

Original Research Paper

# Parameter Measurement and Calibration in Discrete Element Simulation of Broken Sweet Potato Seedlings

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**Abstract:** Given the lack of accurate parameter values in discrete element simulation of sweet potato seedling mechanized recovery, a direct measurement and virtual calibration method was used to study the Discrete Element Method (DEM) simulation parameters of broken sweet potato stems and leaves. The intrinsic parameters, collision recovery coefficient and static friction coefficient of broken seedlings were acquired by physical experiments. Different parameter combinations were designed for DEM simulation. The intrinsic parameters of sweet potato leaves and other unmeasurable DEM simulation parameters were determined by stacking angle optimization simulation. Plackett-Burman test shows that the static friction coefficients of stem-stem and stem-steel and the rolling friction coefficients of stem-stem and stem-leaf all significantly influence the accumulation angle. The parameters that significantly influence the stacking angle of broken seedlings were sent to steepest ascent test and Box-Behnken test. The average stacking angle of 40.51° and the relative error of 0.972% indicate it feasible to calibrate DEM parameters by physical test and optimization simulation and the calibrated parameters can be used in DEM simulation of broken sweet potato stems and leaves.

**Keywords:** Sweet Potato Seedlings, Discrete Element Method, Accumulation Angle, Optimal Design, Calibration

## Introduction

Sweet potato vines are excellent fresh feeds and silage and thus their mechanized recycling has economic and social benefits (Kakahy *et al.*, 2014; Zhao and Gao, 2012; Guizhi *et al.*, 2019). Research on the action mechanism of sweet potato vines and harvesting machinery based on the Discrete Element Method (DEM) provides a theoretical basis for machinery design and optimization. DEM simulation requires many parameters, including intrinsic parameters (e.g., density, shear modulus and Poisson's ratio of sweet potato seedlings) and contact parameters (e.g., collision recovery coefficients, rolling friction coefficients and static friction coefficients between seedling particles and between particles and machine) (Boac *et al.*, 2009; Ucgul *et al.*, 2014; Leblicq *et al.*, 2016). How to determine these parameters is the premise of applying DEM to the research on mechanized recovery of sweet potato vines.

Much research has been conducted to obtain DEM simulation parameters, mainly including direct

measurement and virtual calibration (Martin *et al.*, 2003; Horabik and Molenda, 2016; Sweijen *et al.*, 2020). Grima and Wypych (2011) changed a cylinder lifting device to the left and right separation method and calibrated particle discrete element simulation parameters using the improved collapse test. González-Montellano *et al.* (2012) used direct measurement method to study some parameters in discrete element simulation. Junxiao *et al.* (2015) simulated straw particle accumulation and mixing movement in the rotating drum and calibrated the discrete element parameters of straw particles by comparison with actual experiments. Santos *et al.* (2015) obtained the dynamic angle of acerola residue by rotating drum experiment and calibrated the parameters needed in the discrete element simulation based on response surface method. Lee and Park (2019) designed four simulation friction tests to measure the static and rolling friction coefficients between materials and containers.

At present, no scholar has studied the discrete element simulation parameters of sweet potato seedlings. The above studies indicate that the intrinsic

parameters of materials can be acquired direct measurement, but directly measuring and obtaining accurate contact parameters is difficult. In this study, physical tests were conducted to obtain the intrinsic parameters of broken sweet potato seedling stems, collision recovery coefficient and the static friction coefficient range of seedling particles. The intrinsic parameters of sweet potato leaves and other unmeasurable discrete element simulation parameters were simulated. The parameters were calibrated by simulation of crushed seedling particle accumulation optimization design. Through the Plackett-Burman test, the steepest climbing test and the Box-Behnken optimization test, the basic contact parameters were calibrated. The simulation data were compared with the physical test data, which provides a reference for the measurement and calibration of discrete element simulation parameters of sweet potato seedlings.

## Materials and Methods

### *Measurement of Intrinsic Parameters of Crushed Sweet Potato Seedlings*

#### *Group Measurement*

The broken potato seedlings harvested by a sweet potato seedling recycling machine were classified mainly into broken leaves, short stems and impurities (e.g., dry leaves, weeds, soil blocks). Five groups of mixtures were randomly selected and the average proportions of leaves, stems and impurities were 36.94, 59.2 and 3.85% (very low), respectively. Clearly, seedling leaves and stems were the main particle components used in discrete element simulation. In fact, leaves and short stems were taken as the research objects.

