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Calibration and Testing of Discrete Element Modeling Parameters for Fresh Goji Berries

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Abstract: This paper aims at the standard grading of fresh goji berries and develops a variable gap-type fresh goji berry grading machine. To establish a complete simulation model, the discrete element parameters of the model were calibrated by a combination of physical experiments and simulation experiments. The outline of the goji berry was extracted by the SFM-CMVS technique, and a goji berry model was obtained using the multi-spherical particle model filling method in the EDEM software. By designing the free-fall, suspension collision, slope slip, and slope rolling experiments, we obtained the discrete element simulation parameters: the inter-particle collision restitution coefficient was 0.158, the collision restitution coefficient of fresh goji berry–silicone rubber material was 0.195, the static friction coefficient of fresh goji berry–silicone rubber material was 0.377, and the rolling friction coefficient of fresh goji berry–silicone rubber material was 0.063. By designing the steepest ascent search and central composite design experiments with the angle of repose (AoR) value obtained from the physical experiment as the target value (31.27°), we determined the inter-particle static friction coefficient to be 0.454 and the inter-particle rolling friction coefficient to be 0.037. Validation tests were conducted on the calibrated discrete element modeling parameters, and the results showed that the established fresh goji berry model and the optimally calibrated parameter combination are effective for discrete element studies on fresh goji berries.

Keywords: fresh goji berry; grading machine; discrete element parameters; EDEM software; calibration

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1. Introduction

Goji berry is a tonic quality Chinese herbal medicine with good health effects and is also one of the characteristic crops in the northwest of China [1]. Currently, processed Chinese goji berry products are sought after by domestic and foreign consumers of all ages, and China's fresh goji berry planting area has exceeded 160,000 hectares. The mechanized grading process of fresh goji berries is crucial to improve their drying quality and economic efficiency, but mature fresh goji berries are characterized by thin skin, tender flesh, and high water content as well as short storage time [2]. There is no grading method for fresh goji berries for the time being.

The grading machines in agriculture can be divided into five types according to their working principles: hole, roller-shaft, wind, weighing, and visual recognition. Li et al. [3,4] designed a vibratory grading machine with a differential queuing method for counting to meet the integrated needs of grading and counting scallop seedlings. The high-speed vibration of the screen affects the activity of scallop seedlings, and it is suitable for grading small and hard-shelled crops. Dai et al. [5] added dual front and rear air ducts to the vibratory grading machine to achieve separation and cleaning of the flax threshing material. Lü et al. [6,7] proposed a roller-shaft grading machine for potato grading. The device controls the grading range by changing the lifting angle through a differential grading device, and the equipment is highly productive. However, the fruit rotates forward in the gap between two rollers, and the friction between them causes damage to the fruit surface. Compared to mechanical grading methods, the visual recognition type is an ideal non-destructive grading method. Pourdarbani et al. [8] and Kumar et al. [9] developed a sorting system based on an artificial neural network with machine vision to grade red dates and pomegranates, respectively. The disadvantages of this method are low productivity and high cost.

The grading of fresh goji berries needs to meet the requirements of low damage rate, high grading accuracy, and high productivity at the same time, and none of the above research results can be directly used to grade fresh goji berries. Combining previous research, we designed a variable gap-type fresh goji berry grading machine.

The discrete element method (DEM) is a new numerical computational method for analyzing the laws of motion and mechanical properties of complex discrete systems. In recent years, with the continuous improvement of discrete element theories and related software, more and more scholars have applied the DEM to design and optimize agricultural machinery [10,11]. Liang et al. [12] carried out simulations using EDEM software to investigate the effect of the height, the mounting angle, and the number of guide blades on the threshing output of the combine harvester. Li et al. [13] developed a precision seeder for dry direct-seeded rice with film mulching. Based on the EDEM simulation results in different situations, the optimum working parameters were obtained.

One crucial step to ensure the accuracy of the model is inputting accurate simulation parameters, including intrinsic parameters and contact parameters. The intrinsic parameters of the material (mainly bulk density, Young's modulus, and Poisson's ratio) can be measured directly by equipment, or values reported in the literature can be used [14]. However, the calibration of the contact parameters (mainly collision restitution coefficient, static friction coefficient, rolling friction coefficient) requires simulation in combination with DEM due to the differences in geometry and surface roughness between simulated and real particles [15]. A combination of physical experiments and simulation tests is commonly used for the calibration of the contact parameters. Zhang et al. [16] established a simulation model of mung beans using the Hertz–Mindlin with bonding model, conducted physical experiments and DEM simulation experiments, and calibrated the simulation parameters between mung bean seeds and two contact materials.

The discrete element simulation parameters of bulk materials such as maize kernels [17,18], rice [19], wheat [20], radish seeds [21], and peanuts [22], have been calibrated by domestic and foreign scholars. The parameters were also verified by field tests, and the results showed that the contact parameters varied significantly for different particles. However, the calibration of contact parameters for goji berries has rarely been reported.

In this paper, we took fresh goji berry as the research object, established the simulation model of fresh goji berries using SFM-CMVS technology, and calibrated the discrete element modeling parameters required for the simulation based on its intrinsic parameters. The reliability and scientificity of the simulation model and simulation parameters was verified using field tests, thus providing a reference for the design and simulation study of the device.

2. Materials and Methods

2.1. Fresh Goji Berry Material Characteristics

On 18 July 2021, 100 ripe fresh goji berries were randomly picked from a goji berry plantation in Pingluo County, Ningxia Hui Autonomous Region (38°45′ N, 106°46′ E, altitude 1463 m). The triaxial dimensions (length, width, and thickness) were measured with vernier calipers (range: 0~200 mm, accuracy: 0.02 mm). The mass of each grain was measured with a high-precision electronic scale (range: 0~100 g, accuracy: 0.001 g). The density of the goji berry was measured indirectly with the liquid displacement method [23]. Using the data, the equivalent diameter and sphericity of fresh goji berries were calculated to be 14.03 mm and 54.24% from Equations (1) and (2). As shown in Figure 1, the fresh goji berry has a distinct ellipsoidal appearance.

$$D_p = \sqrt[3]{LWT} \tag{1}$$

$$\varphi = \frac{\sqrt[3]{LWT}}{L} \times 100\% \tag{2}$$

where D_p is the equivalent diameter of fresh goji berry (mm); φ is the sphericity of fresh goji berry (%); and L, W, and T are the average length, width, and thickness of fresh goji berry, respectively (mm).

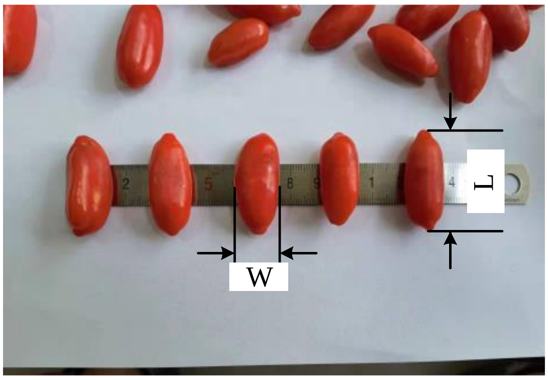

Figure 1. The shape of fresh goji berries.

To measure the intrinsic parameters (Poisson's ratio, shear modulus, and elastic modulus) of fresh goji berries, compression experiments were performed on samples of goji berries using a texture analyzer (Stable Micro Systems) in the mechanics laboratory.

In the compression experiment, pressure was applied to the W direction of the goji berry until it reached the maximum critical deformation (Figure 2), and the loading speed was 8 mm/min [24]. The loading force and transverse deformation of the sample was obtained by post-processing, and the longitudinal deformation was measured by a digital vernier caliper. The Poisson's ratio (ν) of the goji berry can be calculated as 0.420 by Equation (3), the elastic modulus (E) can be calculated as 2.217×10^6 pa by Equation (4), and the shear modulus (G) can be calculated as 7.807×10^5 pa by Equation (5).

$$\nu = \frac{|\varepsilon_2|}{|\varepsilon_1|} = \frac{(L_2 - L_1)/L_1}{(W_1 - W_2)/W_1} \tag{3}$$

where ν is the Poisson's ratio of fresh goji berry; ε_1 is the strain in the loading direction; ε_2 is the strain in the vertical direction; L_1 is the original length of the sample (mm); L_2 is the length of the sample after compression (mm); W_1 is the original width of the sample (mm); W_2 is the length of the sample after compression (mm).

$$E = \frac{F/S}{(W_1 - W_2)/W_1} \tag{4}$$

where E is the elastic modulus of fresh goji berries (Pa); F is the loading force when the sample reaches the critical elastic deformation state (N); S is the cross-sectional area of the sample, with the cross-sectional approximation of an ellipse (mm^2).

$$G = \frac{E}{2(1+\nu)} \tag{5}$$

where G is the shear modulus of fresh goji berries (Pa).

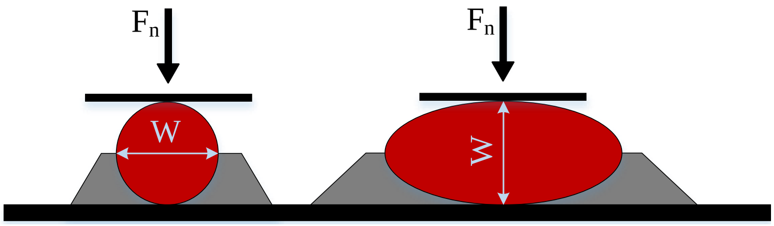

Figure 2. Compression experiment of fresh goji berry.

