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Parameter Calibration of Cabbages (*Brassica oleracea* L.) Based on the Discrete Element Method

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Abstract: The discrete element parameters of cabbages (*Brassica oleracea* L.) were calibrated for the design and parameter optimization of a cabbage harvester. The cabbage model was created based on the study of cabbage material characteristics and the simulation model parameters of cabbage were calibrated. The intrinsic parameters and partial contact parameters of cabbages were obtained by direct measurement. The cabbage accumulation angle was determined by a plate drawing test. Through the steepest ascent test and the orthogonal rotation combination test, a regression model of the cabbage accumulation angle error was established. The optimal contact parameters between the cabbages were obtained by the minimum error modeling. These calibrated parameters were applied in the verification test, and the results indicated that the error between the simulated and measured values of the cabbage accumulation angle was only 1.63%, which demonstrated that the results were dependable. This study can provide a theoretical support for designing and optimizing the parameters of cabbage harvesting machines with the discrete element method (DEM).

Keywords: cabbage; parameter calibration; discrete element method; simulation model

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Citation: Zheng, J.; Wang, L.; Wang, X.; Shi, Y.; Yang, Z. Parameter Calibration of Cabbages (*Brassica oleracea* L.) Based on the Discrete Element Method. *Agriculture* **2023**, *13*, 555. https://doi.org/10.3390/agriculture13030555

Academic Editor: Tao Cui

Received: 6 February 2023
Revised: 20 February 2023
Accepted: 23 February 2023
Published: 24 February 2023

1. Introduction

Cabbage (*Brassica oleracea* L.) is an important and widely cultivated vegetable throughout the world [1,2]. Recently, the cultivation area of cabbage in China has been steadily increasing, and the total area and production are among the highest in the world. Cabbage harvesting requires a large amount of labor and has high costs. Therefore, developing cabbage mechanization is an important way to improve the harvesting efficiency [3,4]. However, due to its tender, crisp and juicy leaves, cabbage leaf tissue is not flexible and it is easily damaged during mechanized harvesting, which directly reduces the commodity value and storability of cabbage [5,6]. Therefore, cabbage harvest technology that causes lower damage and has a higher efficiency is an inevitable future development.

In mechanized harvesting, cabbages usually come into contact with mechanical components (such as clamping devices, conveying devices, leaf-stripping devices, collecting boxes, etc.) [1,5,6]. However, the contact relationship and the dynamic response characteristics of cabbages and mechanical components are complex. Traditional test methods are time-consuming, laborious and seasonally limited when optimizing the relevant mechanical structural and dimensional parameters and analyzing the movement and dynamic response characteristics of cabbages. In recent years, computer simulation analysis technology based on the discrete element method (DEM) has advanced rapidly. The numerical simulation software EDEM has been widely studied and applied in the field of agricultural engineering [7–9]. In discrete element simulation, the parameters of the simulation model need to be defined, including the intrinsic parameters and the contact parameters [10,11]. Among them, the material intrinsic parameters (Poisson's ratio, shear modulus and density) are particle attribute parameters, which can be measured by physical experiments. However, the contact parameters (coefficient of restitution, coefficient of static friction and coefficient of rolling friction) are influenced by the varying shapes of the material particles, which is difficult to measure directly. Thus, there is a need to calibrate the contact parameters [12–14].

At present, domestic and foreign researchers have performed many studies on the calibration of DEM model parameters for different agricultural materials, including soil [15,16], grain seeds [17–20], crop stalks [21–23], fertilizers [24,25], fruits and vegetables [26–29], etc. Wang et al. [15] established a soil discrete element model by combining physical experiments with simulation tests. The soil discrete element parameters were calibrated by accumulation angle and shear angle tests. Field verification tests showed that the calibrated soil model could approximately replace the actual soil for simulation. Thiet et al. [18] established a discrete element model of soybean seeds based on their physical characteristics and calibrated the input parameters of the model through the combination of physical experiments and simulation tests. Mei et al. [21] calibrated the discrete element model of a corn stalk mixture. The static friction coefficient and rolling friction coefficient between particles were calibrated by the direct measuring approach and bulk calibration approach. A two-sample heteroskedasticity t-test showed no significant difference between the simulated and experimental values, and the mean relative error was only 0.29%, verifying the reliability and authenticity of the simulation test. Wen et al. [24] proposed a friction coefficient calibration method based on the overall characteristics of particle materials. The friction coefficient between fertilizer particles and PVC was successfully calibrated by combining simulation tests with real experiments. Fan et al. [28] calibrated the discrete element model of typical pear varieties. The simulation parameters between four typical pear varieties and the contact materials were calibrated by actual and simulation experiments. The simulation results were validated by a bottomless cylinder lifting test. Therefore, it is feasible to calibrate the simulation parameters of a material by combining actual experiments and simulation tests. However, few studies have focused on the discrete element model parameter calibration of cabbages.

Therefore, in this paper, cabbages of the "Zhonggan 21" cultivar were used as the object of study, and a discrete element model of cabbage was constructed by a Hertz–Mindlin (no-slip) contact model. The simulation parameters between the cabbage and contact materials (Q235 steel, PVC, EVA and wood) were calibrated by the free fall collision method, inclined sliding method and inclined rolling method, respectively. Then, the contact parameters between the cabbages were calibrated by free fall collision and cabbage accumulation angle experiments. Finally, the reliability of the calibrated simulation parameters was verified by the bottomless cylinder lifting test. The results of this study can serve as a basis for further research into cabbage harvesting machinery.

2. Materials and Methods

2.1. Model Creation

2.1.1. Cabbages and Their Intrinsic Parameters

In this paper, the cabbage cultivar "Zhonggan 21" was used as the test object, which have been widely planted in the Jiangsu and Zhejiang areas of China. A total of 200 mature cabbages were harvested by artificial methods, which were regular in shape, uniform in size, full and without damage. According to the methods of previous works [27,30,31], the intrinsic parameters of the cabbages were measured. The measured values are shown in Table 1.