Five samples of crushed sweet potato seedlings were randomly selected after removing impurities. Then leaf areas were measured and calculated using graph paper and the length and diameter of stems were detected using vernier calipers. The coefficients of variation in the measurements of sweet potato leaf area and stem length are larger than 15. The S-W tests show neither the measured leaf areas nor stem lengths satisfy normal distribution. To simplify the modeling, further classification and counting were adopted. The leaves were divided by area into two types: Broken leaves (area >2 cm<sup>2</sup>) and finely-shredded leaves (area <2 cm<sup>2</sup>). According to statistics, the average areas of broken leaves and finely-shredded leaves

are 2.40 and 1.5 cm<sup>2</sup>, respectively and the coefficients of variation are 6.13 and 4.35%, respectively. The stems were divided by length into long stems (length >20 mm) and short stems (length <20 mm). The average length and diameter of the long stems are 35.73 and 6.7 mm, respectively and the coefficients of variation are 10.06 and 6.77%, respectively. The average length and diameter of the short stems are 14.56 and 4.56 mm, respectively and the coefficients of variation are 8.35 and 3.72%, respectively. The statistical results of mass proportion of each component are shown in Table 1.

#### *Density Measurement*

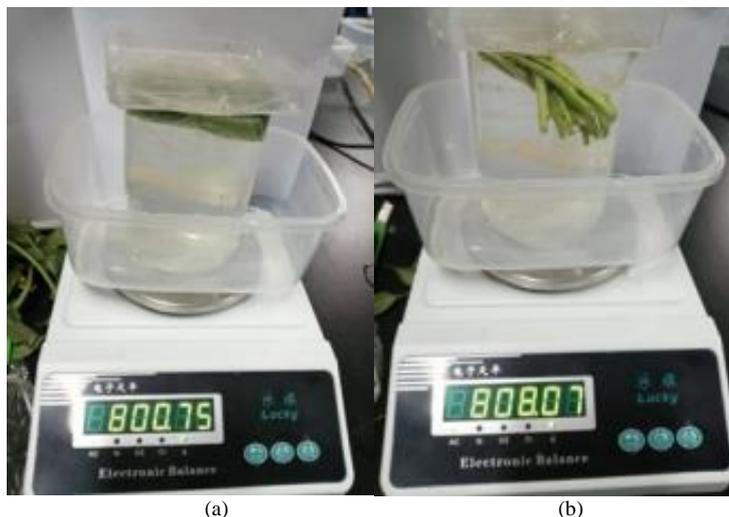
The true density of particles is an important parameter of discrete element simulation. The densities of sweet potato stems and leaves were measured by the overflow equal volume method. Firstly, 50 stems each in length of 20 mm and 50 leaves were randomly selected and every 10 stems and every 10 leaves were bundled together with filaments. Then the stem or leaf quality was measured and the volumes were measured by the immersion method (Fig. 1). Water will overflow after putting the stems in a measuring cup full of pure water. Since the density of fresh sweet potato stems is less than that of water, the top was covered with a flat plate to ensure that all the stems can penetrate water. After the measuring cup was removed, the quality of the overflowing water was measured and the volume of water was calculated, which is the volume of the stems. The average density of sweet potato stems measured from five groups is 987.91 kg/m<sup>3</sup> and the coefficient of variation is 3.34%. The density of sweet potato leaves measured by the same method is 785.36 kg/m<sup>3</sup> and the coefficient of variation is 3.69%.

#### *Determination of Poisson's Ratio of Stems*

At each time, a stem with a diameter of about 7 mm in the middle section of a sweet potato seedling at the mature stage was made into a sample with a length of 20 mm (Fig. 2a). The sample was sent to a compression test on a WDW-5E microcomputer controlled universal testing machine (Fig. 2b). The compressive stress-strain curve of each sample was acquired at the loading speed of 5 mm/min and each test was repeated 10 times. The shear modulus of the sweet potato stem calculated at the mature stage is 6 MPa, the elastic modulus is 15.34 MPa, Poisson's ratio is 0.28 and the coefficients of variation are 7.45, 9.32 and 8.77% respectively.

**Table 1:** Composition statistics of broken sweet potato seedlings

Item stems	Broken leaves	Finely shredded leaves	Long stems	Short
Mass percentage%	20.32	18.10	38.24	23.34



**Fig. 1:** Measuring density with overflow equal volume method; (a) Measure blade density (b) Measure stem density



**Fig. 2:** Compression test of sweet potato stem; (a) Compressed sample (b) Compression test

### Determination of Contact Parameters of Crushed Sweet Potato Seedlings

#### Collision Recovery Coefficient

The length-to-diameter ratio of sweet potato stems is large. If free fall collision test is used to measure the collision recovery coefficient, vertical rebound does not easily occur, which seriously affects the measuring accuracy. Hence, the stem-stem/leaf/45 steel collision recovery coefficient was measured by the inclined plate collision method (Huang *et al.*, 2014) and the measurement principle is shown in Fig. 3.

