Abstract: To improve the accuracy of discrete element simulation parameters for the mechanized picking and collection of pears, the study calibrated the simulation parameters of pears by the method of combining a physical experiment and simulation. Based on the intrinsic parameters of four kinds of pears (Snow pears, Crisp pears, Huangguan pears and Qiuyue pears), their simulation models were constructed by the Hertz-Mindlin with a bonding model. The simulation parameters between pears and the contact material (PVC, EVA foam material) were calibrated by the methods of free fall collision, inclined sliding and rolling, respectively. The experiments of pear accumulation angle were carried out. It was obtained to process the image of pears with Matrix Laboratory software. In order to determine the optimal value interval of influencing factors of the pear accumulation angle, the steepest ascent experiment was carried out. Considering the coefficient of collision recovery, the coefficient of static friction and the coefficient of rolling friction between pears, five-level simulation experiments of the pear accumulation angle were designed for each factor by the method of orthogonal rotation combination. The regression model of the error between the measured value and the simulated value of the pear accumulation angle was established, and the influence of three factors on the pear accumulation angle was analyzed. The results showed that the static friction coefficient and rolling friction coefficient between pears have significant effects on the pear accumulation angle. Therefore, the optimal model of minimum error was constructed according to constraint condition, and the coefficient of collision recovery, coefficient of static friction and coefficient of rolling friction between pears were obtained. The accumulation angle verification experiments were carried out by the method of bottomless barrel lifting. The results showed that the relative error between the simulated and measured accumulation angle of four kinds of pears were 1.42%, 1.68%, 2.19% and 1.83%, respectively, which indicated that the calibrated simulation parameters were reliable. The research can provide a basis for the design and parameters optimization of harvesting machinery of pears.

Keywords: pear; discrete element method; simulation parameter; calibration

1. Introduction

Pears, as one of the main fruits in the world, have a huge market demand and high economic value [1,2]. In recent years, with the increase in pear planting area, the yield has increased year by year [3,4]. Due to the short harvest period and strong harvest seasonality, harvesting machinery is necessary to improve the harvest efficiency of pears [5,6]. However, because pears' skin is thin and their meat is crisp and juicy, it is very easily damaged in the process of mechanized harvesting, which reduces the edible and storage properties of pears, and directly affects the quality and economic benefits of pears [7,8]. Therefore, in
order to improve the harvesting efficiency and to reduce the damage rate of pears, lower damage technologies and machines are an inexorable trend for the development of pear industry in China in the future.

In recent years, EDEM, a numerical simulation software based on discrete element method, has been more and more widely used in agricultural equipment research [9,10]. The method can effectively and intuitively simulate the mechanism of “crop-crop” and “crop-machinery” to realize optimize the structure or working parameters of machinery [11,12]. In discrete element simulation, the intrinsic parameters (such as density, shear modulus, Poisson’s ratio, etc.) and contact parameters (such as “particle-particle”, “particle-material” collision recovery coefficient, static friction coefficient, rolling friction coefficient, etc.) of the simulation model should be defined [13,14]. Among them, the intrinsic parameters are particle attribute parameters, which are basically consistent with the real values. However, the difference between the simulation model and the real particle geometry makes it difficult to measure some contact parameters. Therefore, virtual calibration of contact parameters is necessary [15–17].

At present, relevant scholars have conducted a lot of research on the calibration of grain crops simulation parameters based on discrete element method (DEM) [18–20]. Li Xiaoyu et al. [21] constructed a mathematical model of the corn-mechanical interaction system based on the Hertz-Mindlin, and proposed a new DEM construction method of the corn ear through filling and splicing particles. Thiet Xuan Nguyen et al. [22] analyzed the shape and the physical characteristics of soybeans, and measured the coefficient of static friction between soybeans and materials, and calibrated the DEM input parameters by the combination method of experiment and simulation. Liu Wenzheng et al. [23] calibrated contacting parameters of particle discrete simulation, which were consistent with the experimental conditions. Liu Yan et al. [24] used the method of combining physical experiment and virtual calibration to determine the DEM parameters of adzuki bean seeds, and the relative error between simulated and measured values of AOR (angle of repose) was 0.67%, which indicated that the determined DEM parameters were accurate and reliable.

