficients of 0.091-0.107 were selected as the range of test factor levels for the subsequent Central Composite Designs test.

Table 4

The steepest climbing test design scheme and results

Serial number	Pak Choi seeds - Pak Choi seeds static friction coefficient	Pak Choi seeds - Pak Choi seeds rolling friction coefficient	Angle of repose / (°)	Relative error / %
1	0.36	0.083	19.75	18.72
2	0.43	0.091	22.37	8.65
3	0.50	0.099	23.46	3.45
4	0.57	0.107	25.63	5.47
5	0.63	0.115	29.95	23.25
6	0.72	0.124	32.83	32.7

Central Composite Designs test

Test Methods

After obtaining the optimal range of intervals for the significant factors through the steepest climb test, the optimal parameter combinations for the static friction coefficient and rolling friction coefficients between Pak Choi seeds-Pak Choi seeds in the simulation test were obtained for the further development of Pak Choi seeds. Using the simulated angle of repose as the test index, the two-factor, five-level Central Composite Designs test was conducted using Design-Expert software and EDEM software, and the simulation factor coding table is shown in Table 5.

Table 5

Factor level coding table

Level	Pak Choi seeds - Pak Choi seeds static friction coefficient	Pak Choi seeds - Pak Choi seeds rolling friction coefficient
1.414	0.57	0.107
1	0.55	0.105
0	0.5	0.099
-1	0.45	0.093
-1.414	0.43	0.091

The experimental design scheme and simulation results are shown in Table 6.

Table 6

Experimental design and results

Serial number	Pak Choi seeds - Pak Choi seeds static friction coefficient / A	Pak Choi seeds - Pak Choi seeds static friction coefficient / B	Angle of repose β / °
1	-1	-1	21.43
2	1	-1	24.03
3	-1	1	24.53
4	1	1	27.63
5	-1.414	0	22.28
6	1.414	0	26.64
7	0	-1.414	21.46
8	0	1.414	25.75
9	0	0	23.63
10	0	0	23.11
11	0	0	22.93
12	0	0	24.07
13	0	0	21.26

Angle of repose analysis of variance

Multiple regression was fitted to the experimental data (Table 6) using the software Design-Expert software 10.0, and the results of the analysis of variance of the regression model were obtained, as shown in Table 7. The results show that the p-value of the model is less than 0.01, indicating that the regression model is extremely significant. The P-values of A (static friction coefficient between Pak Choi seeds-Pak Choi seeds) and B (rolling friction coefficient between Pak Choi seeds-Pak Choi seeds) were both less than 0.01, indicating that the effect on angle of repose was extremely significant. The P-value of A^2 (quadratic term of coefficient of static friction between Pak Choi seeds-Pak Choi seeds) was less than 0.05, indicating a significant effect on angle of repose, while the P-values of the other factors were greater than 0.05, indicating a non-significant effect on angle of repose. The out-of-fit term P=0.954>0.05, which is not significant, indicates that the model is well-fitted and there are no other significant factors affecting the test index.

The regression equation between the contact parameters and the angle of repose (β) is obtained by eliminating the factors that do not have a significant effect on the angle of repose as:

$$\beta = +23.28 + 1.48A + 1.6B + 0.77A^2 \tag{12}$$

Table 7

Heap angle analysis of variance results

Source	Sum of squares	Degree of freedom	Mean square	F number	P value
Model	43.34	5	8.67	12.28	0.0024**
A	17.60	1	17.60	24.93	0.0016**
B	20.37	1	20.37	28.86	0.0010**
AB	0.063	1	0.063	0.089	0.7747
A^2	4.71	1	4.71	6.68	0.0363*
B^2	1.09	1	1.09	1.54	0.2542
Residual	4.94	7	0.71		
Lack of fit	0.35	3	0.12	0.10	0.9540
Pure error	4.59	4	1.15		
Sum	48.28	12			

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

Response surface analysis

The Design-Expert software was applied to generate the response surface plots of the coefficient of static friction of Pak Choi Seeds-Pak Choi Seeds versus the rolling friction coefficient of Pak Choi Seeds-Pak Choi Seeds, as shown in Figure 12.