At each time, a stem sample makes a free-fall motion from height  $h_0$  and after colliding with the collision material (45 steel, leaf, or stem) installed on the collision slope ( $v_n$ -instantaneous velocity after particle collision), it makes a parabolic motion and falls on the receiving plate. When the relative height between the collision point  $o$  and the receiving plate is  $h_1$  (or  $h_2$ ), the measured horizontal displacement of the stem is  $s_1$  (or  $s_2$ ). The backward movement only has  $x$ -direction displacement. At this

time, the coefficient  $e$  of restitution between the stem and the inclined plate is calculated as Eq. (1):

$$e = \frac{\sqrt{(v_x^2 + v_y^2)} \cdot \cos \left[ 45^\circ + \arctan \left( \frac{v_y}{v_x} \right) \right]}{v_0 \cdot \sin 45^\circ} \quad (1)$$

where,  $v_0$ - instantaneous velocity before particle collision, mm/s;  $v_x$  and  $v_y$ - horizontal and vertical velocity components after particle collision, respectively, mm/s.

The  $v_0$ ,  $v_x$  and  $v_y$  in Eq. (1) are calculated by Eq. (2) and (3):

$$v_0 = \sqrt{2gh_0} \quad (2)$$

$$\begin{cases} v_x = \sqrt{\frac{gs_1s_2(s_1 - s_2)}{2(h_1s_2 - h_2s_1)}} \\ v_y = \frac{h_1v_x}{s_1} - \frac{gs_1}{2v_x} \end{cases} \quad (3)$$

A self-made collision coefficient measuring device is shown in Fig. 4. In the measurement of stem-stem recovery coefficient, the tested stem is prone to rotation after colliding with the stem stuck on the collision slope. As a result, displacement occurs in both the  $x$  and  $y$  directions of the splice plate. This fact is inconsistent with the calculation assumption that the stem has only  $x$ -direction displacement. Therefore, a 50-mm-wide layer of glue is applied to the splice plate to "capture" the stem. The stem reduces collision and rebound.

when the stem falls outside the range of the red line on the splicing plate, it is an invalid test and the drop point distribution of the sample is shown in Fig. 4b. Totally 50 stems were selected for measurement, 25 in one group and the height of the splicing plate was changed for two tests. The average value of  $x$ -direction displacement was recorded in each group and the recovery coefficient was calculated by Eq. (1)-(3). The measurement and calculation determine that the recovery coefficients of stem-stem, stem-leaf and stem-steel plate collision are 0.32, 0.28 and 0.44, respectively and the coefficients of variation are 6.33, 8.36 and 9.03% respectively.

### Static Friction Coefficient

The static friction coefficients of stem-stem, stem-leaf and stem-45 steel were measured by the inclined surface sliding method (Fangyuan *et al.*, 2018). The self-made static friction coefficient measuring instrument mainly consists of a lifting plate and a digital display angle measuring instrument (Fig. 5). Sweet potato stems with similar diameters were pasted on the lifting plate to measure the stem-stem static friction coefficient. During measurement, the lifting plate was slowly lifted until it

stopped when the stem slid on the inclined surface. Then the inclination angle of the inclined plate on the digital angle measuring instrument installed on one side was read. The static friction coefficient,  $\mu$ , is calculated as Eq. (4):

$$\mu = \tan \alpha \tag{4}$$

where,  $\alpha$ - inclination angle of the inclined plate ( $^{\circ}$ ).

The measured static friction coefficient between stem-stem ranges from 0.2 to 0.8. Clean and tidy sweet potato leaves were pasted on the lifting plate. The static friction coefficients between stem-leaf and between leaf-leaf range from 0.3 to 0.6 and from 0.3 to 0.8 respectively. The static friction coefficients between the stem or leaf and the 45 steel measured by the same method range from 0.3 to 0.8 and 0.3 to 0.7, respectively.

### Pile Angle of Crushed Sweet Potato Seedlings

The pile-up angle of broken seedling particles was determined by the cylinder lifting method. The broken seedlings harvested by the sweet potato seedling recovery machine (to remove impurities) were collected as samples. According to the test requirements of the cylinder lifting method (Jia *et al.*, 2014), a steel cylinder with an inner diameter of 160 mm and a height of 480 mm was selected and the steel cylinder filled with crushed seedlings was lifted upward at a speed of 0.05 m/s using a CNC milling machine. A pile of crushed seedling particles was formed on the horizontally-fixed bottom plate (Fig. 6). The experiment was repeated 5 times and the average accumulation angle of the crushed seedlings was measured to be  $40.12^{\circ}$  and the coefficient of variation was 2.36%.