In addition, there are some research on other crops. Using 3D scanning, Hao Jianjun et al. [25] established the simulation of oil sunflower seeds by DEM, and bottomless barrel lifting experiments were carried out and the error between experimental and simulation accumulation angle was only 0.24%. By the method of orthogonal rotating combination, Yu Qingxu et al. [26] determined the optimal contact parameters between the Panax notoginseng seeds in EDEM simulation experiment. Bai Shenghe et al. [27] calibrated the contact parameters between “cotton seeds-cotton seeds”, “cotton seeds-stainless steel” and “cottonseed-nylon”, and carried out physical and simulation experiments to obtain the inter species collision recovery coefficient. Using the Plackett-Burman experiment, Hou Zhanfeng et al. [28] analyzed the significance of simulation parameters of agropyron seeds, and constructed the second-order regression equation of the repose angle and the significant parameter to determine the simulated parameters of agropyron seeds.

In summary, it is accurate and feasible to use the combination method of physical experiment and DEM simulation to calibrate the discrete element parameters of material particles. However, there are few studies on the calibration of simulation parameters of pears. Compared with corn, rice and wheat, the size of pears is larger, which requires a lot of relevant experiments to explore more complex movement characteristics. There are various pears in China, including, Snow pear, Crisp pear, Huangguan pear and Qiuyue pear and more. So in the paper, the intrinsic parameters of the four kinds of pears were measured, and their simulation models were constructed by the Hertz-Mindlin with bonding model. The simulation parameters between pears and the contact material (PVC, EVA foam material) were calibrated by the methods of free fall collision, inclined sliding and rolling, respectively. Carrying out the experiments of pear accumulation angle and the steepest ascent experiment, the optimal value interval of influencing factors of the pear accumulation angle was determined. Using orthogonal rotation combination and considering the coefficient of collision recovery, the coefficient of static friction and the
coefficient of rolling friction between pears, five-level simulation experiments of the pear accumulation angle were designed for each factor. The influence of three factors on the pear accumulation angle was analyzed, and the optimal model of minimum error between the measured value and the simulated value of the pear accumulation angle was constructed according to constraint condition. Thus the coefficient of collision recovery, coefficient of static friction and coefficient of rolling friction between pears were obtained. In order to indicate that the calibrated simulation parameters are reliable, the accumulation angle verification experiments were carried out. The research can provide a basis for the design and parameters optimization of harvesting machinery of pears.

2. Materials and Methods

2.1. Model Establishment

2.1.1. Physical Model of Pears

Snow pear, Crisp pear, Huangguan pear and Qiuyue pear were planted in China. 100 mature pears of each variety were selected, and they were divided into 5 groups on average. According to the method of [27–29], the intrinsic parameters were measured, and the results were shown in Table 1.

Table 1. Intrinsic parameters of typical pears.

| Variety       | Snow Pear | Crisp Pear | Huangguan Pear | Qiuyue Pear |
|---------------|-----------|------------|----------------|-------------|
| Transverse diameter D/mm | 79.61 ± 4.8 | 76.81 ± 4.6 | 77.39 ± 3.9 | 70.69 ± 2.7 |
| Longitudinal height H/mm    | 88.38 ± 4.5 | 69.14 ± 4.4 | 73.74 ± 4.2 | 61.77 ± 2.5 |
| Mass/g                           | 381.95 ± 50.11 | 272.87 ± 43.89 | 301.56 ± 37.52 | 207.59 ± 26.04 |
| Density/(kg·m⁻³)              | 985.07 ± 17.35 | 944.64 ± 54.93 | 1049.30 ± 45.61 | 1012.80 ± 40.77 |
| Moisture content/% | 89.28 ± 4.85 | 87.14 ± 2.78 | 87.53 ± 0.27 | 89.56 ± 0.15 |
| Poisson’s ratio             | 0.48       | 0.36       | 0.40           | 0.24        |
| Young’s modulus/MPa         | 3.16       | 2.69       | 2.18           | 0.84        |
| Shear modulus/MPa           | 1.07       | 0.99       | 0.78           | 0.34        |

Because the shape of pears is irregular, it is impossible to simulate directly with a single spherical discrete element model. According to the intrinsic parameters of pears, a center line with the same height as the pear was drawn in SolidWorks, which was divided into 10 parts in the height direction. The outer contour points of the same width as the corresponding positions of the pears were cut out, and these points (including the peak and the bottom) were connected with curves in sequence (Figure 1), the geometric models of pears fruit each variety were constructed, as shown in Figure 2.
Figure 2. Geometric models of typical pears. Snow pear (a); Crisp pear (b); Qiuyue pear (c); Huangguan pear (d). Note: Blue is the origin of the coordinate system for the pear geometric model.