Table 1. Intrinsic parameters of cabbages.

Parameter	Value
Transverse diameter, D/mm	160.31 ± 17.53
Longitudinal height, H/mm	155.64 ± 11.28
Sphericity	0.95 ± 0.05
Mass/g	958.36 ± 211.44
Density/(kg·m^{-3})	850
Moisture content/%	85.33 ± 8.25
Poisson's ratio	0.32
Elastic modulus/MPa	2.87
Shear modulus/MPa	1.09

2.1.2. DEM Simulation Model of Cabbage

Due to the complex irregular geometries of cabbages, it is not feasible to simulate them directly using individual spherical simulation particles. In addition, because the cabbage leaf venation bulges outward, it is more vulnerable to contact damage during the harvesting process. Therefore, the cabbage was approximated as a structure composed of an internal sphere and some outer leaf veins. According to Table 1, the diameter of the internal sphere was set to 160 mm. The three-dimensional (3D) model of the cabbage was created in SolidWorks 2020, as shown in Figure 1.

(**a**) (**b**)

Figure 1. Three-dimensional model construction of a cabbage. (**a**) Real cabbage and (**b**) 3D model of cabbage.

The three-dimensional model of the cabbage (.stp format) was imported into the DEM software EDEM 2020. Based on the multi-sphere particle method, the discrete element model of the cabbage was constructed with 203 sub-spheres [32], as shown in Figure 2.

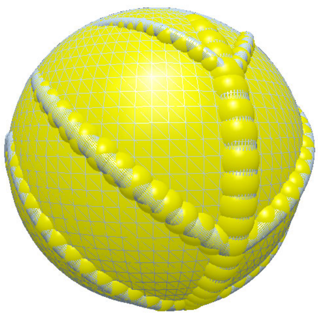


Figure 2. DEM simulation model of a cabbage.

2.1.3. Selection of Contact Model

During mechanized harvesting and transportation of cabbages, in addition to the contact between cabbage particles, the contact with other materials also produces force. In this paper, based on the analysis of the contact relationship between cabbages and machinery, four materials (Q235 steel, PVC, EVA and wood) commonly used in vegetable harvesting equipment were selected for the test contact materials, and the relevant parameters are provided in Table 2 [12,28,33,34]. Due to the large size of cabbage particles and the minimal adhesion between the particle surfaces, the influence of surface energy was ignored in the experiment. Therefore, the cabbage simulation test was performed in EDEM with the Hertz–Mindlin (no-slip) model.

Table 2. Material parameters of the discrete element simulation.

Material	Parameter		
	Poisson's Ratio	Shear Modulus/MPa	Density/(kg·m^{-3})
Q235 Steel	0.28	8.20×10^4	7850.00
PVC	0.47	2.00	1282.00
EVA	0.30	0.46	79.09
Wood	0.24	0.38×10^2	578.32

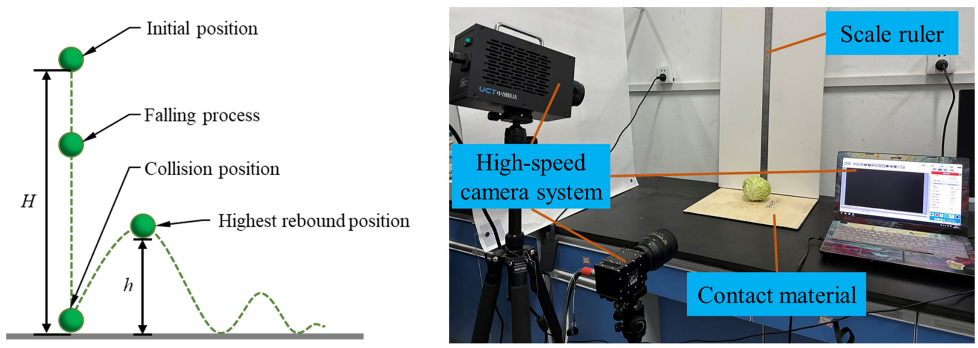
2.2. Contact Parameters between Cabbage and Materials

2.2.1. Coefficient of Restitution

The coefficient of restitution between the cabbage and contact materials was calibrated by the free fall collision method [35,36]. As shown in Figure 3, a cabbage was selected to be released from a height of H = 500 mm to drop to the horizontal contact material. The highest rebound position was captured by a high-speed camera (Japanese NAC company, Q2m), and the height h was measured with the scale ruler. According to Newton's law of collision, the coefficient of restitution is the ratio of the final to initial relative speed between two objects after they collide. Since the contact material does not work, the velocity before and after the contact material is 0, and the relative velocity is the cabbage velocity. Additionally, it is as follows:

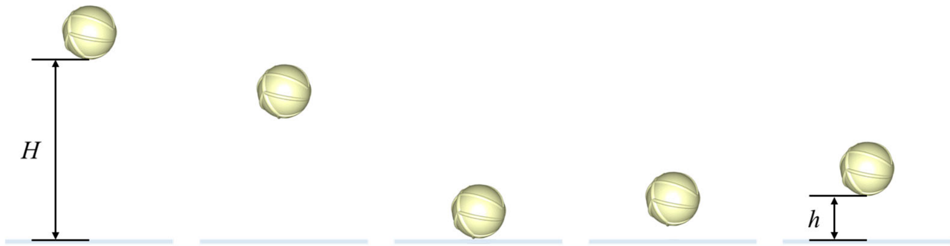
$$e = \frac{|v_1|}{|v_0|} = \frac{\sqrt{2gh}}{\sqrt{2gH}} = \sqrt{\frac{h}{H}} \tag{1}$$

where e is the coefficient of restitution between the cabbage and contact materials; v_0 and v_1 designate the instantaneous velocity of cabbage before and after the collision, respectively, m/s; g is gravity acceleration, 9.8 m/s^2; H is the falling height of cabbage, mm; and h is the maximum rebound height of cabbage, mm.