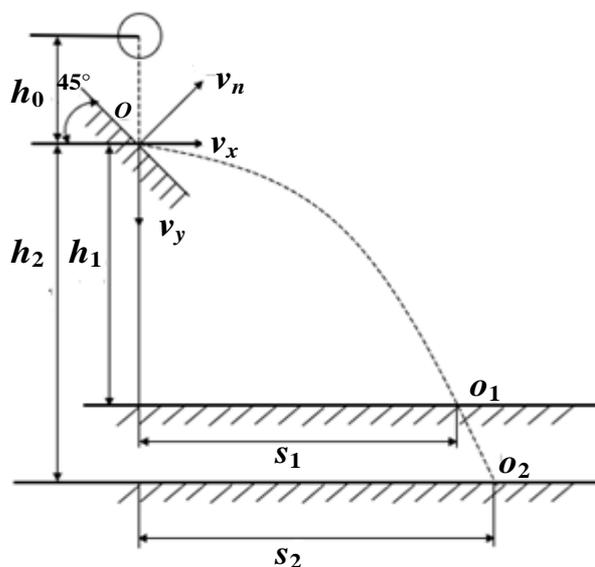
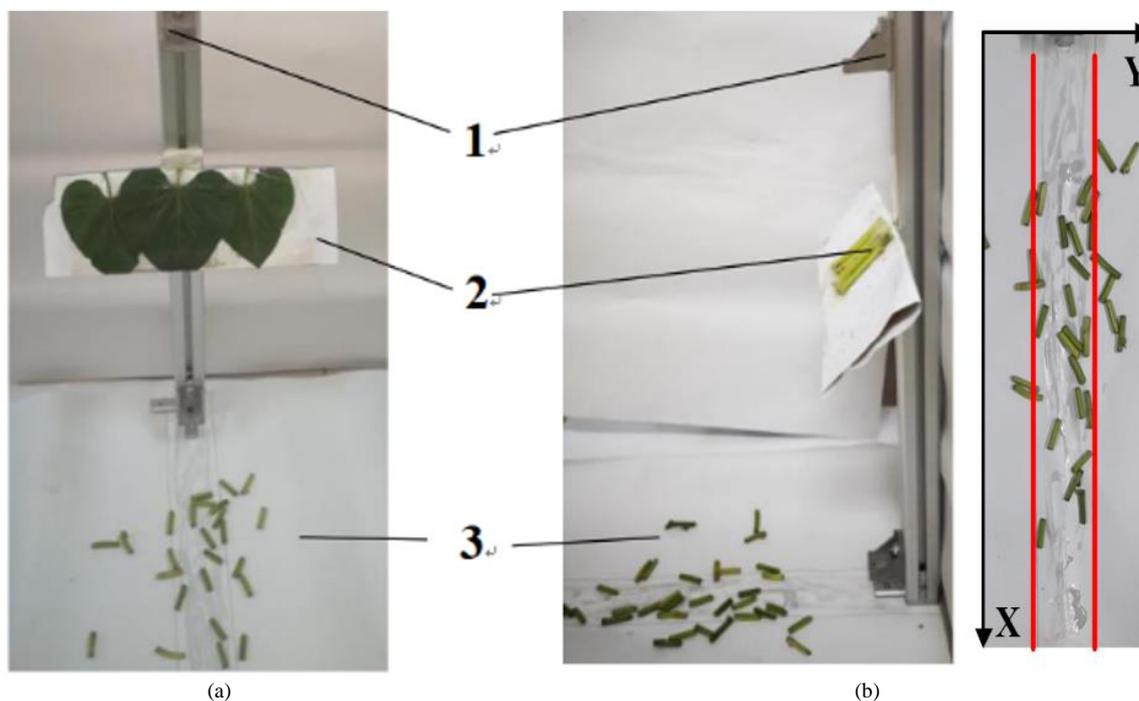
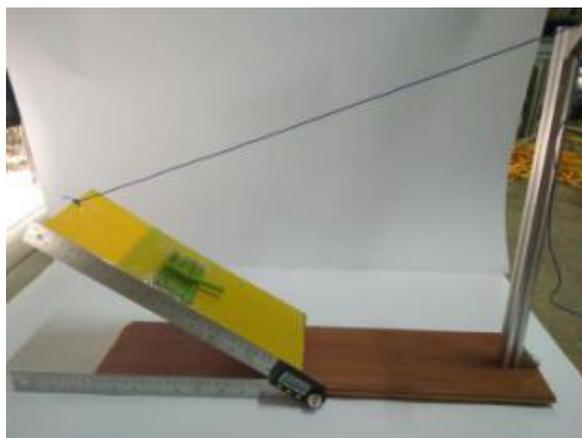


Fig. 3: Principle of measurement



**Fig. 4:** Collision recovery coefficient determination 1 feeding point, 2 collision plate, 3 material receiving plate; (a) Inclined plate collision test (b) Distribution of falling points of stems