2.2. Design of Variable Gap-Type Fresh Goji Berry Grading Machine

2.2.1. Overall Structure and Working Principle of the Machine

The intrinsic parameters of the fresh goji berries show that the fresh goji berries are characterized by thin skin and tender flesh. For non-destructive grading of fresh goji berries, we designed the variable gap-type fresh goji berry grading machine.

The variable gap-type fresh goji berry grading machine is mainly composed of the sieving unit, the orientation device, the grading range adjustment component, the frame structure, and the driving component, as shown in Figure 3. In the operation process, the sieving unit is driven forward by the driving component. The fresh goji berries enter the sieve surface and move forward together with the belts, and there is no relative movement between them. The gap between the belts gradually increases from 5 mm to 20 mm. The goji berries fall into the basket through the belt conveyor. Finally, they are divided into several grades according to the size of the horizontal diameter.

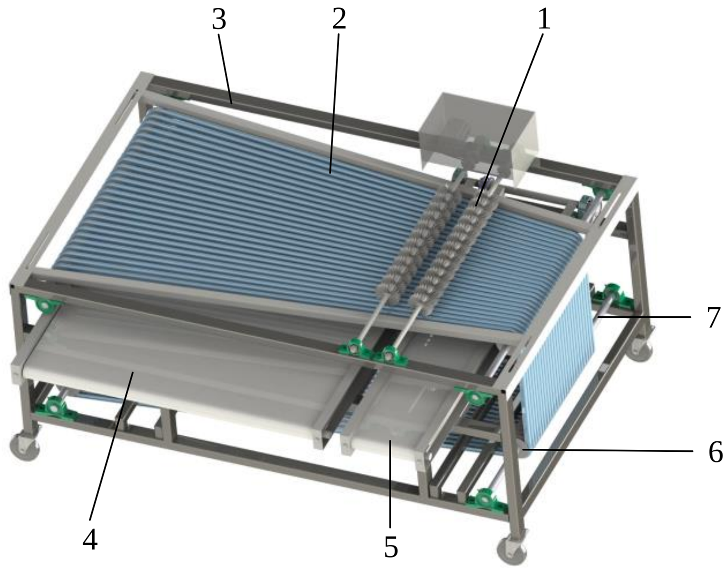

Figure 3. Structure of variable gap-type fresh goji berry grading machine. 1. Directional brush. 2. Belt. 3. Frame. 4. Belt conveyor for large fruit discharge. 5. Belt conveyor for small fruit discharge. 6. Belt pulley. 7. Drive shaft.

2.2.2. Design of Grading Belt

The belt used for grading is one of the key components of the machine, and its shape is shown in Figure 4. The grading belt has no inner core, so it can be freely bent and driven. To restrain the belt from sagging, there is a belt guide below each belt, and the belt slides in the guide. The material of the belt is silicone rubber. Silicone rubber materials are characterized by non-toxicity, softness, and chemical stability, as well as high elasticity. The material parameters are shown in Table 1 [25,26].

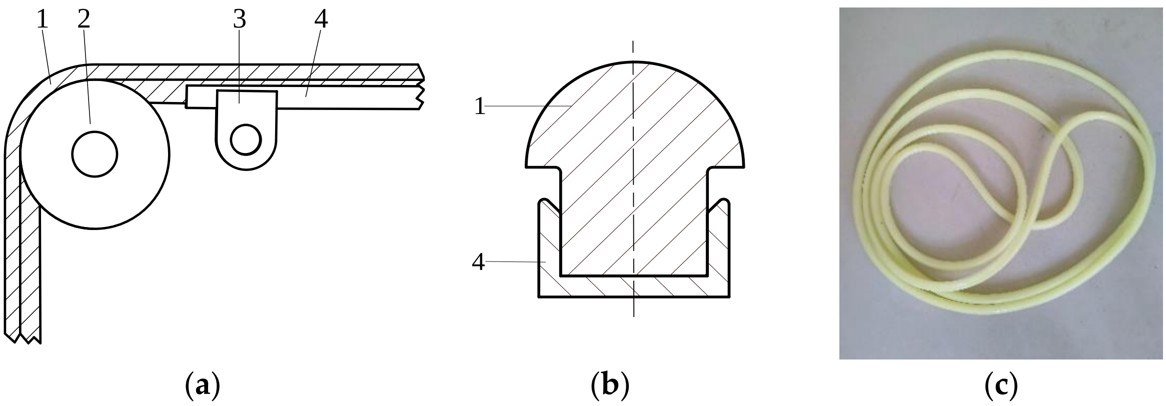

Figure 4. The shape of grading belt. (**a**) Assembly of grading belt and guide groove; (**b**) Cross-sectional shape of belt; (**c**) A grading belt in kind. 1. Grading belt. 2. Pulley. 3. Support clip. 4. Belt guide groove.

Table 1. Material properties of silicone rubber material.

Material Properties	Values
Shore A hardness/HA	55
Elongation/%	200~600
Tensile strength/Pa	5×10^6~10×10^6
Density/$kg \cdot m^{-3}$	1150
Poisson's ratio	0.480
Elastic modulus/Pa	1.30×10^6

2.3. Physical Experiments for the Calibration of Contact Parameters

2.3.1. Collision Restitution Coefficient of Fresh Goji Berry–Silicone Rubber Material

The free-fall experiment was used to calibrate the collision restitution coefficient of fresh goji berry–silicone rubber material [27]. The collision restitution coefficient is calculated by Equation (6).

$$Ex_1 = \frac{v_1}{v_0} = \frac{\sqrt{2gH_1}}{\sqrt{2gH_2}} = \sqrt{\frac{H_1}{H_0}} \tag{6}$$

where Ex_1 is the collision restitution coefficient of fresh goji berry–silicone rubber plate; v_0 is the normal relative approach velocity of fresh goji berry–silicone rubber plate (mm/s); v_1 is the normal relative separation velocity of fresh goji berry–silicone rubber plate (mm/s); g is the acceleration of gravity (980 mm/s^2); H_0 is the initial height of the goji berry (mm); H_1 is the maximum rebound height of the goji berry after collision with silicone rubber plate (mm).

The experiment was conducted to release a fresh goji berry from a certain height, and to fell onto a horizontally placed silicone rubber plate. The test process is shown in Figure 5. The highest point where the particle rebound up was captured by a high-speed camera, and the highest point was read by graph paper. Changing the initial release height of goji berry has no significant effect on the collision restitution coefficient, and H_0 = 300 mm was selected as the initial condition to carry out the experiment. The collision restitution coefficient was calculated by Equation (6). The experiment was repeated five times, and the results were averaged.

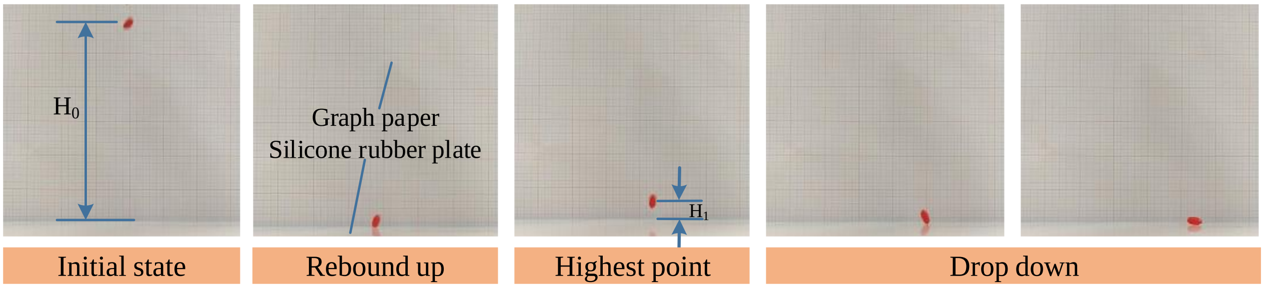

Figure 5. Physical experiment for calibrating the collision restitution coefficient of fresh goji berry–silicone rubber material.

The experiment results show that the average maximum rebound height of goji berry is 11.5 mm. Under real test conditions, the collision restitution coefficient of fresh goji berry–silicone rubber material was 0.196.

2.3.2. Collision Restitution Coefficient of Fresh Goji Berry-Fresh Goji Berry

To determine the collision restitution coefficient between the fresh goji berry particles, two fresh goji berries were selected for a suspension collision experiment [28]. The collision restitution coefficient of fresh goji berry–fresh goji berry was calculated by Equation (7).

$$Ex_2 = \frac{\sqrt{2gH_b} - \sqrt{2gH_a}}{\sqrt{2gH_2}} = \frac{\sqrt{H_b} - \sqrt{H_a}}{\sqrt{H_2}} \tag{7}$$

where Ex_2 is the collision restitution coefficient of fresh goji berry–fresh goji berry; H_2 is the height of fresh goji berry A being lifted (mm); H_a is the maximum rising height of the goji berry A after collision (mm); H_b is the maximum rising height of the goji berry B after collision (mm).

As shown in Figure 6, the particles A and B were each attached to a nylon rope with a length of 160 mm, and the two particles were at the same height in the natural hanging state. During the experiment, the natural hanging points of particles A and B were adopted as the base point. We lifted particle A (keeping the nylon rope in a stretched state) to the height in the vertical direction of the base point, and the particle B was in a natural hanging state. Releasing particle A with zero initial velocity, it moved to the base point and collided with particle B, and they swung around the nylon rope with a radius of 160 mm. At this time, the maximum heights of particles A and B from the base point in the vertical direction were H_a and H_b, respectively. The whole process was recorded by a high-speed camera.