(a) (b)

Figure 3. *Cont.*



(**c**)

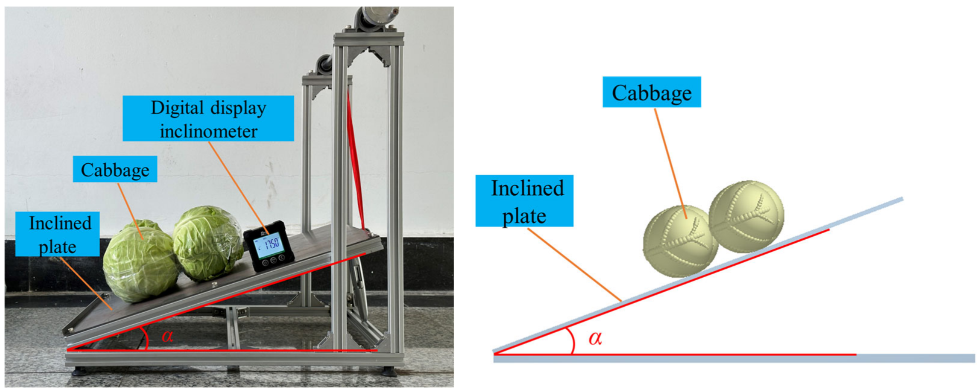
Figure 3. Measurement experiment of the coefficient of restitution between the cabbage and the contact materials. (**a**) Experimental schematic; (**b**) photograph of the experiment; (**c**) simulation test.

2.2.2. Static Friction Coefficient

The static friction coefficient between the cabbage and the materials was measured by the inclined sliding method [19]. As shown in Figure 4, the inclined plate angle was measured by a digital display inclinometer (Model: PT181, INSTRUMENTS R&D). The inclined plate angle was calculated as follows:

$$\mu_s = \tan \alpha \tag{2}$$

where μ_s is the coefficient of static friction between the cabbage and materials and α is the inclined plate angle, °.



(**a**) (**b**)

Figure 4. Measurement of the static friction coefficient between cabbages and materials. (**a**) Photograph of the experiment and (**b**) simulation test.

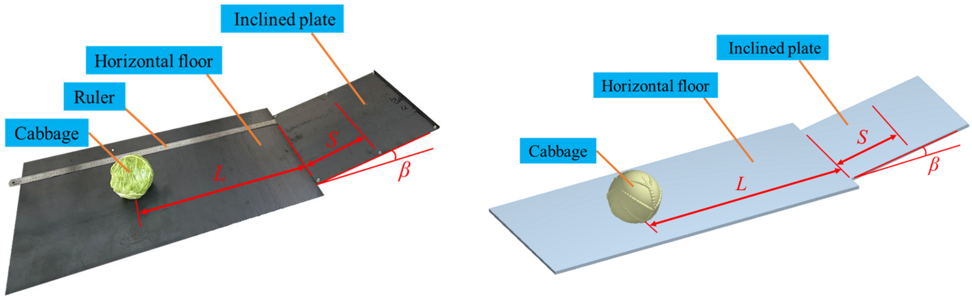
During the experiment, the contact materials (Q235 steel, PVC, EVA and wood) were tiled and fixed on the inclined plate sequentially. The digital display inclinometer was mounted onto the inclined plate. To prevent the single cabbage from rolling, four cabbages were bonded into one group in a rectangular distribution and placed on the plate. The right end of the inclined plate was slowly raised at a constant speed. When the cabbage began to slide along the inclined plane, the numerical value α was recorded from the digital display inclinometer. The experiment was repeated 30 times and the average value was obtained.

2.2.3. Rolling Friction Coefficient

The rolling friction coefficient between the cabbage and the materials was measured by the inclined rolling method [12]. As shown in Figure 5, during the experiment, the cabbage was released with zero velocity and rolled down the inclined plate, and the rolling distance of cabbage on the horizontal plate was measured. In terms of the law of conservation of energy, the calculation equation was as follows:

$$\mu_r = \frac{S \sin \beta}{S \cos \beta + L} \quad (3)$$

where μ_r is the rolling friction coefficient; S is the rolling distance of cabbage on the inclined plate, mm; β is the inclination angle of the inclined plate, °; and L is the rolling distance of the cabbage on the horizontal plate, mm.



(**a**) (**b**)

Figure 5. Measurement of rolling friction coefficient between the cabbage and the materials. (**a**) Photograph of the experiment and (**b**) simulation test.

As a result of the large size of the cabbage, it is necessary to select the appropriate β and S values to guarantee the accuracy of the measurement. Therefore, referring to previously published research by Fan, G. et al. [28], after a large number of pre-experiments, β was selected as 10° and S was 260 mm. Cabbages with similar size and quality were selected for experiments. Each group of experiments was repeated 30 times and the average of the maximum rolling distance was obtained.

2.3. Contact Parameters between Cabbages

2.3.1. Coefficient of Restitution

Using the same method as described in Section 2.2.1, the coefficient of restitution between the cabbages was measured. To minimize the effect of individual differences in cabbages, spherical cabbages of similar size and mass were used for the experiment. As shown in Figure 6, multiple cabbages were bonded together and fixed on the bottom plate, and a single cabbage was selected to be released from a height of 500 mm above them. The experiment was repeated 30 times and the range of the maximum rebound height, h, of the cabbage was obtained.