The angle of repose increases with the increase in the rolling friction coefficient between the Pak Choi Seeds-Pak Choi Seeds due to the increase in the Pak Choi Seeds-Pak Choi Seeds rolling friction coefficient and the corresponding increase in the shear stress and consequent increase in the angle of repose.

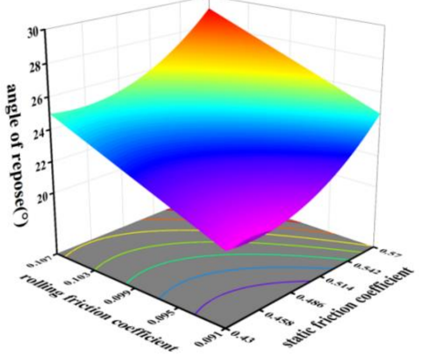


Fig. 12 - Pak Choi seed packing angular response surface

Optimization of parameters

Using the optimization module of Design-Expert software, the regression model was optimally solved with the measured angle of repose as the target value to minimize the error between the angle of repose simulation test results and the physical test angle of repose results, and the objective and constraint Equations are shown below:

$$\begin{cases} \beta(A,B) = 24.3 \\ s.t\begin{cases} 0.41 \le A \le 0.57 \\ 0.091 \le B \le 0.107 \end{cases} \end{cases} \tag{13}$$

The resulting optimization results in a Pak Choi seeds - Pak Choi seeds static friction coefficient of 0.486, Pak Choi seeds - Pak Choi seeds rolling friction coefficient of 0.104.

Verification test

Angle of repose verification test

To verify the reliability and authenticity of Pak Choi seeds after simulation calibration, the results of the angle of repose simulation test were compared with those of the physical test angle of repose. For the angle of repose simulation test, the above-determined static friction coefficient of 0.522 and rolling friction coefficient of 0.101 between Pak Choi species were used as simulation parameters, and the average values of the physical tests were used for other non-significant parameters. The relative error between the simulation test result of 24.23° and the physical test angle of repose of 24.30° was obtained to be 0.288%, and the results proved the validity of the calibrated simulation parameters.

Seed-metering device verification test

To further verify the reliability of the discrete meta-model and simulation parameters of Pak Choi seeds, the homemade horizontal disk type cabbage precision seeder was used to carry out the simulation test of seeding performance and bench test in the intelligent agricultural machinery and equipment engineering laboratory of Harbin Cambridge College, and to calculate the relative errors of its simulation value and the measured value of the qualification rate, the reseeding rate, and the leakage rate with the formula:

$$\begin{gathered} g = \frac{n_1}{n} \times 100\% \\ j = \frac{n_2}{n} \times 100\% \\ k = \frac{n_3}{n} \times 100\% \end{gathered} \tag{14}$$

where: n is the number of theoretical rows of particles, grains; n_1 is the number of seeds single qualified, grains; n_2 is the number of seeds reseeded, grains; n_3 is the number of seeds missed, grains.