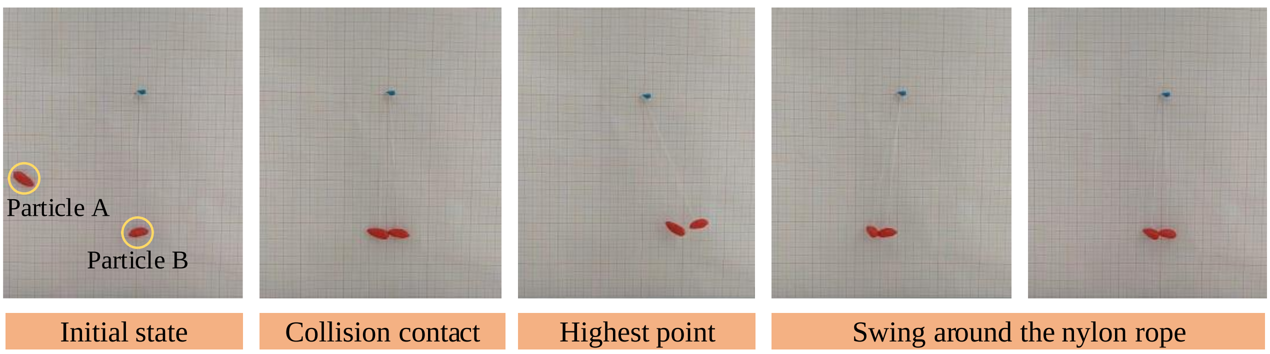

Figure 6. Physical experiment for calibrating the collision restitution coefficient of fresh goji berry–fresh goji berry.

Varying the initial release height of particle A had no significant effect on the value of the interparticle collision restitution coefficient, thus H_2 = 60 mm was selected as the initial condition for the suspension collision experiments. The experiment results show that the average maximum rising height of fresh goji berry B was 18.0 mm, and the average maximum rising height of fresh goji berry A was 9.5 mm. After the calculation of Equation (7), the collision restitution coefficient of fresh goji berry–fresh goji berry was 0.150.

2.3.3. Static Friction Coefficient of Fresh Goji Berry–Silicone Rubber Material

The static friction coefficient of fresh goji berry–silicone rubber material was calibrated by the slope slip method. The static friction coefficient of fresh goji berry–silicone rubber material can be calculated by Equation (8).

$$\mu_{s1} = \frac{f}{T} = \frac{mg\sin\theta}{mg\cos\theta} = \tan\theta \tag{8}$$

where μ_{s1} is the static friction coefficient of fresh goji berry–silicone rubber material; m is the mass of the goji berry (kg); θ is the angle between silicone rubber plate and horizontal direction when the fresh goji berry sliding occurs (°).

A silicone rubber plate was placed on the support plate to form the experimental slope, as shown in Figure 7. To prevent the single fresh goji berry from rolling on the slope, three fresh goji berries were bonded together and placed on the plate. One side of the slope and the horizontal experimental bench always fit, and we slowly and uniformly lifted the other side. When the fresh goji berries started to slide on the plate, the angle between the plate and the test bench was measured with an angle ruler (range: 0°~360°, accuracy: 0.05°). The slope slip experiment was repeated five times, and the average of the results was taken.

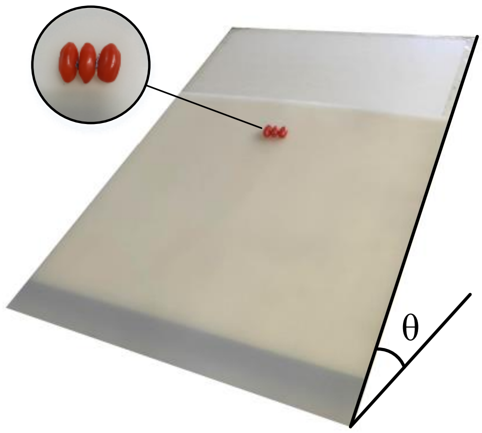

Figure 7. Physical experiment for calibrating the static friction coefficient of fresh goji berry–silicone rubber material.

The slope slip experiment results show that the average slope angle was 21.77°. Under real test conditions, the static friction coefficient of fresh goji berry–silicone rubber material was 0.340.

2.3.4. Rolling Friction Coefficient of Fresh Goji Berry–Silicone Rubber Material

The rolling friction coefficient of fresh goji berry–silicone rubber material was calibrated by the slope rolling method [28]. In the process of the experiment, without considering the influence of static friction, Equation (9) can be obtained from the law of conservation of energy, and the rolling friction coefficient can be calculated from Equation (10).

$$mgS\sin\alpha = \mu_{r1}mg(S\cos\alpha + Y) \tag{9}$$

where μ_{r1} is the rolling friction coefficient of fresh goji berry–silicone rubber plate; α is the angle of inclination of the slope (°); S is the rolling distance of the goji berry on the slope (mm); Y is the rolling distance of the goji berry on the horizontal plate (mm).

$$\mu_{r1} = \frac{S \sin \alpha}{S \cos \alpha + Y} \tag{10}$$

As shown in Figure 8, a silicone rubber plate was placed at an inclined angle of 30°. A fresh goji berry was released along the slope at the initial velocity of 0. The fresh goji berry rolled down along the slope, and the rolling distance of the particle on the slope was 30 mm. Due to the rolling friction, the goji berry rolled on the horizontal plate for a distance, and finally it stood still. The rolling distance (Y) of the particle on the horizontal plate was measured by a tape measure.

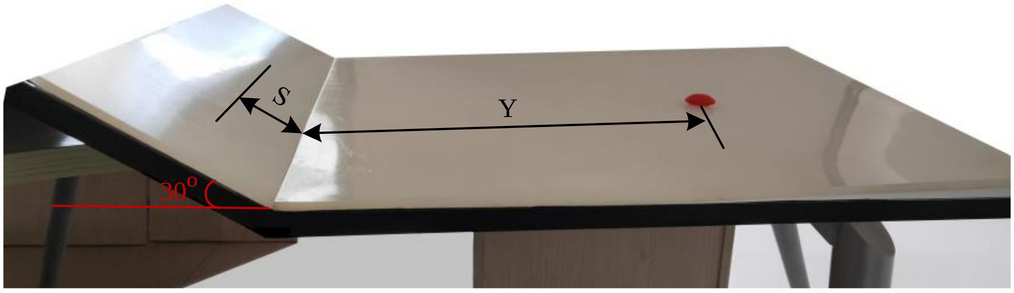

Figure 8. Physical experiment for calibrating the rolling friction coefficient of fresh goji berry–silicone rubber material.

The slope rolling experiment results show that the average horizontal rolling distance was 237.2 mm, and the rolling friction coefficient of fresh goji berry–silicone rubber material under real test conditions was 0.057.

2.3.5. Angle of Repose Experiment

The AoR of fresh goji berries was measured by the cylinder lifting method [29]. We poured 1 kg of fresh goji berries from the top of a hollow cylinder. After all of the dumping, the hollow cylinder was lifted up at a speed of 5 mm/s. The fresh goji berries fell naturally due to gravity and gathered at an angle on the silicone rubber plate, as shown in Figure 9a. We used Python (version 3.7) for grayscale processing (Figure 9b), binarization processing (Figure 9c), hole filling (Figure 9d), boundary extraction (Figure 9e), and least-squares fitting (Figure 9f) of the image [30]. The average AoR from the physical experiment of fresh goji berries was obtained at 31.27°.

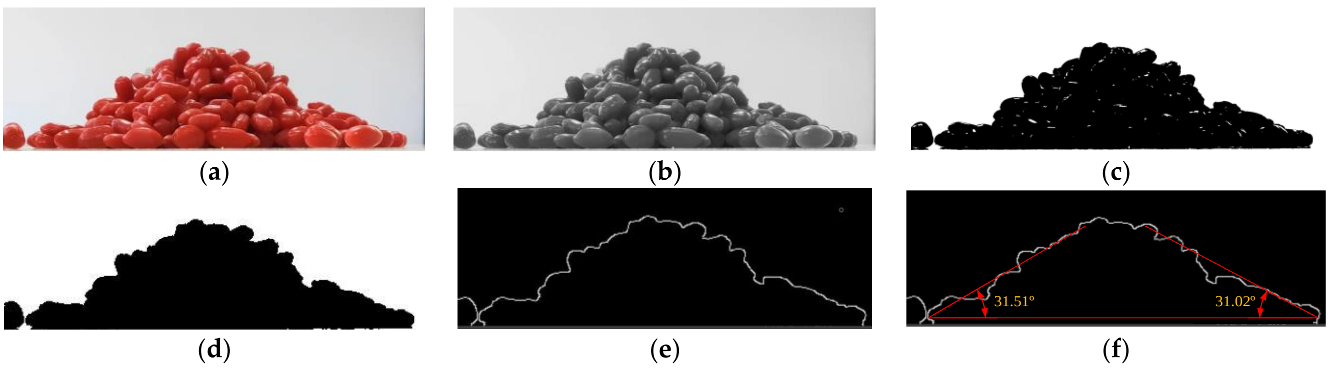

Figure 9. The analysis process of the value of AoR. (**a**) Original image; (**b**) Grayscale processing; (**c**) Binarization processing; (**d**) Hole filling processing; (**e**) Boundary extraction; (**f**) Least-squares fitting.