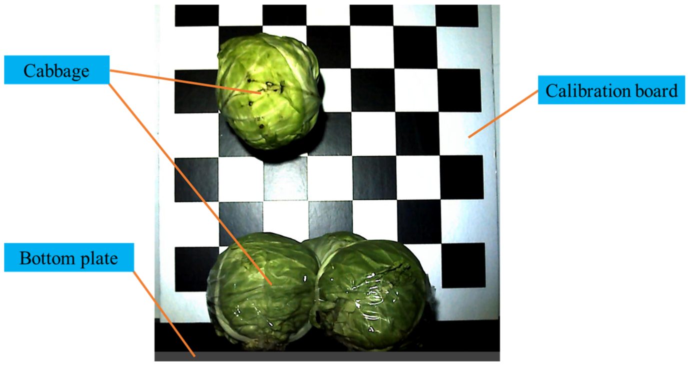
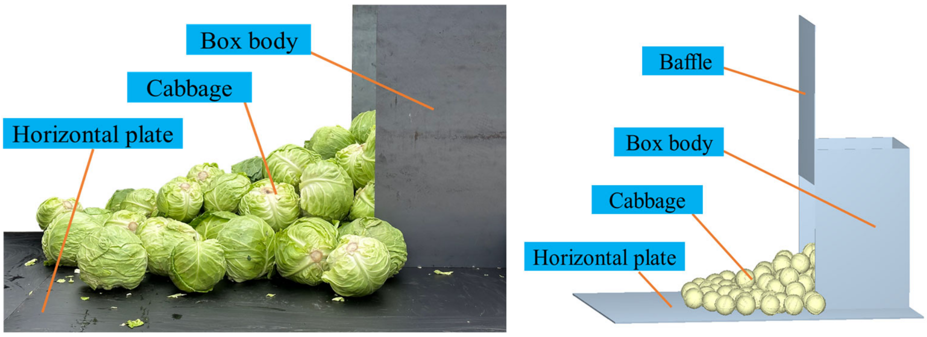


Figure 6. Measurement experiment of coefficient of restitution between cabbages.

2.3.2. Friction Coefficient between Cabbages

(1) Calibration of Cabbage Accumulation Angle

Complex movement states are reproduced during the formation of the granular material accumulation angle, which can better characterize the dispersion, flow and friction properties [30,37,38]. The accumulation angle experiment was conducted based on the drawing plate method [28,39]. As shown in Figure 7, the experimental apparatus (Q235 steel material) consisted of a rectangular box (100 height × 60 length × 60 width cm), a baffle (100 height × 60 length cm) and a horizontal plate (200 length × 200 width cm). Various contact materials (Q235 steel, PVC, EVA and wood) were used sequentially as the inner wall material of the rectangular box. After a large number of pre-experiments, 80 cabbages were selected for the experiment. To allow the cabbages to form an unconstrained particle heap on the horizontal plate, the baffle was slowly raised at a slow velocity (0.05 m/s) [12]. The experiment results indicated no significant correlation between the rectangular box material and the cabbage accumulation angle. Therefore, the rectangular box and baffle used Q235 steel material, and the horizontal plate used PVC material. After all the cabbages were stabilized, a front view photograph of the cabbage group was taken with a digital camera.



(**a**) (**b**)

Figure 7. Measurement experiment of cabbage accumulation angle. (**a**) Photograph of the experiment and (**b**) simulation test.

(2) Test of the Steepest Ascent

To determine the suitable ranges which tend to approach the optimal value, the steepest ascent test was designed based on significant factors, which were the coefficient of restitution, the static friction coefficient and the rolling friction coefficient between cabbages. The accumulation angle error between the simulated and observed values was calculated. During the simulation test, the particle size of the simulated cabbage was set to 0.8–1.2 times the cabbage physical model in EDEM software, and the contact parameters were set to be consistent with the calibration values.

(3) Test of the Orthogonal Rotation Combination

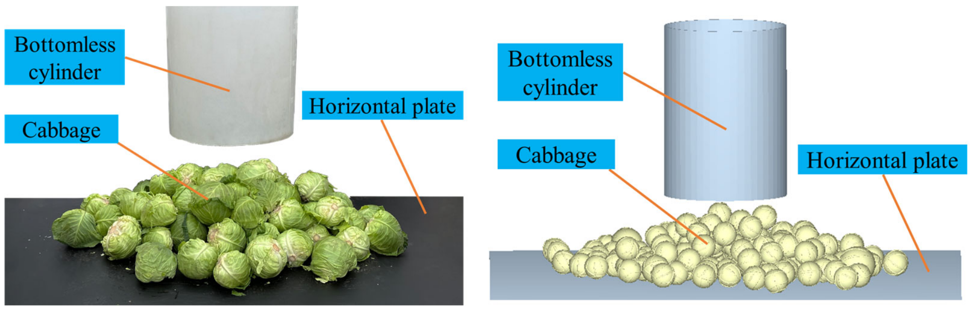
To further obtain the optimal contact parameter combination, the coefficient of restitution (e), the coefficient of static friction (μ_s) and the coefficient of rolling friction (μ_r) between cabbages were used as test factors. Using the cabbage accumulation angle error as a test indicator, an orthogonal rotation combination test was designed. The test factor codes are given in Table 3.

Table 3. Codes of simulation test factors.

Code	Test Factors		
	e	μ_s	μ_r
−1.682	1	1	1
−1	2	2	2
0	3	3	3
1	4	4	4
1.682	5	5	5

2.4. Verification Test

To further verify the accuracy of the above simulation results, a verification test was performed by the bottomless cylinder lifting method [12]. As shown in Figure 8, the test apparatus consisted of a bottomless cylinder (PVC material, inner diameter 60 cm and height 100 cm) and a horizontal plate (200 length × 200 width cm). After a large number of pre-experiments, 80 cabbages were selected for the experiment. The bottomless cylinder was raised at a slow velocity (0.05 m/s). After all the cabbages were stabilized, a photograph of the cabbage group was taken with the digital camera. The cabbage accumulation angle was obtained with image-processing software. The test was replicated ten times and averaged.



(**a**) (**b**)

Figure 8. Test of simulation parameter verification. (**a**) Photograph of the experiment and (**b**) simulation experiment.

3. Results and Discussion

3.1. Calibration of Contact Parameters between Cabbages and Materials

3.1.1. Coefficient of Restitution

According to Section 2.2.1, cabbages with similar size and quality were used for experiments. The experiments were repeated 30 times for each group, and the average value of the maximum rebound height was calculated. If the cabbage was damaged during the experiment, the result was considered as invalid and repeated with new cabbage. Furthermore, the coefficient of restitution between the cabbage and materials was obtained by Equation (1). The results are shown in Table 4.