Seed-metering device simulation test

The horizontal disk-type Pak Choi precision seed discharger used in this study has a total of 12 type holes evenly distributed on the discharging disk, and a brush is installed at the exit of the seed box for seed cleaning. SolidWorks software was used to model the seed displacer in three dimensions, and it was saved in stl format and imported into EDEM software, the material of the wall of the seed displacer was set as PLA material, and the material of the brushes was set as nylon plastic. Referring to the above calibration results and related literature, the material and contact parameters of the seed displacer wall, seed cleaning brush, and Pak Choi seeds were set as shown in Table 8 *(Dun et al., 2020; Li et al., 2024)*. Hertz-Mindlin (no slip) contact model was used between the seeds and the seed discharger, between the brushes and between the seeds, and the rotational speed of the seed discharging disk was set to 30 r/min, and a total of 800 Pak Choi seed models were generated in the seed box, and the simulation time was set to 18 s, as shown in Figure. 13. Continuously measure the number of seed filling in 200 type holes in the simulation test, 1 seed filling in the type holes for seed filling qualified n_1, 2 or more for reseeding n_2, less than 1 for leakage n_3, using the Equation (14) to calculate the rate of qualified, reseeding rate, leakage rate of the seed in the type holes, repeat the three tests to take the average value.

Table 8

Material parameters required for seeding simulation

Project	Attribute	Numeric value
Pak Choi seeds	Poisson's ratio	0.375
	Shear modulus / Pa	1.66×10^7
	Density / （kg·m³）	1082
PLA plastic	Poisson's ratio	0.3
	Shear modulus / Pa	1.04×10^7
	Density / （kg·m³）	1290
Nylon plastic	Poisson's ratio	0.4
	Shear modulus / Pa	1.1×10^8
	Density / （kg·m³）	1150
Pak Choi seeds - Pak Choi seeds	collision recovery coefficient	0.292
	Coefficient of static friction	0.52
	Coefficient of rolling friction	0.098
Pak Choi seeds - PLA plastic	collision recovery coefficient	0.473
	Coefficient of static friction	0.46
	Coefficient of rolling friction	0.163
Pak Choi seeds - nylon plastic	collision recovery coefficient	0.45
	Coefficient of static friction	0.50
	Coefficient of rolling friction	0.01

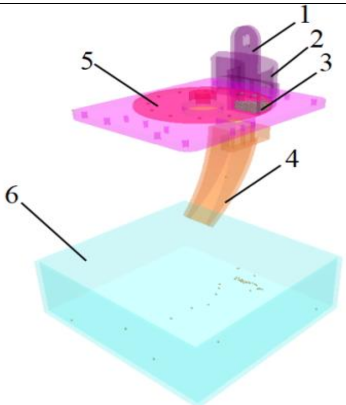


Fig. 13 - Sowing device simulation experiment

1. Brush; 2. Seed box; 3. Pak Choi seeds; 4. Seed tubes; 5. Seed tray; 6. Seed collection bin.

Seed-metering device bench test: The same batch of Jinyu Shenghui four-season Pak Choi seeds as the above test was selected for the bench test, and the seed-metering device was made with 3D rapid prototyping technology, and the material was PLA plastic. The test setup consisted of a seed-metering device, seed-metering device mounting bracket, motor with the motor controller, homemade sand spreader with sand spreader controller, and conveyor belt as shown in Figure 14. To better achieve the experimental effect, according to the actual small Pak Choi breeding agronomic requirements, the plant spacing is 10 cm as a standard, the seed grain spacing is greater than 1.5 times the theoretical grain spacing for the leakage of seed, the seed grain spacing is less than or equal to 0.5 times the theoretical grain spacing for the re-sowing. At the beginning of the test, the white sand was poured into the sand spreader, the sand spreader was started and the operating speed of the conveyor belt was set to 0.5 m/s. After the sand was discharged uniformly and continuously, the motor speed was set to 25 r/min seed rowing was started, and the test was conducted to measure the plant spacing of 200 seeds, and the statistical data were brought into Equation (14) to calculate the qualification rate of the seeds, the reseeding rate, and the omission rate, and the trial was repeated for three times. The average value was taken.