2.4. Simulation Experiments for the Calibration of Contact Parameters

The discrete element parameters were calibrated using the DEM. We built the simulation test models in EDEM 2020 software (DEM Solutions Ltd., Edinburgh, Scotland, UK), and designed single-factor simulation experiments. The simulation experiments were performed in the same way as the physical experiments.

2.4.1. Three-Dimensional Reconstruction of the Fresh Goji Berry Model

In order to establish an accurate 3D model of the fresh goji berry and improve the realism of the simulation, we used the structure from motion coupled with clustering views for multi-view stereo (SFM-CMVS) technique to acquire the model of a fresh goji berry [31,32]. The main steps include: image data acquisition, point cloud data pre-processing, point cloud data materialization, mesh partitioning, and mesh filling.

As shown in Figure 10, we selected a fresh goji berry with near-average size and uniform shape as the object, took 128 2D images with an industrial camera, and imported the images into Visual SFM software to obtain the dense point cloud model of the goji berry. The point cloud filter tool of MeshLab software was used to remove noise and redundant points from the point cloud file and extract the contour area of the goji berry. The solid model of the goji berry was obtained by surface fitting the point cloud data, and the solid model was imported into HyperMesh software for meshing. The mesh was filled as a particle template in the EDEM software. The desired fresh goji berry model was obtained by using the modeling method of multiple spherical cells overlapping to form a particle cluster.

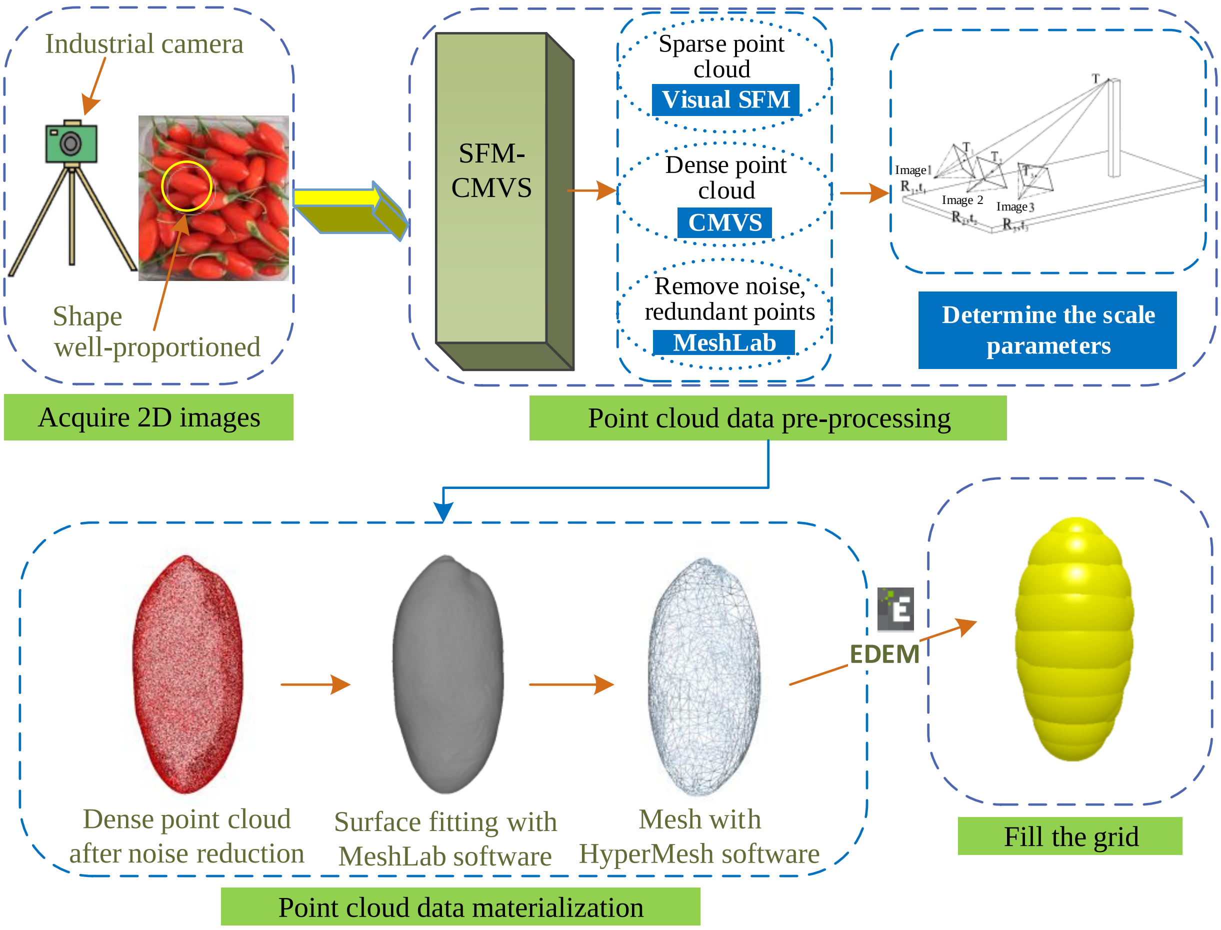

Figure 10. The process of inverse acquisition of a 3D model of fresh goji berry.

2.4.2. Simulation Experiment for Collision Restitution Coefficient of Fresh Goji Berry–Silicone Rubber Material

As with the physical experiment, the simulation experiment was carried out with H_0 = 300 mm as the initial condition. The particle displayed a free-fall motion to the silicone rubber plate with 0 initial velocity, as illustrated in Figure 11. The contact model between fresh goji berry and silicone rubber material was taken as Hertz–Mindlin (no slip) in the EDEM software. When setting the contact parameters between the fresh goji berry and contact material, the static friction coefficient and rolling friction coefficient had no effect on the rebound height of the particle; hence, these two parameters were set to 0.

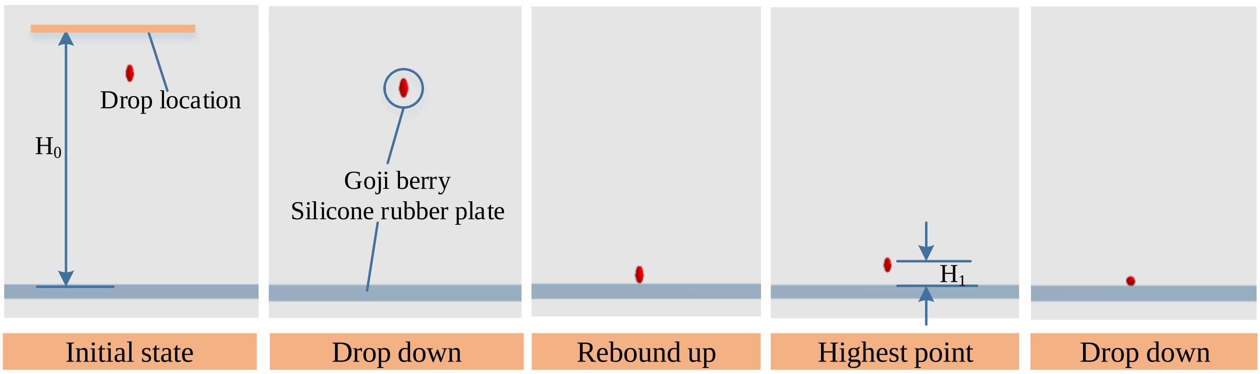

Figure 11. Simulation experiment for calibrating the collision restitution coefficient of fresh goji berry–silicone rubber material.

Table 2 presents the design scheme and results of the simulation experiment, where the collision restitution coefficient (Ex_1) was considered as a factor and the highest rebound height (H_1) was adopted as an index.

Table 2. Design scheme and results of free-fall experiment.

Group No.	Ex_1	H_1/mm
1	0.1	2.214
2	0.2	14.220
3	0.3	30.659
4	0.4	43.573
5	0.5	74.025
6	0.6	110.760
7	0.7	151.756
8	0.8	198.919
9	0.9	256.737

2.4.3. Simulation Experiment for Collision Restitution Coefficient of Fresh Goji Berry–Fresh Goji Berry

As shown in Figure 12, a semicircular hollow pipe with a diameter of 320 mm was added to the EDEM software. In the pipe, two particles were generated at the bottom and 60 mm from the base point in the vertical direction. The intrinsic parameters of the pipe did not have a significant effect on the experimental process, so the pipe intrinsic parameters were set to be the same as the silicone rubber material. The collision restitution coefficient, static friction coefficient, and rolling friction coefficient were set to 0.

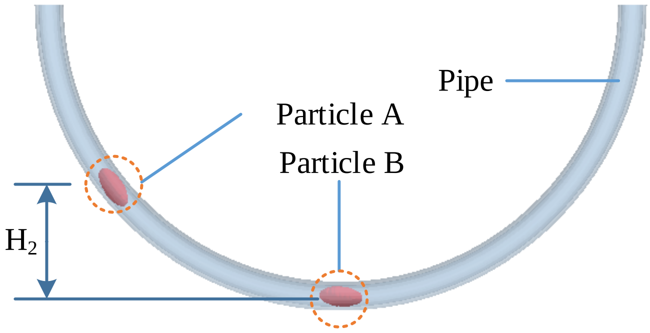

Figure 12. Simulation experiment for calibrating the collision restitution coefficient of fresh goji berry–fresh goji berry.