**Fig. 5:** Static friction coefficient measuring instrument



**Fig. 6:** Heap of broken sweet potato seedlings

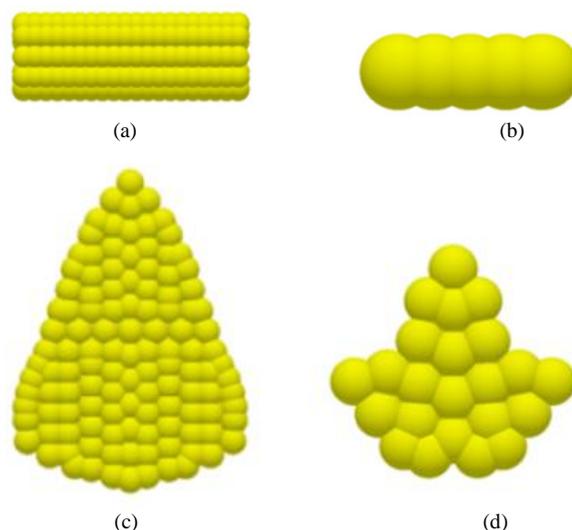
### *Establishment of DEM of Broken Seedlings and Calibration of Main Parameters*

#### *Model of Broken Sweet Potato Seedlings*

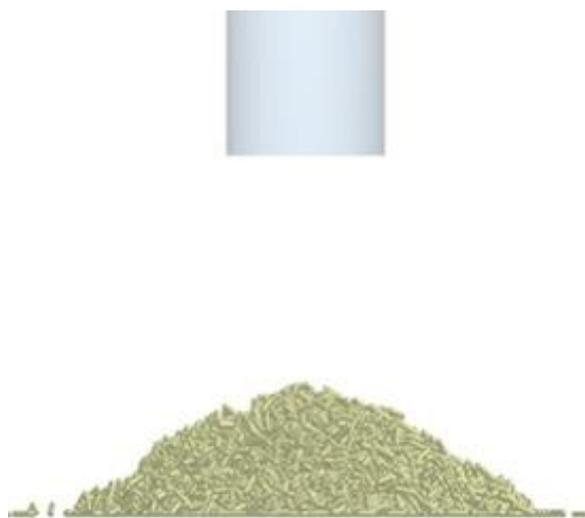
To make the broken sweet potato seedling model structurally close to the real broken sweet potato seedling, the geometric model of each component of the broken seedling drawn by SolidWorks was imported into EDEM. Then spherical particles were quickly filled to obtain 4 types of particles, including long-diameter stems (length 30 mm, diameter 7 mm), short-diameter stems (length 15 mm, diameter 5 mm), broken leaves (area 2.4 cm<sup>2</sup>) and finely-broken leaves (area 1.5 cm<sup>2</sup>) (Fig. 7).

#### *Simulation of Accumulation Angle of Crushed Sweet Potato Seedlings*

In EDEM 2018, a virtual cylinder with an inner diameter of 160 mm and a height of 480 mm was established as a pellet factory. Four types of pellets were set in the pellet factory. The pellet factory type was set to be a dynamic factory. According to the actual proportion of crushed seedlings, the generation speeds of long-diameter rod, short-diameter rod, broken leaf and fine broken-leaf were set as 0.33, 0.29, 0.62 and 0.38 kg/s, respectively and the generation time was 7 s. The contact model between particles was a Hertz-Minglin (no-slip) model. After particles of crushed seedlings were formed, the lifting speed of the cylinder was set at 0.05 m/s. After the particles were stationary on the substrate, a pile of crushed seedlings was formed (Fig. 8).



**Fig. 7:** Discrete element model of broken sweet potato seedlings; (a) Long stem (b) Short stem (c) Broken blade (d) Finely crushed blade



**Fig. 8:** Schematic diagram of movement path of end point of the knife

**Table 2:** Test parameters of Plackett-Burman

Simulation parameters of sweet potatoes	Level	
Poisson's ratio of leaves $x_1$	-1.00	1.0
Shear modulus of leaves $x_2$ /MPa	0.20	0.5
Static friction coefficient of stem-stem $x_3$	6.00	500.0
Static friction coefficient of stem-leaf $x_4$	0.30	0.6
Static friction coefficient of stem-45 steel $x_5$	0.20	0.8
Static friction coefficient of leaf-leaf $x_6$	0.30	0.8
Static friction coefficient of leaf-45 steel $x_7$	0.30	0.7
Rolling friction coefficient of stem-stem $x_8$	0.05	0.3
Rolling friction coefficient of stem-leaf $x_9$	0.00	0.3
Rolling friction coefficient of stem-45 steel $x_{10}$	0.00	0.3
Rolling friction coefficient of leaf-leaf $x_{11}$	0.00	0.3
Rolling friction coefficient of leaf-45 steel $x_{12}$	0.00	0.3
Collision recovery coefficient of leaf-leaf $x_{13}$	0.10	0.5
Impact recovery coefficient of leaf-45 steel $x_{14}$	0.10	0.5