Table 4. Measured values of the coefficient of restitution between cabbage and materials.

Material	Maximum Rebound Height/mm	Coefficient of Restitution Value
Q235 Steel	93.80	0.43
PVC	100.10	0.45
EVA	134.82	0.52
Wood	82.21	0.41

The established simulation model of cabbage particles was selected for the simulation test, as shown in Figure 3c. The particles were released at zero initial velocity at a distance of 500 mm above the contact materials.

In the calibration process, the coefficient of restitution between the cabbage and materials was set between 0.1 and 0.9, with an increment of 0.1, and the coefficients of static friction and rolling friction were set as 0. The maximum rebound height of the cabbage was measured by the analysis module of the EDEM software. Each experiment was repeated 30 times, and the average value was recorded. The fitting results are shown in Figure 9. Thus, the following fitting equation was obtained:

$$\begin{cases} h_1 = -3.55892e_1^3 + 504.58092e_1^2 - 8.0706e_1 + 2.8031 & R^2 = 0.9965 \\ h_2 = -46.9167e_2^3 + 554.55823e_2^2 - 17.24406e_2 + 5.212626 & R^2 = 0.9971 \\ h_3 = 265.37963e_3^3 + 184.48499e_3^2 + 51.28399e_3 + 4.81823 & R^2 = 0.9969 \\ h_4 = -0.378704e_4^3 + 505.1864e_4^2 - 8.46492e_4 + 2.88952 & R^2 = 0.9976 \end{cases} \quad (4)$$

where h_1, h_2, h_3 and h_4 are the maximum rebound heights of cabbage colliding with Q235 steel, PVC, EVA and wood, respectively, in mm and e_1, e_2, e_3 and e_4 are the coefficients of restitution of cabbage with Q235 steel, PVC, EVA and wood, respectively.

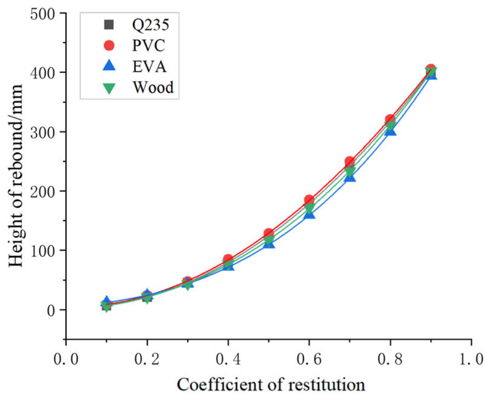


Figure 9. Relationship between the maximum rebound height and the coefficient of restitution.

According to Equation (4), the reliability of the fitting equation was high (coefficient of determination R^2 > 0.99). The maximum rebound height between the cabbage and the materials (Table 4) was substituted into Equation (4), and e_1, e_2, e_3 and e_4 were 0.43, 0.44, 0.55 and 0.41, respectively. The above coefficients of restitution were entered into the EDEM software. Each simulation test was repeated three times, and the average values were recorded. The simulated maximum rebound heights of the cabbage were 95.52, 99.45, 131.96 and 84.02 mm, respectively. The errors between simulated and measured values were 1.80%, 0.64%, 2.12% and 2.15%, respectively, which indicated that the error was within a reasonable range. Therefore, the coefficients of restitution of the cabbage with Q235 steel, PVC, EVA and wood were calibrated at 0.43, 0.44, 0.55 and 0.41, respectively.

3.1.2. Static Friction Coefficient

According to Section 2.2.2, the static friction coefficients between the cabbage and the contact materials were obtained by Equation (2), and the actual measured values are shown in Table 5.

Table 5. Measurement results of static friction coefficient between the cabbage and the contact materials.

Material	Inclination Angle/°	Static Friction Coefficient
Q235 Steel	35.31	0.71
PVC	20.24	0.37
EVA	37.17	0.76
Wood	33.82	0.67

The model of the static friction coefficient measuring instrument was simplified and imported into EDEM software. The model and parameters settings of the simulation test were consistent with the actual experiment. As shown in Figure 4b, four cabbage particle models were bonded together for the simulation test. The coefficient of restitution was set to the calibrated value. The range of the static friction coefficient was set between 0.1 and 0.9, with an increment of 0.1, and the coefficient of rolling friction was set to 0. The maximum inclination angle was measured by the analysis module of EDEM software. The fitting results are shown in Figure 10. Thus, the following fitting equation was obtained:

$$\begin{cases} \alpha_1 = -16.7687\mu_{s1}^3 + 13.83309\mu_{s1}^2 + 45.26707\mu_{s1} + 3.27797 & R^2 = 0.9968 \\ \alpha_2 = 23.78017\mu_{s2}^3 - 53.13228\mu_{s2}^2 + 77.50156\mu_{s2} - 1.07403 & R^2 = 0.9986 \\ \alpha_3 = 12.89455\mu_{s3}^3 - 39.25649\mu_{s3}^2 + 74.05492\mu_{s3} - 1.11075 & R^2 = 0.9977 \\ \alpha_4 = -0.77338\mu_{s4}^3 - 13.78027\mu_{s4}^2 + 59.20023\mu_{s4} + 1.39223 & R^2 = 0.9991 \end{cases} \quad (5)$$

where α_1, α_2, α_3 and α_4 are the inclination angle of cabbage on the slope of Q235 steel, PVC, EVA, and wood respectively, in mm and μ_{s1}, μ_{s2}, μ_{s3} and μ_{s4} are static friction coefficients of cabbage with Q235 steel, PVC, EVA and wood, respectively.

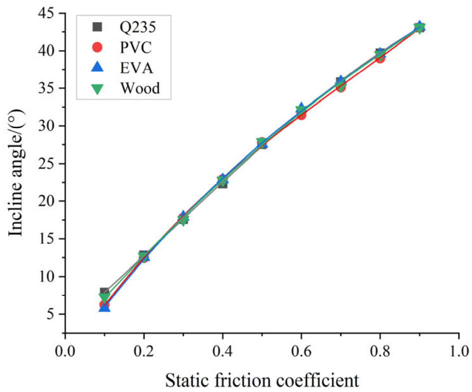


Figure 10. Relationship between the inclination angle and the static friction coefficient.