Table 3 presents the design scheme and results of the simulation experiment, where the collision restitution coefficient (Ex_2) was considered as a factor and the highest rising heights were adopted as indexes.

Table 3. Design scheme and results of suspension collision experiment.

Group No.	Ex_2	H_a/mm	H_b/mm
1	0.1	11.488	16.523
2	0.2	8.066	20.650
3	0.3	7.417	25.301
4	0.4	6.003	33.752
5	0.5	5.223	39.096
6	0.6	4.143	44.803
7	0.7	3.575	52.447
8	0.8	1.947	55.170
9	0.9	0.530	60.933

2.4.4. Simulation Experiment for Static Friction Coefficient of Fresh Goji Berry–Silicone Rubber Material

A rectangular body (500 mm in length, 500 mm in width, and 10 mm in height) was added in the EDEM software, and its intrinsic parameters were set to be the same as those of the silicone rubber material. A multi-sphere combination method was used to generate three combined particles to simulate the bonded fresh goji berries under real test conditions, as illustrated in Figure 13. The collision restitution coefficient of fresh goji berry–silicone rubber material was taken to be the calibrated value of 0.195, and the rolling friction coefficient was taken to be 0.

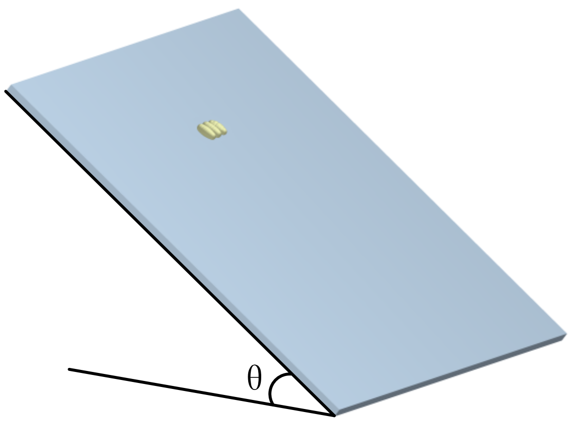

Figure 13. Simulation experiment for calibrating the static friction coefficient of fresh goji berry–silicone rubber material.

In the simulation experiment, one side of the plate was always attached to the ground, and the other side was slowly raised at a speed of 2°/s. When the particles started to slide, the slope inclination (θ) was read by the post-processing module. Table 4 presents the design scheme and results of the simulation experiment.

Table 4. Design scheme and results of static friction coefficient experiment.

Group No.	μ_{s1}	θ/°
1	0.1	5.696
2	0.2	14.745
3	0.3	19.388
4	0.4	22.130
5	0.5	27.012
6	0.6	31.447
7	0.7	35.240
8	0.8	39.457
9	0.9	43.503

2.4.5. Simulation Experiment for Rolling Friction Coefficient of Fresh Goji Berry–Silicone Rubber Material

A plate with an inclined angle of 30° and a horizontally placed plate were added in the EDEM software, with the bottom end of the inclined plate touching the horizontally placed plate (Figure 14). The intrinsic parameters of the two plates were set in the software to be the same as those of the silicone rubber material. In setting the simulation parameters, the collision restitution coefficient and the static friction coefficient of fresh goji berry–silicone rubber material were taken as the calibrated values above, that is, Ex_1 = 0.195, μ_{s1} = 0.377.

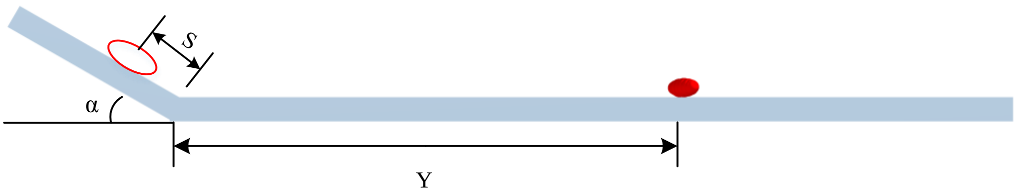

Figure 14. Simulation experiment for calibrating the rolling friction coefficient of fresh goji berry–silicone rubber material.

A fresh goji berry particle was generated at a distance of S = 30 mm along the inclined flat surface, and the particle rolled down the sloping surface with an initial velocity of 0. When the particle was stationary, the rolling distance (Y) of the particle on the horizontally placed plate was measured. Table 5 presents the design scheme and results of the simulation experiment.

Table 5. Design scheme and results of rolling friction coefficient experiment.

Group No.	μ_{r1}	Y/mm
1	0.01	1396.870
2	0.02	1031.026
3	0.03	813.731
4	0.04	670.109
5	0.05	403.698
6	0.06	238.752
7	0.07	163.066
8	0.08	104.283
9	0.09	59.407

2.5. Calibration of Static and Friction Rolling Friction Coefficients of Fresh Goji Berry–Fresh Goji Berry

2.5.1. Simulation of the Angle of Repose

The AoR simulation experiment is the same as the physics experiment. A particle factory was set up on top of the hollow cylinder, and particles were generated at a rate of 0.2 kg/s for a total of 1 kg. Particles of different sizes were generated according to a normal distribution. In the simulator module, the Rayleigh time step was set to 20%, the simulation time was set to 30 s, the data writing time step was 0.5 s, and the grid cell size was two times the minimum particle radius.

After stabilization, the cylinder was lifted vertically upward at a speed of 0.005 m/s, and a stable pile of particles was formed on a horizontally placed silicone rubber plate, as illustrated in Figure 15. Eventually, the AoR image was processed, and the angle value was read by the same method as the physical experiment.

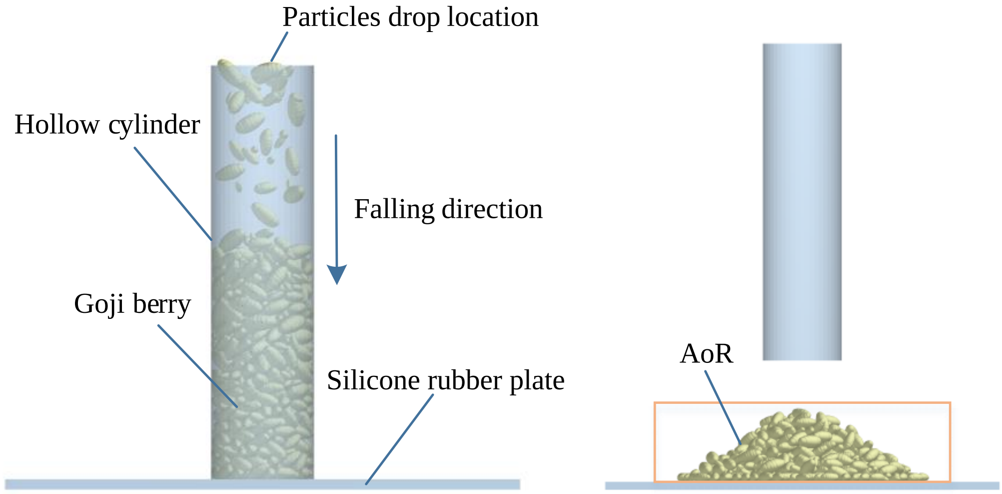

Figure 15. Simulation experiment for calibrating the AoR.

2.5.2. Central Composite Design Experiment

To determine the optimal value interval of each factor, we performed a steepest ascent search experiment. The experiment was carried out with the inter-particle static friction and rolling friction coefficients as the factors, and the relative error between the measured AoR and the simulated AoR as the index. The relative error of AoR is calculated by Equation (11).

$$\varepsilon = \frac{|\gamma - \beta|}{\beta} \tag{11}$$

where ε is the relative error of AoR between simulation and physical experiment (%); β is the physical experiment value of AoR (°); γ is the simulation experiment value of AoR (°).

After extensive pre-simulation experiments, the inter-particle static friction coefficient was determined to range from 0.450 to 0.550, and the inter-particle rolling friction coefficient was determined to range from 0.030 to 0.040. The Design-Expert V12 software (Stat-Ease Inc., Minneapolis, MN, USA) was used to design a central composite design experiment. Table 6 presents the scheme and results of the central composite design experiment.

2.6. Validation Tests

To verify that the above calibrated simulation parameters can be applied to the simulation of the grading machine, validation tests were performed.

Table 6. Design scheme and results of central composite design experiment. (μ_{s2} is the static friction coefficient of fresh goji berry–fresh goji berry, and μ_{r2} is the rolling friction coefficient of fresh goji berry–fresh goji berry.)

Group No.	μ_{s2}	μ_{r2}	ε/%
1	0.5	0.0279289	7.04
2	0.5	0.035	2.33
3	0.5	0.035	2.50
4	0.570711	0.035	5.81
5	0.5	0.035	1.98
6	0.5	0.035	2.07
7	0.45	0.04	0.62
8	0.429289	0.035	0.95
9	0.5	0.0420711	1.77
10	0.55	0.04	4.82
11	0.5	0.035	2.29
12	0.55	0.03	6.92
13	0.45	0.03	3.71

2.6.1. Discrete Element Simulation of the Grading Process

The geometric model of the grading machine is shown in Figure 16. The model was drawn at a 1:1 scale using SolidWorks 2019 software and saved in “-*.igs” format and imported into EDEM software.