### Calibration Test of Parameters

#### Screening of Influencing Parameters of Particle Stacking Angle of Broken Sweet Potato seedlings

Many parameters are required to simulate the pile-up angle of the broken seedlings. The stem density, leaf density, shear modulus of stems and Poisson's ratio are 998.91 kg/m<sup>3</sup>, 885.36 kg/m<sup>3</sup>, 6 MPa and 0.28 respectively. The coefficients of collision recovery in stem-stem, stem-leaf and stem-steel plate are 0.32, 0.28 and 0.44 respectively based on the measured values. The shear modulus, Poisson's ratio and density of 45 steels are taken as 0.30 and 7850 kg/m<sup>3</sup>. The coefficient of static friction between the grains of crushed seedlings was determined by the test value to determine the parameter ranges. The 14 parameters such as sweet potato leaf shear modulus, Poisson's ratio, rolling friction coefficient between crushed seedling particles and leaf-leaf/45 steel recovery coefficient cannot be tested easily. The value ranges were determined as reported (Lenaerts *et al.*, 2014; Liao *et al.*, 2020). Plackett-Burman test design was carried out on Design-Expert 8.0.6 to immediately screen out the parameter combinations that significantly impact the test results. The minimum and maximum values of the 14 parameters are coded as -1 and +1 levels respectively (Table 2).

In the Plackett-Burman test, the middle value of the high and low levels was taken as level 0 and a center point test was set up. Totally 21 tests were performed. The test design and results are shown in Table 3. The variance and significance analysis of the test results are shown in Table 4. Clearly, the static friction coefficient of stem-stem  $x_3$ , the static friction coefficient of stem-steel  $x_5$ , the rolling friction coefficient of stem-stem  $x_8$  and the rolling friction coefficient of stem-leaf  $x_9$  all significantly affect the stacking angle. Therefore, in the

subsequent steepest climb test and Box-Behnken test, only these 4 significant parameters were considered and the other 10 insignificant factors were taken at the intermediate levels. The values of  $x_1, x_2, x_4, x_6, x_7, x_{10}, x_{11}, x_{12}, x_{13}$  and  $x_{14}$  are 0.35, 253, 0.5, 0.55, 0.5, 0.15, 0.15, 0.15, 0.3, 0.3 respectively.

### Steepest Climb Test

Since the accumulation angle of broken sweet potato seedling particles is enlarged with the increase of 4 significant parameters, 6 sets of steepest climbing experiments were designed and the values of the 4 parameters increased uniformly. The experimental design and results are shown in Table 5. With the gradual increase of the 4 test parameters, the relative error between the simulation and physical test of accumulation angle first decreases and then increases. The relative error of the accumulation angle is the smallest in test No. 3, so the optimal parameter is near test No. 3.

### Box-Behnken Test and Analysis of Significant Contact Parameters

In the steepest climbing test, the 4 significance parameters in test No. 3 were taken as the intermediate level (0) and the corresponding parameters in tests No. 2 and No. 4 were taken as the low level (-1) and the high level (+1) respectively. The values of the other 10 parameters are the same as the steepest climbing test. Response surface test was designed on Design-Expert 8.0.6 to obtain the optimal values of the 4 significant contact parameters. The Box-Behnken experiment design and results are shown in Table 6.

The test results in Table 6 were fitted on Design-Expert 8.0.6 and the quadratic regression full model of the broken

sweet potato seedling particle packing angle and the 4 significant contact parameters was expressed as Eq. (5):

$$\begin{aligned} \theta = & 39.58 + 0.96x_3 + 1.06x_5 + 0.96x_8 + 0.98x_9 \\ & + 0.14x_3x_5 + 0.11x_3x_8 + 0.38x_3x_9 + 0.40x_5x_8 \\ & + 0.36x_5x_9 + 0.24x_8x_9 - 0.27x_3^2 - 0.44x_5^2 \\ & - 0.41x_8^2 - 0.36x_9^2 \end{aligned} \quad (5)$$

The variance analysis of the model test results is shown in Table 7. The fitted model  $P < 0.0001$  and the coefficient of determination  $R^2 = 0.9938$  close to 1 indicate the regression model is extremely significant and can predict the target accumulation angle. The lack of fit term  $P = 0.181 > 0.05$  and the low coefficient of variation  $CV = 0.39\%$  indicate the regression equation has a good fit.

### Verification and Determination of Simulation Optimal Parameter Combination

With the optimization module in Design-Expert 8.0.6, Eq. (7) was optimized with the tested accumulation angle of  $40.12^\circ$  as the target value. The values of  $x_3, x_5, x_8$  and  $x_9$  are 0.41, 0.53, 0.17 and 0.13, respectively. The result is the best when the remaining non-significant parameters are taken at the middle values. To test the accuracy of the optimal parameter combination, the above parameter values were used to carry out 5 particle accumulation simulation tests. The average value of particle accumulation angle of crushed sweet potato seedlings was measured to be  $40.51^\circ$  and the relative error between the accumulation angle  $40.12^\circ$  and the actual physical test was 0.972%, indicating the calibrated granular parameters of crushed seedlings are feasible. The values of each parameter are shown in Table 8.