According to Equation (5), the reliability of the fitting equation was high (coefficient of determination $R^2 > 0.99$). The inclination angle in Table 5 was substituted into Equation (5), and μ_{s1}, μ_{s2}, μ_{s3} and μ_{s4} were 0.67, 0.34, 0.73 and 0.65, respectively. The above parameters were imported into the EDEM simulation software, and tests were performed in triplicate and averaged. The simulated inclination angles were 35.21°, 20.47°, 37.51° and 34.44°, respectively. The errors between the simulated and measured values were 0.28%, 1.12%, 0.91% and 1.80%, respectively, which indicated that the error is within a reasonable range. Therefore, the static friction coefficients of cabbage with Q235 steel, PVC, EVA and wood were calibrated at 0.67, 0.34, 0.73 and 0.65, respectively.

3.1.3. Rolling Friction Coefficient

According to Section 2.2.3, the rolling friction coefficient between the cabbage and the materials was obtained from Equation (3), and the actual measured values are displayed in Table 6.

Table 6. Measurement results of rolling friction coefficient between the cabbage and the materials.

Material	Rolling Distance/mm	Rolling Friction Coefficient
Q235 Steel	682.6	0.0481
PVC	673.8	0.0486
EVA	653.8	0.0496
Wood	586.9	0.0536

As shown in Figure 5b, the model of the rolling friction coefficient measuring device was simplified and imported into EDEM software. The parameters used in simulation test model were consistent with the actual experiment. The coefficient of restitution and the static friction were set to the calibrated value. The rolling friction coefficient between the cabbage and materials was set between 0.04 and 0.06, with an increment of 0.0025. The maximum rolling distance was measured by the analysis module of EDEM software. The fitting results are shown in Figure 11. Thus, the following fitting equation was obtained:

$$\begin{cases} L_1 = -7811447.8111\mu_{r1}^3 + 1586262.62621\mu_{r1}^2 - 117664.30976\mu_{r1} + 3531.05051 & R^2 = 0.9995 \\ L_2 = -9373737.37335\mu_{r2}^3 + 1778874.45882\mu_{r2}^2 - 125219.76912\mu_{r2} + 3619.20779 & R^2 = 0.9987 \\ L_3 = -5925925.92525\mu_{r3}^3 + 1281269.84117\mu_{r3}^2 - 101578.83597\mu_{r3} + 3244.93651 & R^2 = 0.9992 \\ L_4 = 1346801.34807\mu_{r4}^3 + 206810.96662\mu_{r4}^2 - 48381.43337\mu_{r4} + 2349.32612 & R^2 = 0.9985 \end{cases} \quad (6)$$

where L_1, L_2, L_3 and L_4 are the maximum rolling distance of cabbage on Q235 steel, PVC, EVA and wood, respectively, in mm and μ_{r1}, μ_{r2}, μ_{r3} and μ_{r4} are rolling friction coefficients of cabbage with Q235 steel, PVC, EVA and wood, respectively.

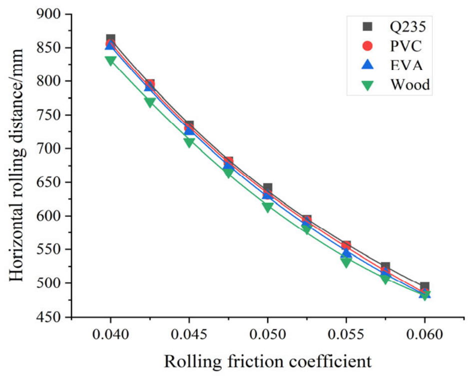


Figure 11. Relationship between the maximum rolling distance and the rolling friction coefficient.

According to Equation (6), the reliability of the fitting equation was high (coefficient of determination $R^2 > 0.99$). The values of maximum rolling distance in Table 6 were substituted into Equation (6), and μ_{r1}, μ_{r2}, μ_{r3} and μ_{r4} were 0.67, 0.34, 0.73 and 0.65, respectively. The above rolling friction coefficients were imported into the EDEM simulation software, and tests were performed in triplicate and averaged. The simulated rolling distances were 671.37, 672.35, 652.24 and 599.88 mm, respectively. The errors between the simulated and the measured values were 1.65%, 0.22%, 0.24% and 2.16%, respectively, which indicated that the error was within a reasonable range. Therefore, the rolling friction coefficients of cabbage with Q235 steel, PVC, EVA and wood were set as 0.0476, 0.0478, 0.0486 and 0.0517, respectively.

3.2. Calibration of Contact Parameters between Cabbages

3.2.1. Coefficient of Restitution

According to Section 2.3.1, if the cabbage was damaged during the experiment, the result was considered as invalid and repeated with a new cabbage. The coefficients of restitution between the cabbages and the contact materials were obtained by Equation (3), and the actual measured values are displayed in Table 7.

Table 7. Measurement of coefficient of restitution between cabbages.

Contact Material	Maximum Rebound Height/mm	Coefficient of Restitution Value
Cabbage–Cabbage	71.45–116.32	0.38–0.48

3.2.2. Cabbage Accumulation Angle

The cabbage accumulation angle experiments were conducted referring to Section 2.3.2 (1), and the collected images were processed with MATLAB software [30]. The original image (Figure 12a) was subjected to grayscale processing (Figure 12b), binarization processing (Figure 12c), hole filling (Figure 12d), boundary contour extraction (Figure 12e) and linear fitting (Figure 12f). The experiment was replicated ten times and averaged. The resulting measured value of the cabbage accumulation angle was 17.52°.