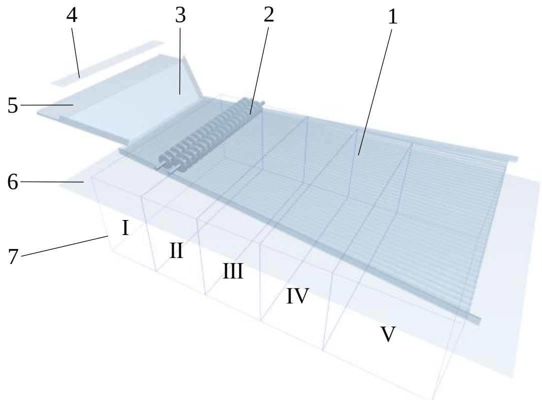

Figure 16. Geometric model of the grading machine. 1. Grading belt. 2. Directional brush. 3. Slipway. 4. Particles factory. 5. Infeed conveyor belt. 6. Discharge conveyor belt. 7. Five mass sensors.

In the EDEM software, the goji berry–belt contact model was set as a Moving Plane model, the goji berry–goji berry contact model was a Liner Spring model, and the contact model of the goji berry with other components was a Hertz–Mindlin (no-slip) model [33]. In the simulator module, the Rayleigh time step was set to 20%. The simulation time and output frequency were 30 s and 0.01 s, respectively. The size of the grid cells was given as two times the minimum particle radius. The material properties and contact parameters in the simulation model were calibrated values, as shown in Table 7.

Table 7. All discrete element simulation parameters of the model.

Material Properties	Fresh Goji Berry	Silicone Rubber Material
Poisson’s ratio	0.420	0.480
Elastic modulus/Pa	2.217×10^6	1.30×10^6
Density/kg·m^{-3}	689.550	1150
Contact Parameters	**Fresh Goji Berry–Fresh Goji Berry**	**Fresh Goji Berry–Silicone Rubber Material**
Collision restitution coefficient	0.158	0.195
Static friction coefficient	0.454	0.377
Rolling friction coefficient	0.037	0.063

2.6.2. Prototype Experiment

On 7 September 2021, a field experiment was carried out at the Ningxia Lianqi Zhihui Technology Limited Company (38°55′ N, 106°32′ E, altitude 1528 m). The experimental object was mature fresh goji berries of Ningqi No.5. The experiment was prepared by randomly picking 20 kg of fresh goji berries at the goji berry planting base, which were cleaned, air-dried, and inspected for damage, as shown in Figure 17a.

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

Figure 17. Experimental equipment for field tests. (**a**) The experiment target is mature fresh goji berries of Ningqi No.5; (**b**) A variable gap-type fresh goji berry grading machine.

The prototype is shown in Figure 17b. The device started feeding after stable operation. The field experiment was carried out with continuous feeding, and the motor speed of the feeding conveyor was controlled by a frequency converter to adjust the feeding volume of fresh goji berries. The timing started when the goji berries reached the sieving unit, and the motor was switched off after 30 s. The graded goji berries were collected for manual measurement and the grading accuracy was calculated.

2.6.3. Evaluation Index

The grading accuracy was used to describe the accuracy of the machine when screening fresh goji berries. A larger value indicates a higher percentage of correctly graded goji berries. As shown in Figure 18, the red box shows the goji berries mixed with other sizes, and the more goji berries mixed with other sizes, the lower the grading accuracy. The grading accuracy can be calculated from Equation (12).

$$\begin{cases} N_1 = \sum_{i=1}^{5} q_i \\ y = \frac{N_1}{N} \times 100\% \end{cases} \quad (12)$$

where N is the total mass of fresh goji berries entering the grading machine from the feeding device (kg); q_i (i = 1, 2, . . . , 5) is the mass of fresh goji berries going out from the discharge device of each level (kg); N_1 is the total mass of fresh goji berries meeting the specifications of each level after grading (kg); y is the grading accuracy of the machine (%).

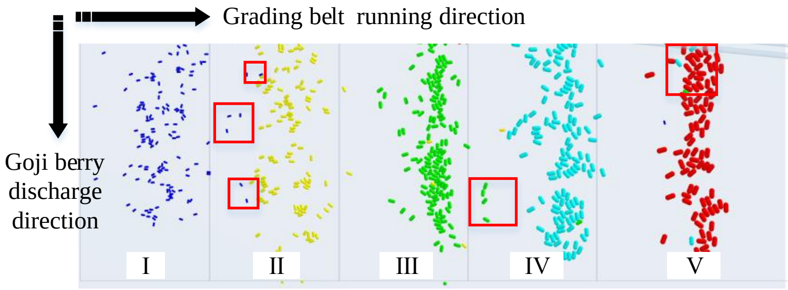

Figure 18. Evaluation index of grading accuracy. The five colored particles represent five different granularities of fresh goji berries, and the red boxes show the goji berries mixed with other granularities.

3. Results and Discussion

3.1. Determination of Collision Restitution Coefficient of Fresh Goji Berry–Silicone Rubber Material

To clarify the relationship between the maximum rebound height and the collision restitution coefficient, we fitted the experimental data in Table 2 using Origin software (Version 2017). Figure 19a shows the fitting curve with the fitting equation expressed as Equation (13).

$$Y_1 = 344.06{X_1}^2 - 30.466X_1 + 4.376 \tag{13}$$

where X_1 is the collision restitution coefficient of fresh goji berry–silicone rubber material; Y_1 is the maximum rebound height of the goji berry after collision with the silicone rubber plate (mm).

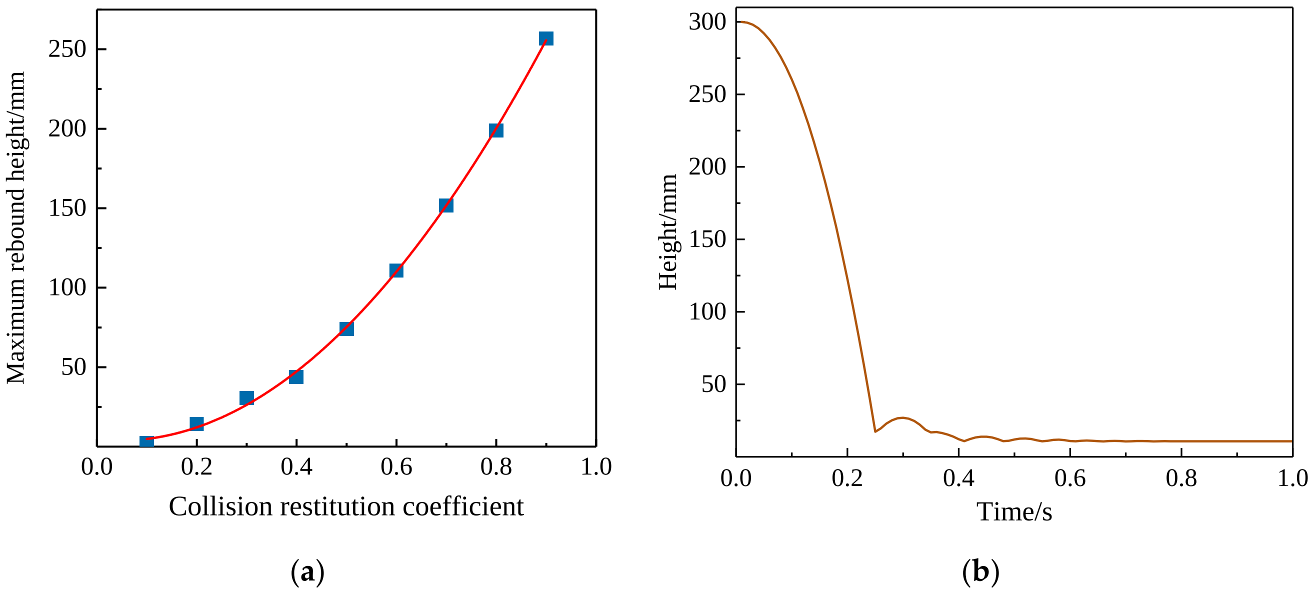

Figure 19. Results of the simulation tests. (**a**) Second-order polynomial fitting curve of the collision restitution coefficient of fresh goji berry–silicone rubber material; (**b**) Height–time curve of the particle motion.

The coefficient of determination (R^2) of the curve was 0.9992, which was close to 1, indicating that the fitting equation was accurate and reliable. The average maximum rebound height of the physical experiment (11.5 mm) was substituted into the fitting Equation (13) to obtain X_1 = 0.195. Three repetitions of the free-fall simulation experiment were performed using a collision restitution coefficient of 0.195, and Figure 19b shows the height–time curve of the particle motion. The maximum rebound heights of fresh goji berries were read by the post-processing module of the software as 11.587 mm, 11.696 mm, and 11.532 mm. The average value of 11.605 mm was taken, which had a relative error of 0.91% with the rebound height obtained from the physical experiment. This indicates that the calibrated simulation results are consistent with the physical experimental results, so the collision restitution coefficient of fresh goji berry–silicone rubber material was determined to be 0.195.

3.2. Determination of Collision Restitution Coefficient of Fresh Goji Berry–Fresh Goji Berry

To clarify the relationship between the maximum rising heights and the collision restitution coefficient, we fitted the experimental data in Table 3 with Origin software. Figure 20a shows the fitting curve with the fitting equation expressed as Equation (14).

$$\begin{cases} Y_2 = 4.515{X_2}^2 - 16.470X_2 + 12.182 \\ Y_3 = -4.310{X_2}^2 + 62.068X_2 + 9.073 \end{cases} \tag{14}$$

where X_2 is the collision restitution coefficient of fresh goji berry–fresh goji berry; Y_2 is the maximum rising height of fresh goji berry A (mm); Y_3 is the maximum rising height of fresh goji berry B (mm).