**Table 3:** Plackett-Burman experiment design scheme and response value

Serial number	$x_1$	$x_2$	$x_3$	$x_4$	$x_5$	$x_6$	$x_7$	$x_8$	$x_9$	$x_{10}$	$x_{11}$	$x_{12}$	$x_{13}$	$x_{14}$	Numerical
1	1	-1	1	1	-1	-1	1	1	1	1	-1	1	-1	1	41.55
2	-1	1	-1	-1	-1	-1	1	1	-1	1	1	-1	-1	1	34.51
3	1	1	-1	1	1	-1	-1	1	1	1	1	-1	1	-1	42.35
4	-1	1	-1	1	-1	-1	-1	-1	1	1	-1	1	1	-1	32.22
5	1	1	-1	-1	1	1	1	1	-1	1	-1	1	-1	-1	36.82
6	1	-1	1	-1	-1	-1	-1	1	1	-1	1	1	-1	-1	41.24
7	-1	1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	42.49
8	-1	-1	1	1	-1	1	1	-1	-1	1	1	1	1	-1	31.83
9	-1	1	1	-1	-1	1	1	1	1	-1	1	-1	1	-1	41.46
10	-1	-1	1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	43.05
11	1	-1	-1	-1	-1	1	1	-1	1	1	-1	-1	1	1	31.22
12	1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	1	39.16
13	1	-1	1	-1	1	-1	-1	-1	-1	1	1	-1	1	1	38.35
14	1	1	-1	1	-1	1	-1	-1	-1	-1	1	1	-1	1	30.55
15	-1	1	1	-1	1	1	-1	-1	1	1	1	1	-1	1	42.50
16	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	1	-1	38.91
17	-1	-1	-1	-1	1	1	-1	1	1	-1	-1	1	1	1	41.76
18	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	26.21
19	1	-1	-1	1	1	1	1	-1	1	-1	1	-1	-1	-1	37.42
20	-1	-1	-1	1	1	-1	1	1	-1	-1	1	1	1	1	36.62
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41.04

**Table 4:** Variance and significance analysis of Plackett-Burman test

Parameter	The sum of square	Variance	F-value	P-value
x1	1.210	1	23.560	0.3916
x2	6.880	1	0.880	0.0753
x3	129.390	1	5.010	0.0002**
x4	0.910	1	94.300	0.4521
x5	126.660	1	0.660	0.0002**
x6	0.086	1	92.310	0.8125
x7	1.040	1	0.063	0.4248
x8	109.560	1	0.750	0.0003**
x9	73.000	1	79.850	0.0008**
x10	0.100	1	53.210	0.7958
x11	0.590	1	0.075	0.5415
x12	0.250	1	0.430	0.688
x13	0.310	1	0.180	0.6571
x14	2.600	1	0.220	0.2271

Note: P<0.01(highly significant,\*\*), P<0.05(significant,\*)

**Table 5:** Experimental results of the steepest ascent test

Parameter	x3	x5	x8	x9	Stacking angle $\theta$ (°)	Relative error/%
1	0.30	0.30	0.05	0.00	30.35	24.35%
2	0.36	0.40	0.10	0.06	36.69	8.55%
3	0.42	0.50	0.15	0.12	39.55	1.42%
4	0.48	0.60	0.20	0.18	41.56	3.59%
5	0.54	0.70	0.25	0.24	44.33	10.49%
6	0.60	0.80	0.30	0.30	48.03	19.71%

**Table 6:** Box-Behnken experimental design and results of significant parameters

Serial number	x3	x5	x8	x9	Numerical
1	1	0	1	0	41.06
2	0	0	0	0	39.41
3	0	0	0	0	39.63
4	1	0	0	-1	38.65
5	0	1	0	1	41.06
6	1	1	0	0	40.87
7	-1	0	0	-1	37.53
8	0	0	-1	1	38.69
9	0	0	1	1	41.03
10	0	0	-1	-1	36.98
11	0	0	0	0	39.67
12	-1	1	0	0	38.87
13	0	-1	-1	0	37.22
14	0	1	-1	0	38.57
15	1	0	-1	0	38.80
16	0	1	1	0	41.21
17	0	-1	0	1	38.23
18	-1	-1	0	0	37.06
19	1	0	0	1	41.33
20	0	0	1	-1	38.37
21	-1	0	1	0	38.70
22	-1	0	0	1	38.67
23	-1	0	-1	0	36.89
24	0	-1	1	0	38.26
25	0	-1	0	-1	37.15
26	0	0	0	0	39.63
27	0	1	0	-1	38.54
28	0	0	0	0	39.57
29	1	-1	0	0	38.51