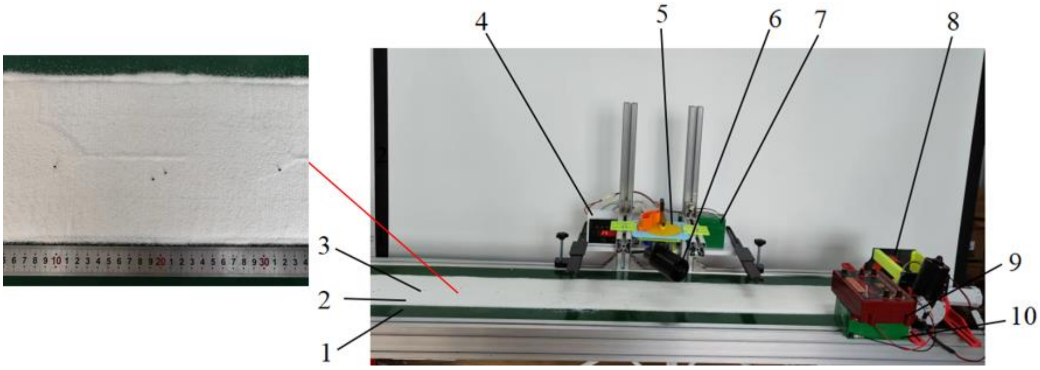


Fig. 14 - Sowing device test rig experiment

1. Conveyor belt; 2. Sand; 3. Pak Choi seeds; 4. Seeding Controller; 5. Seed-metering device；6. Electrical machinery; 7. Battery; 8. Sand laying machine; 9. Sand spreading machine controller; 10. Sand paver battery.

Test results and analyses

The results of simulation and bench test are obtained as follows: the average values of qualified rate are 85.33% and 84.67%, respectively, with a relative error of 0.78%; the average values of replay rate are 8.17% and 8.5%, respectively, with a relative error of 3.88%; and the average values of missed seeding rate are 6.5% and 6.83%, respectively, with a relative error of 4.83%. The results of the simulation test and the bench test were less than 5%. The results show that the seed discrete element model and simulation parameter calibration are reliable, and the simulation and test qualification rate, reseeding rate and leakage rate meet the agronomic requirements of Pak Choi sowing.

CONCLUSIONS

(1) The basic physical parameters of Pak Choi seeds were determined through physical tests mainly including triaxial dimensions, mass, density, water content, Poisson's ratio, modulus of elasticity, shear modulus, and the equivalent diameters, sphericities, and volumes of the seeds were calculated by applying formulas, and the static friction coefficients, rolling friction coefficients, collision recovery coefficients, and angle of reposes of the seeds were measured through the mechanical property test device constructed by the company independently.

(2) The physical property parameters determined in the physical tests were used as the basis for the selection of parameters for the simulation tests, the Plackett-Burman test was carried out to select the parameters that highly significantly affected the angle of repose: Pak Choi seeds - Pak Choi seeds static friction coefficient and Pak Choi seeds - Pak Choi seeds rolling friction coefficient. The optimal range interval of the highly significance parameter was further determined by the steepest climb test.

(3) Using the simulated angle of repose as the test index, the Design-Expert software and EDEM software were used to carry out the Central Composite Designs test, and the regression equation between the highly significance parameter and the angle of repose was obtained. The regression equation was optimally solved using the measured angle of repose (24.3°) as the target value. It was obtained the optimal simulation parameters: Pak Choi seed - Pak Choi seed static friction coefficient of 0.486, Pak Choi seed - Pak Choi seed rolling friction coefficient of 0.104.

(4) Pak Choi seeds angle of repose simulation and bench test error rate of 0.288%, seed dispenser simulation test and bench test qualified sowing rate of 85.33%, 84.67%, respectively, replanting rate of 8.17%, 8.5%, missed sowing rate of 6.5%, 6.83%, respectively, verified that the relative error rate between the two is not more than 5%, there is no significant difference, so the simulation of the calibration parameters with a certain degree of reliability and authenticity, can be used as a reference for the operation simulation of Pak Choi seed dispenser. The simulation parameters have certain reliability and authenticity, which can provide a certain reference for the relevant operation simulation of Pak Choi seed discharger.

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