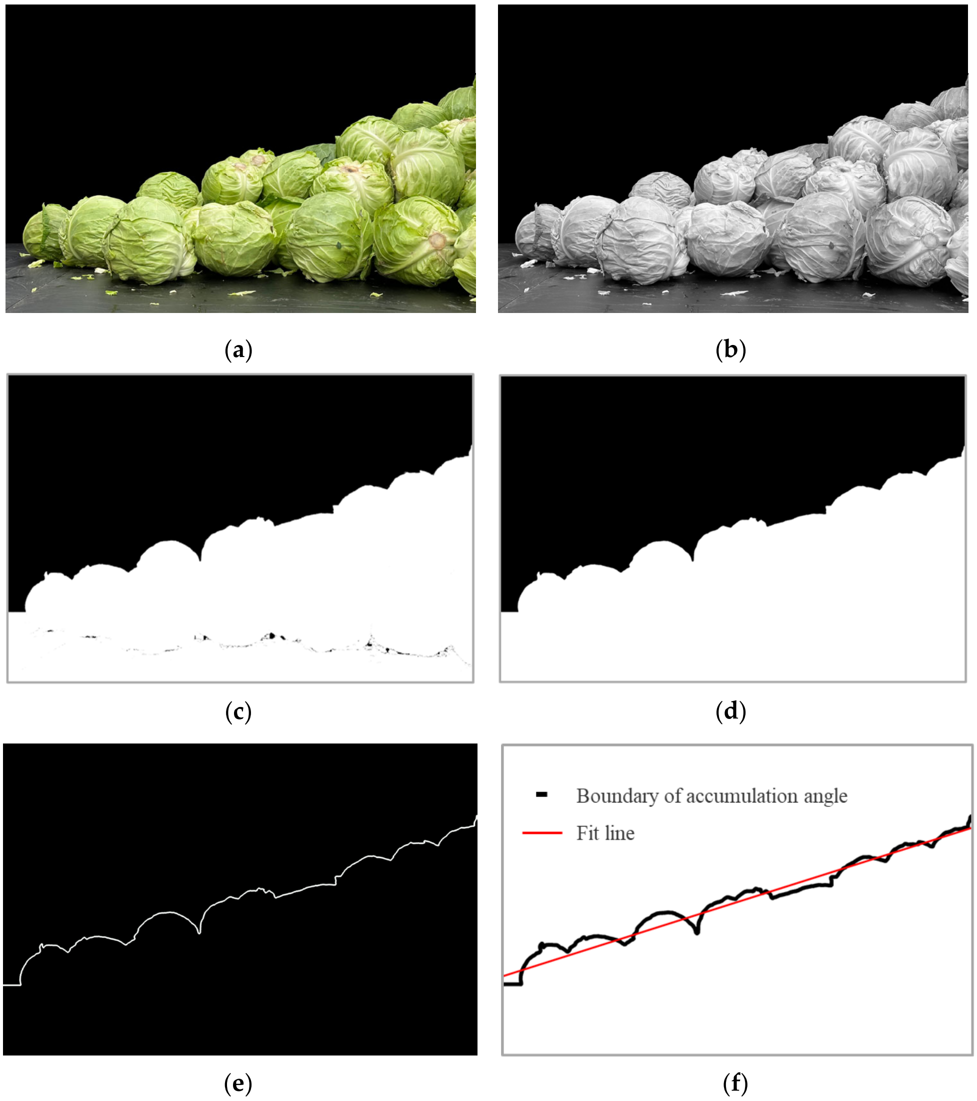


Figure 12. Experimental image processing of cabbage accumulation angle. (**a**) Original image; (**b**) grayscale image; (**c**) binarization processing; (**d**) hole filling image; (**e**) boundary contour extraction; and (**f**) linear fitting image.

3.2.3. Test of the Steepest Ascent

According to Table 7, the measured values of the coefficient of restitution between cabbages were between 0.38 and 0.48. Referring to the previously published work of most agricultural materials, the static friction coefficient was set to 0.20–0.50 [17,37,40], and the rolling friction coefficient was set to 0.01–0.05 [26,32]. As a consequence, the plan and the results of the steepest ascent test are illustrated in Table 8. Of these, the cabbage accumulation angle error values were calculated by the following equation:

$$\sigma = \frac{|\theta - \theta\prime|}{\theta\prime} \times 100\% \tag{7}$$

where σ is the error between the simulated and measured values of the cabbage accumulation angle; θ is the measured value of the cabbage accumulation angle, °, and θ' is the simulated value of the cabbage accumulation angle, °.

Table 8. Steepest ascent test plan and results.

Number	Test Factors			Test Results	
	e	μ_s	μ_r	θ'/(°)	σ/%
1	0.38	0.1	0.01	13.39	30.84
2	0.40	0.2	0.02	15.30	14.51
3	0.42	0.3	0.03	17.08	2.58
4	0.44	0.4	0.04	20.62	15.03
5	0.46	0.5	0.05	24.81	41.61
6	0.48	0.6	0.06	28.69	63.24

As shown in Table 8, with the increase in e, μ_s and μ_r, the cabbage accumulation angle error, σ, decreased initially and then subsequently increased. Test No.3 has the minimum relative error. Therefore, in the subsequent orthogonal rotation combination test, test No.3 was set as the intermediate level, and the values for tests No.2 and No.4 were identified as low and high levels, respectively.

3.2.4. Analysis of Calibration Results of Contact Parameters between Cabbages

The coefficient of restitution (e), the coefficient of static friction (μ_s) and the coefficient of rolling friction (μ_r) between the cabbages were used as test factors, and the accumulation angle error was used as the test indicator. The orthogonal rotation combination simulation test was performed using Design-Expert 10. The test factor code is shown in Table 9.

Table 9. The code table of the orthogonal rotation combination test.

Level	Test Factors		
	e	μ_s	μ_r
−1.682	0.386	0.132	0.013
−1	0.400	0.200	0.020
0	0.420	0.300	0.030
1	0.440	0.400	0.040
1.682	0.454	0.468	0.047

Each group of tests was performed in triplicate and averaged. The test scheme and results are shown in Table 10.