Figure 3. EDEM simulation models of typical pears. Snow pear (a); Crisp pear (b); Qiuyue pear (c); Huangguan pear (d).

2.1.2. Selection of Contact Model

In the process of the mechanized picking and collection of pears, except for the contact between pear fruit particles, there is contact with other materials during the buffer collection. In this paper, the materials in contact with pear fruit were PVC and EVA foaming materials [30,31], and their parameters were shown in Table 2 [32,33]. During the collection process, the surface of pear fruit and material was smooth and almost had no adhesion, so the Hertz-Mindlin non-slip contact model was selected for discrete element simulation.

Table 2. Simulation parameters of contact materials.

| Material | Parameter                  | Value    |
|----------|----------------------------|----------|
| PVC      | Poisson’s ratio            | 0.47     |
| PVC      | Shear modulus/MPa          | 2.00     |
| PVC      | Density/(kg·m\(^{-3}\))    | 1282.00  |
| EVA      | Poisson’s ratio            | 0.30     |
| EVA      | Shear modulus/MPa          | 0.46     |
| EVA      | Density/(kg·m\(^{-3}\))    | 79.09    |

2.2. Calibration of Contact Parameters between Typical Pears and Materials

2.2.1. Calibration of Collision Recovery Coefficient between Typical Pears and Materials

As shown in Figure 4a, the collision recovery coefficients between “pear-PVC material” and “pear-EVA foaming material” were calibrated by the method of free fall collision. A pear was released at a height of \( H = 400 \) mm from the contact material plate, and it was rebounded when it hit the material plate. The highest rebound height \( h \) was measured by the high-speed camera system (Figure 4b). The collision recovery coefficient \( e_x \) is the ratio of normal instantaneous separation velocity \( v_1 \) to instantaneous contact velocity \( v_0 \) at the collision contact point before and after the collision between pears and materials, and it is as follows:

\[
e_x = \frac{v_1}{v_0} = \frac{\sqrt{2gh}}{\sqrt{2gH}} = \sqrt{\frac{h}{H}}
\]
According to Tables 1 and 2, simulation experiments were carried out by EDEM (Figure 4c). \( H \) and \( h \) were recorded, respectively.

2.2.2. Calibration of Static Friction Coefficient between Typical Pears and Materials

The static friction coefficient between pears and materials was calibrated by the method of inclined sliding. The relationship between the static friction coefficient \( \mu_s \) and the inclined plane angle \( \alpha \) was as follows:

\[
\mu_s = \tan \alpha
\]  

(2)

The measuring instrument of static friction coefficient was shown in Figure 5, which mainly included an inclined plate and a digital display inclinometer (resolution: 0.05°, accuracy: ±0.2°, range: 0°~90°).

Figure 4. Calibration experiment of collision recovery coefficient between pears and materials. Experiment principle (a); Physical experiment (b); Simulation experiment (c).

Figure 5. Calibration experiment of static friction coefficient between pears and materials. Physical experiment (a); Simulation experiment (b).
The digital display inclinometer was placed on one end of the inclined plate, and the PVC and EVA foam material were fixed on the inclined plate in turn. In order to prevent a pear rolling, four pears with similar sizes were bonded into one group. Placing a pear on the left end of the contact material on the inclined plate and raising it slowly and uniformly, the angle $\alpha$ of the digital display inclinometer when the pear began to slide was recorded.

2.2.3. Calibration of Rolling Friction Coefficient between Typical Pears and Materials

The rolling friction coefficient between pears and materials was calibrated by the method of inclined plane rolling, as shown in Figure 6. According to the law of conservation of energy, there was as follows:

$$mgS \sin \beta = \mu_r mg(S \cos \beta + L)$$  \hspace{1cm} (3)

where $\mu_r$ is rolling friction coefficient; $m$ was the fruit mass of pear, g; $g$ is gravity acceleration, 9.8 m/s$^2$; $S$ is the rolling distance of the inclined plane, mm; $\beta$ is the inclination angle of the inclined plane, $^\circ$; $L$ is the rolling distance, cm.

Figure 6. Calibration experiment of rolling friction coefficient between pears and materials. Physical experiment (a); Simulation experiment (b).

Because of the big size of pears, the rolling distance was longer if $\beta$ and $S$ were bigger, which had caused deviation from the straight line. If $\beta$ and $S$ were smaller, the rolling distance was smaller, and it was difficult to measure. Therefore, after a lot of rolling experiments, $\beta$ was 5$^\circ$, and $S$ was 100 mm.