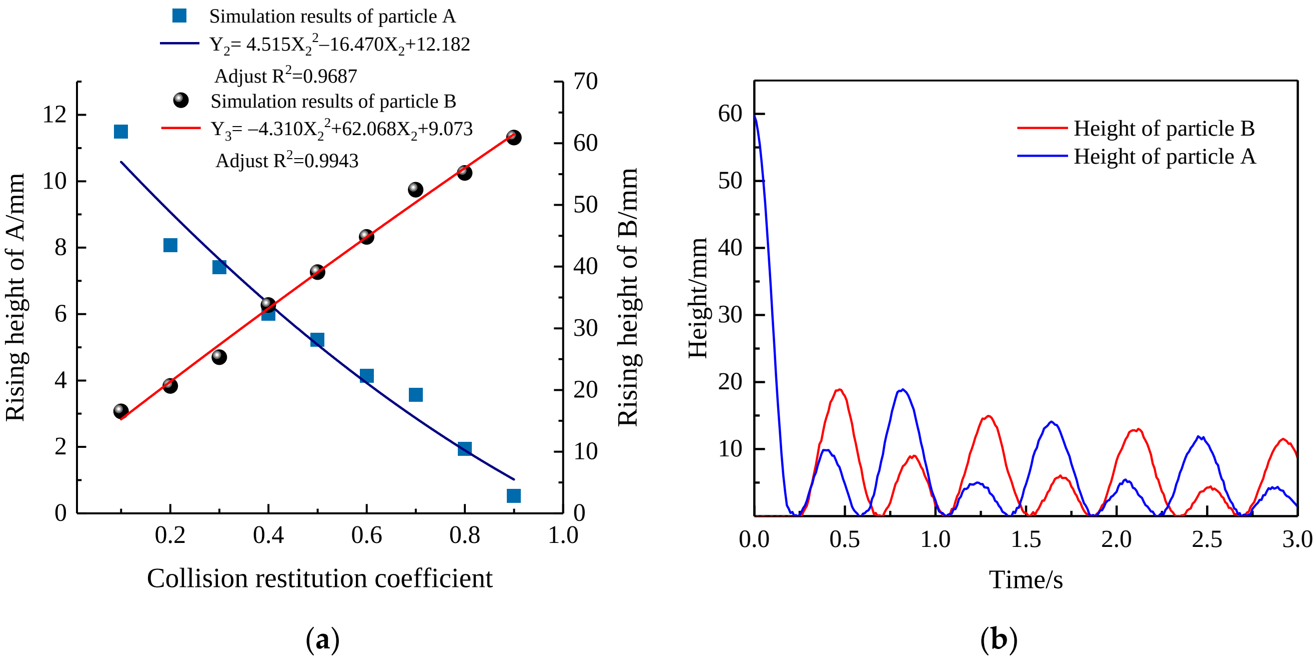

Figure 20. Results of the simulation tests. (**a**) Second-order polynomial fitting curve of the collision restitution coefficient of fresh goji berry–fresh goji berry; (**b**) Height–time curve of the motion of the two particles.

The coefficient of determination (R^2) of the two curves were 0.9687 and 0.9943, respectively. The measured values from the physical experiment were substituted into Equation (14) to obtain X_2 = 0.158. Three repetitions of the suspension collision simulation experiment were performed using a collision restitution coefficient of 0.158, and Figure 20b shows the height–time curve of the motion of the two particles. The average value of H_a was 9.703 mm and the average value of H_b was 18.67 mm. The relative errors with the heights obtained from the physical experiment were 2.14% and 3.72%, respectively. This indicates that the calibrated simulation results are consistent with the physical experimental results, so the collision restitution coefficient of fresh goji berry–fresh goji berry was determined to be 0.158.

3.3. Determination of Static Friction Coefficient of Fresh Goji Berry–Silicone Rubber Material

To clarify the relationship between the critical sliding angle and the static friction coefficient, we fitted the experimental data in Table 4 with Origin software. Figure 21a shows the fitting curve with the fitting equation expressed as Equation (15).

$$Y_4 = -14.187{X_3}^2 + 58.584X_3 + 1.713 \tag{15}$$

where X_3 is the static friction coefficient of fresh goji berry–silicone rubber material; Y_4 is the angle between the silicone rubber plate and horizontal direction when the fresh goji berry sliding occurs (°).

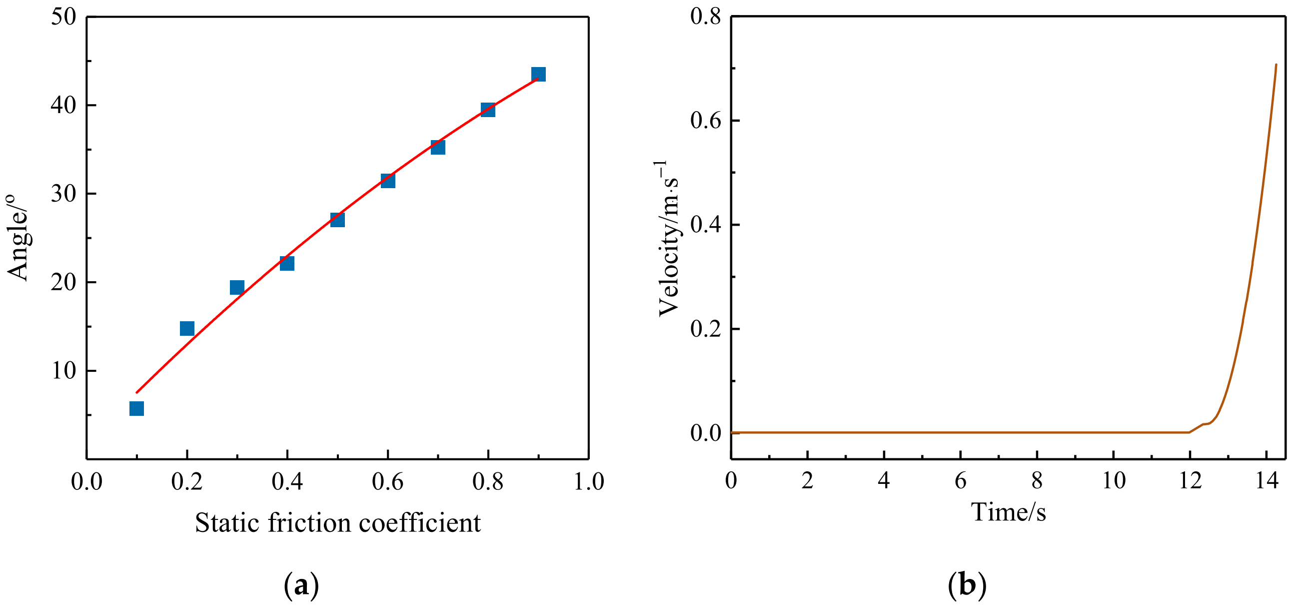

Figure 21. Results of the simulation tests. (**a**) Second-order polynomial fitting curve of the static friction coefficient of fresh goji berry–silicone rubber material; (**b**) Velocity–time curve of the particle motion.

The coefficient of determination (R^2) of the curve was 0.9918. We substituted the average inclination angle of the physical experiment (21.77°) into Equation (15) to obtain X_3 = 0.377. Three repetitions of the slope slip simulation experiment were performed using a static friction coefficient of 0.377, and Figure 21b shows the velocity–time curve of the particle motion. The angles were read by the post-processing module of the software as 21.146°, 21.025°, and 20.859°. The average value of 21.010° was taken, which had a relative error of 3.49% with the angle obtained from the physical experiment. This indicates that the calibrated simulation results are consistent with the physical experimental results, so the static friction coefficient of fresh goji berry–silicone rubber material was determined to be 0.377.

3.4. Determination of Rolling Friction Coefficient of Fresh Goji Berry–Silicone Rubber Material

To clarify the relationship between the horizontal rolling distance and the rolling friction coefficient, we fitted the experimental data in Table 5 with Origin software. Figure 22a shows the fitting curve with the fitting equation expressed as Equation (16).

$$Y_5 = 188138X_4{}^2 - 35252X_4 + 1709.1 \quad (16)$$

where X_4 is the rolling friction coefficient of fresh goji berry–silicone rubber material; Y_5 is the horizontal rolling distance of the goji berry (mm).

The coefficient of determination (R^2) of the curve was 0.9948. The average rolling distance of the physical experiment (237.2 mm) was substituted into Equation (16) to obtain X_4 = 0.063. Three repetitions of the slope rolling simulation experiment were performed using a rolling friction coefficient of 0.063, and Figure 22b shows the rolling distance–time curve of the particle motion. The rolling distances were read by the post-processing module of the software as 236.025 mm, 230.667 mm, and 233.159 mm. The average value of 233.284 mm was taken, which had a relative error of 1.65% with the rolling distance obtained from the physical experiment. This indicates that the calibrated simulation results are consistent with the physical experimental results, so the rolling friction coefficient of fresh goji berry–silicone rubber material was determined to be 0.063.