The test results were analyzed by Design-Expert 10. The regression model of error was obtained as follows:

$$Y = 1.37 + 0.048A - 1.81B - 0.68C + 0.083AB + 0.32AC + 1.07BC + 0.57A^2 + 1.89B^2 + 0.72C^2 \tag{8}$$

The analysis of variance results are shown in Table 11. A regression model p-value of <0.0001 (<0.01), and the lack-of-fit term p-value of 0.2052 (>0.05), suggest that the model was highly significant. In addition, the most significant parameters affecting the accumulation angle of the cabbages were the coefficient of static friction and the rolling friction between cabbages, while the coefficient of restitution between the cabbages had little effect. Therefore, the optimized accumulation angle error model of cabbage is as follows:

$$Y = 1.37 - 1.81B - 0.68C + 1.07BC + 0.57A^2 + 1.89B^2 + 0.72C^2 \quad (9)$$

Table 10. The orthogonal rotation combination test scheme and results.

Number	Parameter			$Y(\sigma)$/%
	$A(e)$	$B(\mu_s)$	$C(\mu_r)$	
1	0	0	1.682	1.82
2	0	0	0	0.88
3	1.682	0	0	2.66
4	0	1.682	0	3.55
5	−1.682	0	0	2.54
6	−1	−1	−1	9.18
7	−1	−1	1	4.34
8	0	0	0	1.96
9	0	−1.682	0	9.14
10	1	−1	1	5.71
11	1	1	−1	2.71
12	0	0	0	1.67
13	0	0	0	1.86
14	1	−1	−1	7.71
15	−1	1	−1	2.27
16	0	0	−1.682	4.24
17	1	1	1	3.39
18	0	0	0	1.22
19	0	0	0	0.74
20	−1	1	1	3.27

Table 11. Variance analysis of cabbage accumulation angle error.

Source	Sum of Squares	Degree of Freedom	Mean Square	F-Value	p-Value
Model	118.38	9	13.15	30.89	<0.0001 **
A	0.032	1	0.032	0.075	0.7893
B	44.68	1	44.68	104.92	<0.0001 **
C	6.24	1	6.24	14.65	0.0033 **
AB	0.054	1	0.054	0.13	0.7281
AC	0.79	1	0.79	1.86	0.2021
BC	9.07	1	9.07	21.31	0.0010 **
A^2	4.69	1	4.69	11.01	0.0078 **
B^2	51.72	1	51.72	121.47	<0.0001 **
C^2	7.52	1	7.52	17.66	0.0018 **
Residual	4.26	10	0.43		
Lack of Fit	2.92	5	0.58	2.19	0.2052
Pure error	1.34	5	0.27		
Sum	122.64	19			

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

Based on the above analysis results, the coefficient of restitution was set at an intermediate level (0.42). Using the minimum error of accumulation angle as the optimization target, the coefficients of static friction and rolling friction between cabbages were used as the optimization objects of study. The Optimization-Numerical module in the Design-

Expert 10 software was used for optimization solution of the regression equation model, with the constraints as follows:

$$\begin{cases} \min Y(B, C) \\ s.t. \begin{cases} A = 0.42 \\ -1.682 \leq B \leq 1.682 \\ -1.682 \leq C \leq 1.682 \end{cases} \end{cases} \quad (10)$$

Through optimization, the results were as follows: the coefficient of restitution was selected as 0.42, the static friction coefficient was selected as 0.457, the rolling friction coefficient was selected as 0.039 and the relative error of accumulation angle was 0.96%. Under this condition, the simulation value of the accumulation angle was 17.64°, in good agreement with the experimental measurements.

3.3. Analysis of the Results of Simulation Parameters Verification

According to Section 2.4, the reliability and accuracy of the calibrated simulation parameters were verified. The above-determined simulation parameters were imported into EDEM. The experiment was replicated ten times and averaged. Both measured and simulated values of the cabbage accumulation angle were obtained. The results of the verification test are displayed in Table 12.

Table 12. Results of the verification test.

Subject	Measured Value/°	Simulated Value/°	Error/%
Cabbage	17.56	17.85	1.63

According to Table 12, the error between the simulated and measured values was only 1.63%, demonstrating that the calibration parameters based on DEM had a high reliability.

4. Conclusions

(1) Based on the measurement of cabbage critical intrinsic parameters, a 3D model of a cabbage was established, and a simulation model was constructed based on DEM. The simulation parameters between the cabbage and the contact materials (Q235 steel, PVC, EVA and wood) were calibrated. The coefficients of restitution of the cabbage with Q235 steel, PVC, EVA and wood were 0.43, 0.44, 0.55 and 0.41, respectively; the static friction coefficients were 0.67, 0.34, 0.73 and 0.65, respectively; and the rolling friction coefficients were 0.0476, 0.0478, 0.0486 and 0.0517, respectively.

(2) The contact parameters between cabbages were calibrated. The coefficient of restitution between cabbages was measured by a free fall collision experiment, and the accumulation angle of the cabbages was measured by actual experiment. Through the steepest ascent test and the orthogonal rotation combination test, a regression model of the cabbage accumulation angle error was established. The optimal contact parameters between the cabbages were obtained by the minimum error modeling. The coefficient of restitution between cabbages was 0.42, the coefficient of static friction between cabbages was 0.457 and the coefficient of rolling friction between the cabbages was 0.039.

(3) A verification test of the cabbage accumulation angle was conducted with the bottomless cylinder lifting method, and the relative error between the simulated and the measured values was 1.63%, thus verifying the reliability of the calibrated simulation parameters. This study can provide a theoretical support for designing and optimizing the parameters of cabbage harvesting machines with DEM.

Author Contributions: Conceptualization, J.Z. and X.W.; methodology, J.Z. and X.W.; software, J.Z. and Z.Y.; validation, Y.S. and X.W.; investigation, J.Z. and L.W; resources, L.W. and X.W.; data curation, J.Z.; writing—original draft preparation, J.Z.; writing—review and editing, X.W.; visualization, Y.S.; supervision, X.W.; funding acquisition, L.W. and X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Project of State Key Laboratory of Power System of Tractor (grant no. SKT2022005).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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