2.3. Calibration of Contact Parameters between Typical Pears

2.3.1. Calibration of Collision Recovery Coefficient between Typical Pears

In order to reduce the influence of the shape and quality of pears, the pears with a similar size and quality were selected when collision recovery coefficient between pears was measured. As shown in Figure 7, several pears with similar shape were bonded together, and a single pear was released at the height of 400 mm. If it collided with one of the pears, the highest rebound height was measured by the high-speed camera system. If it fell into the space between pears, the experiment had to be repeated.
2.3.2. Calibration of Pear Accumulation Angle

(1) Experiment of Pear Accumulation Angle

As shown in Figure 8, the experiment device was composed of a box body (length 400 mm, width is 300 mm, height 600 mm), baffle plate (length 400 mm, height 600 mm) and bottom plate (length 1500 mm, width 1500 mm). The inner wall materials of the box body were PVC and EVA in turn. By the method of extracting the baffle on one side of the box at a constant speed upward (0.05 m/s) [23], the experiments were carried out, and the results showed that the inner wall material of the box body had no significant difference on the accumulation angle. Therefore, PVC material was used. After the pear group was stable, the angle between the inclined plane formed by the pear group and the horizontal floor plane was the pear accumulation angle.

(2) Experiment of the steepest ascent

In order to determine the optimal value of influencing factors of the pear accumulation angle, the steepest ascent experiment was carried out. Considering the coefficient of collision recovery, the coefficient of static friction and the coefficient of rolling friction between pears, the accumulation angle error between the experiment and simulation value was calculated. When the pear accumulation angle was simulated by EDEM, the radius of the pear was 0.8–1.2 times that of the physical model because pears varied in size and the contact parameters were set according to their calibration values.

(3) Experiment of horizontal rotation combinations

According to the optimal value interval of the coefficient of collision recovery (ε), the coefficient of static friction (μs) and the coefficient of rolling friction (μr) between pears, five-level simulation experiments of the pear accumulation angle were designed for each factor by the method of orthogonal rotation combination, whose codes were shown in Table 3.
(3) Experiment of horizontal rotation combinations

According to the optimal value interval of the coefficient of collision recovery ($e$), the coefficient of static friction ($\mu_n$) and the coefficient of rolling friction ($\mu_f$) between pears, five-level simulation experiments of the pear accumulation angle were designed for each factor by the method of orthogonal rotation combination, whose codes were shown in Table 3.

Table 3. Codes of simulation experiment factors.

| Code  | $e$  | $\mu_n$ | $\mu_f$ |
|-------|------|---------|---------|
| −1.682| 1    | 1       | 1       |
|  − 1  | 2    | 2       | 2       |
|   0   | 3    | 3       | 3       |
|    1  | 4    | 4       | 4       |
|  1.682| 5    | 5       | 5       |

(4) Experiment of verification

In order to verify the above simulation parameters, the experiment was carried out by the method of lifting bottomless barrel. As shown in Figure 9, lifting the barrel upward at the speed of 0.05 m/s, after the pear group was stable, the angle between the inclined plane formed by the pear group and the horizontal floor plane was the pear accumulation angle.

Figure 9. Experiment of simulation parameters verification. Physical experiment (a); Simulation experiment (b).

3. Results and Discussion

3.1. Contact Parameters between Typical Pears and Materials

3.1.1. Collision Recovery Coefficient between Typical Pears and Materials

According to the Section 2.2.1, when selecting pears of similar size and quality, the experiments for each variety were carried out five times. The average of the maximum rebound height was substituted into Formula (1), and collision recovery coefficient between typical pears and materials was obtained. The results were shown in Table 4.

Table 4. Measured values of collision recovery coefficients between typical pears and materials.

| Variety        | Contact Material | Maximum Rebound Height/mm | Value of Collision Recovery Coefficient |
|---------------|------------------|---------------------------|-----------------------------------------|
| Snow pear     | PVC              | 141.28                    | 0.594                                   |
|               | EVA              | 143.62                    | 0.599                                   |
| Crisp pear    | PVC              | 96.14                     | 0.490                                   |
|               | EVA              | 120.80                    | 0.550                                   |
| Huangguan pear| PVC              | 138.58                    | 0.589                                   |
|               | EVA              | 152.18                    | 0.617                                   |
| Qiuyue pear   | PVC              | 105.05                    | 0.512                                   |
|               | EVA              | 131.24                    | 0.573                                   |

In order to reduce the interference factors, the static friction coefficient and rolling friction coefficient between the pear and material were set as 0, and the collision recovery coefficient was from 0.1 to 0.9 at an equal interval of 0.1 in EDEM. The experiments for each variety were carried out five times, and the average of the maximum rebound height was
recorded. Taking Snow pear as an example, the relationship between the collision recovery coefficient and the maximum rebound height was shown in Figure 10.