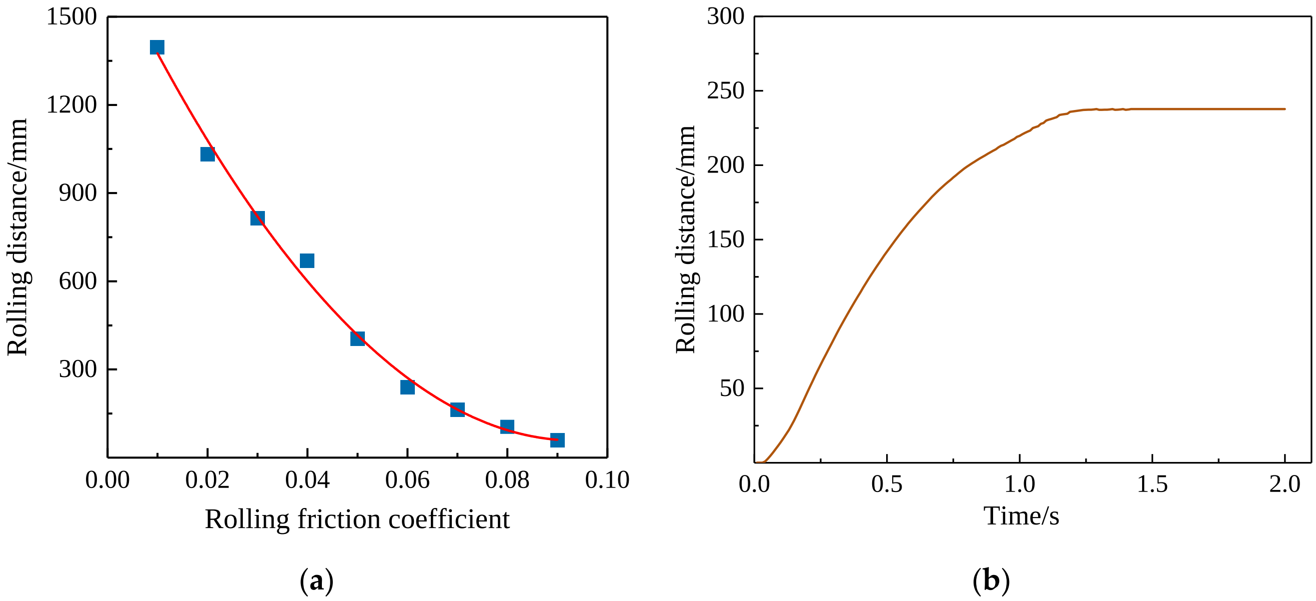

Figure 22. Results of the simulation tests. (**a**) Second-order polynomial fitting curve of the rolling friction coefficient of fresh goji berry–silicone rubber material; (**b**) Rolling distance–time curve of the particle motion.

3.5. Determination of Static and Rolling Friction Coefficients of Fresh Goji Berry–Fresh Goji Berry

The ANOVA of the regression model for the central composite design experiment is shown in Table 8. The overall fitting degree of the regression model was $p < 0.0001$, the lack of fit term was $p = 0.0684$, and the coefficient of determination (R^2) was 0.9845. The regression model was significant, the lack of fit term was not significant, and the coefficient of determination was close to 1, indicating a good fit of the regression model. All factors that have a significant effect on the index have been taken into account, and we obtained well-fitted and analytically meaningful regression: Equation (17).

$$R_1 = 2.23 + 1.79A - 1.58B + 0.25AB + 0.60A^2 + 1.12B^2 \quad (17)$$

Table 8. Analysis of variance for regression model.

Error Source	Sum of Squares	Freedom	Mean Square	F-Value	*p*-Value
Model	55.89	5	11.18	88.72	<0.0001 **
A-A	25.50	1	25.50	202.41	<0.0001 **
B-B	19.98	1	19.98	158.59	<0.0001 **
AB	0.2450	1	0.2450	1.94	0.2058
A^2	2.54	1	2.54	20.16	0.0028 **
B^2	8.68	1	8.68	68.86	<0.0001 **
Residual	0.8819	7	0.1260		
Lack of fit	0.7074	3	0.2358	5.40	0.0684
Pure error	0.1745	4	0.0436		

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

The AoR value obtained from the physical experiment was used as the target value (31.27°), and the optimization module of Design-Expert software was used to make the simulation results closest to the target value. The regression model was optimally solved with the constrained objectives (Equation (18)).

$$\begin{cases} \min R_1(A, B) \\ s.t. \begin{cases} 0.45 \le A \le 0.55 \\ 0.03 \le B \le 0.04 \end{cases} \end{cases} \quad (18)$$

Finally, we obtained the fresh goji berry–fresh goji berry static friction and rolling friction coefficients as 0.454 and 0.037.

3.6. Validation Tests

To verify the accuracy of the calibrated discrete element simulation parameters, field experiments and simulation tests of the machine were conducted. We performed three simulations for the parameters determined in Table 7, and the simulation process is shown in Figure 23. Eventually, we obtained an average grading accuracy of 95.67% for the model.

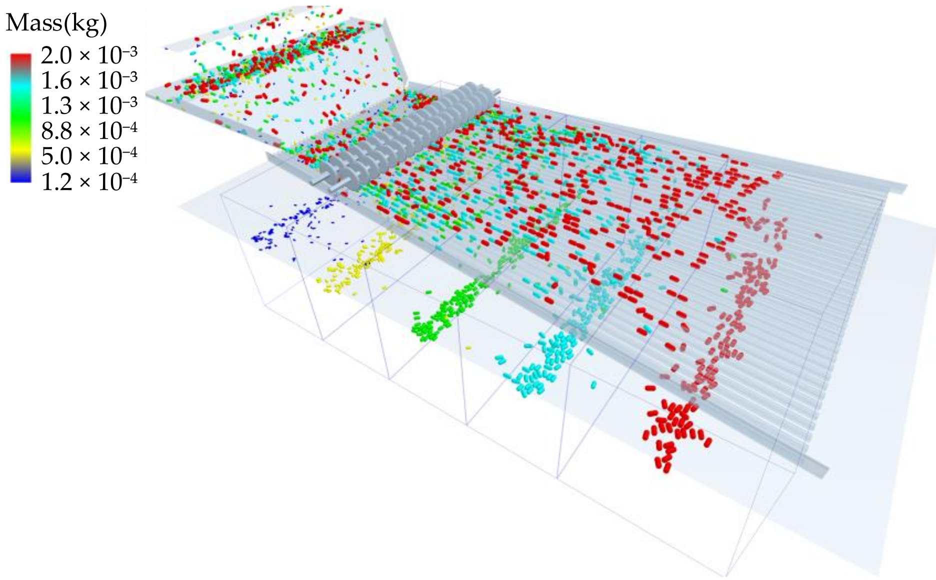

Figure 23. Simulation of grading process.

Moreover, the result of the field tests is shown in Figure 24, and the average grading accuracy of the field tests was 94.43%. The error of the grading accuracy between simulation and field experiments was 1.31%. The results show that the calibrated discrete element simulation model is applicable to the discrete element simulation of fresh goji berries.

Figure 24. Result of field test.

3.7. Discussion

One crucial step to ensure the accuracy of the model is inputting accurate simulation parameters. Through Newton's second law, Newton's third law, and Hertz–Mindlin contact theory, we can know that the main parameters affecting the accuracy of the model are the intrinsic parameters and the contact parameters. In this paper, we took fresh goji berry as the research object, and the discrete element parameter acquisition models were established on the basis of creating a simulation model of fresh goji berries. We used a method that combines physical and simulation experiments, where all discrete element modeling parameters were obtained sequentially. However, it should be noted that due to the wide variety of fresh goji berries and the wide distribution of physical properties, the shape and volume of the particles vary greatly among the different varieties. In this paper, only the Ningqi No.5. mature fresh goji berry, which is widely planted in China, is the subject of study. The discrete element modeling parameters need to be recalibrated if the experimental subject changes.

4. Conclusions

(1) For the accurate and non-destructive grading of fresh goji berries, we designed a variable gap-type fresh goji berry grading machine. The key component of the machine, the grading belt, was made of silicone rubber material.
(2) Intrinsic parameters such as the triaxial size, density, Poisson's ratio, elastic modulus, and shear modulus of fresh goji berries were determined by physical experiments. By free-fall, suspension collision, slope slip, and slope rolling experiments, the collision restitution, static friction, and rolling friction coefficients of fresh goji berry–silicone rubber material were determined to be 0.196, 0.340, and 0.057, respectively. The collision restitution coefficient of fresh goji berry–fresh goji berry was 0.150.
(3) We used the SFM-CMVS technique to extract the outline of the goji berry, and we obtained the dense point cloud and fitted model of the goji berry. The model was meshed to obtain a 3D model of the fresh goji berry, which was used in EDEM. A discrete element simulation particle model of fresh goji berry was established by using the multi-sphere particle aggregation method.
(4) By simulation, the collision restitution, static friction, and rolling friction coefficients of fresh goji berry–silicone rubber material were calibrated to 0.195, 0.377, and 0.063, respectively; the collision restitution coefficient of fresh goji berry–fresh goji berry was calibrated to 0.158. We designed the steepest ascent search and central composite design experiments to calibrate the static friction and rolling friction coefficients of fresh goji berry–fresh goji berry to 0.454 and 0.037.
(5) Validation tests were conducted on the calibrated discrete element parameters, and the results showed that the grading accuracy obtained from the simulation model matched that under real test conditions.

This study aims to determine the discrete element parameters required in the model for the mechanized grading process of fresh goji berries, and to provide a DEM simulation model of fresh goji berries to fill the gaps in the study of parameters and models of fresh goji berries. Meanwhile, the study provides the theoretical basis for the design and optimization of the variable gap-type fresh goji berry grading machine.

5. Patents

One Chinese invention patent applied for: CN112317325A.

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

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