**Table 7:** Variation analysis of Box-Behnken design quadratic model

Parameter	Sum of square	Variance	F-value	P-value
Model	51.510	14.00	160.99	<0.0001**
$x_3$	11.020	1.00	482.25	<0.0001**
$x_5$	13.420	1.00	587.22	<0.0001**
$x_8$	10.980	1.00	480.58	<0.0001**
$x_9$	11.580	1.00	506.88	<0.0001**
$x_3x_5$	0.076	1.00	3.31	0.0903
$x_3x_8$	0.051	1.00	2.22	0.1588
$x_3x_9$	0.590	1.00	25.94	0.0002
$x_5x_8$	0.640	1.00	28.01	0.0001
$x_5x_9$	0.520	1.00	22.68	0.0003
$x_8x_9$	0.230	1.00	9.87	0.0072
$x_3^2$	0.460	1.00	20.27	0.0005
$x_5^2$	1.260	1.00	55.20	<0.0001**
$x_8^2$	1.100	1.00	48.24	<0.0001**
$x_9^2$	0.820	1.00	35.97	<0.0001**
residual	0.320	14.00		
Missing item	0.280	10.00	2.64	0.181
Pure error	0.042	4.00		
Sum	51.830	28.00		

**Table 8:** Discrete element simulation parameter values

Simulation parameters of sweet potatoes	Level
Stem density /kg/m <sup>3</sup>	998.91
Leaf density/kg/m <sup>3</sup>	885.36
45 steel density/kg/m <sup>3</sup>	7850.00
Poisson's ratio of stem	0.28
Poisson's ratio of leaf	0.35
45 steel Poisson's ratio	0.30
Shear modulus of stem	6.00
Shear modulus of leaf	253.00
Shear modulus of 45 steel	70000.00
Collision recovery coefficient of stem-stem	0.32
Collision recovery coefficient of stem-leaf	0.28
Impact recovery coefficient of stem-45 steel	0.44
Collision recovery coefficient of leaf-leaf	0.30
Impact recovery coefficient of leaf-45 steel	0.30
Static friction coefficient of stem-stem	0.41
Static friction coefficient of stem-leaf	0.50
Static friction coefficient of stem-45 steel	0.53
Static friction coefficient of leaf-leaf	0.55
Static friction coefficient of leaf-45 steel	0.50
Rolling friction coefficient of stem-stem	0.17
Rolling friction coefficient of stem- leaf	0.13
Rolling friction coefficient of stem-45 steel	0.15
Rolling friction coefficient of leaf- leaf	0.15
Rolling friction coefficient of leaf-45 steel	0.15

## Conclusion

The stem density of sweet potato measured by the overflow equal volume method is 987.91 kg/m<sup>3</sup> and the coefficient of variation is 3.34%. The leaf density is 785.36 kg/m<sup>3</sup> and the coefficient of variation is 3.69%. The coefficients of recovery from the collision between stem-stem, stem-leaf and stem-steel plate are 0.32, 0.28 and 0.44, respectively and the coefficients of variation are 6.33, 8.36 and 9.03%, respectively. The elastic modulus, shear modulus and Poisson's ratio of the mature sweet

potato seedling stems measured by the compression test are 15.34, 6 MPa and 0.28, respectively and the coefficients of variation are 7.45, 9.32 and 8.77%, respectively. Through cylinder lifting method particle accumulation test, the average accumulation angle of broken sweet potato seedlings is 40.51° and the coefficient of variation is 2.36%.

Plackett-Burman simulation shows the static friction coefficient and rolling friction coefficient significantly affect the accumulation angle. Box-Behnken test was performed on the significant parameters on the stacking angle of crushed sweet potato seedlings and a second-order regression model between stacking angle and significance parameters was established. The optimization was performed with the goal of 40.12° and the optimal solution was obtained. The stem-stem, stem-steel static friction coefficients and the stem-stem, stem-leaf rolling friction coefficients are 0.41, 0.53, 0.17 and 0.13, respectively. With the obtained contact parameters, a simulation test of the particle accumulation of crushed sweet potato seedlings was carried out. The measured average accumulation angle is 38.71° and the relative error between the simulation result and the measured value is 0.972%, indicating the optimal parameter combination is desirable.

Although the accumulation angle of broken sweet potato seedling particles is determined by the typical lifting method, the stalk length of the broken sweet potato seedling particles is relatively large and it is difficult to form a continuous flow boundary. The calibration results may be affected by the calibration test and the shape of the particles.

In the future research, more virtual calibration experiments and particle shapes should be selected to further study the calibration of simulation parameters, so as to establish a discrete element simulation parameter database of crushed sweet potato.

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## Author Contributions

**Guizhi Mu and Xieteng Qi:** Designed and performed the experiments, analyzed the data and prepared the paper.

**Wangzhi Zhang and Zhaoqin Lv:** Participated to collect the materials related to the experiment.

**Tingting Zhang and Shuwen Wang:** Designed the experiments and revised the manuscript.

## Conflict of Interest

The authors declare that they have no competing interests. The corresponding author affirms that all of the authors have read and approved the manuscript.

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