![Figure 10. Fitting curve of the collision recovery coefficient and the maximum rebound height.](image)

Thus, by the method of origin, the fitting equations were shown as follows:

\[
h_1 = 425.40e_{x1}^2 - 30.80e_{x1} - 0.17, \quad (R^2 = 0.99) \tag{4}
\]

\[
h_2 = 488.05e_{x2}^2 - 114.60e_{x2} + 10.93, \quad (R^2 = 0.99) \tag{5}
\]

The rebound height between Snow pear and contact material in Table 4 was substituted into Equations (4) and (5), and \(e_{x1} = 0.542\), and \(e_{x2} = 0.652\). The collision recovery coefficients were set as the above parameters in EDEM, the maximum simulated rebound height of Snow pear and contact materials were 143.71 mm and 145.87 mm, respectively, which were consistent with measured values. The errors between simulated values and measured value were 1.72% and 1.57%, respectively, which indicated that \(e_{x1}\) and \(e_{x2}\) were accurate and reliable.

Thus, the simulated values of collision recovery coefficients between other pear varieties and materials were shown in Table 5.

### Table 5. Simulated values of collision recovery coefficients between typical pears and materials.

| Variety            | Contact Material | Collision Recovery Coefficient |
|--------------------|------------------|--------------------------------|
| Snow pear          | PVC              | 0.542                          |
|                    | EVA              | 0.652                          |
| Crisp pear         | PVC              | 0.516                          |
|                    | EVA              | 0.608                          |
| Huangguan pear     | PVC              | 0.624                          |
|                    | EVA              | 0.678                          |
| Qiuyue pear        | PVC              | 0.573                          |
|                    | EVA              | 0.641                          |

#### 3.1.2. Static Friction Coefficient between Typical Pears and Materials

According to the Section 2.2.2, the experiments for each variety were carried out five times. The average of the maximum inclination angle was substituted into Formula (2), and static friction coefficient between typical pears and materials was obtained. The results were shown in Table 6.
3.1.2. Static Friction Coefficient between Typical Pears and Materials

Table 6. Measured values of static friction coefficient between typical pears and materials.

| Variety          | Contact Material | Inclination Angle | Static Friction Coefficient |
|------------------|------------------|-------------------|-----------------------------|
| Snow pear        | PVC              | 34.26°            | 0.681                       |
|                  | EVA              | 24.54°            | 0.457                       |
| Crisp pear       | PVC              | 33.21°            | 0.655                       |
|                  | EVA              | 22.78°            | 0.420                       |
| Huangguan pear   | PVC              | 32.06°            | 0.626                       |
|                  | EVA              | 21.60°            | 0.396                       |
| Qiuyue pear      | PVC              | 33.43°            | 0.660                       |
|                  | EVA              | 29.90°            | 0.575                       |

According to Table 5, the collision recovery coefficient was set, and the rolling friction coefficient was set as 0, the static friction coefficient was from 0.1 to 0.9 at an equal interval of 0.1 in EDEM. The experiments for each variety were carried out five times, and the average of the maximum inclination angle was recorded. Taking Snow pear as an example, the relationship between the static friction coefficient and the maximum inclination angle was shown in Figure 11.

![Figure 11. Fitting curve of static friction coefficient and inclination angle.](image-url)

Thus, by the method of origin, the fitting equations were shown as follows:

\[
\alpha_1 = -14.91\mu_1^2 + 60.34\mu_1 - 0.12, \quad (R^2 = 0.99) \tag{6}
\]

\[
\alpha_2 = -24.79\mu_2^2 + 64.78\mu_2 - 0.52, \quad (R^2 = 0.99) \tag{7}
\]

where, \(\alpha_1, \alpha_2\) is inclination angle of Snow pears and PVC and EVA foam materials, respectively; \(\mu_1, \mu_2\) is static friction coefficient between Snow pears and PVC and EVA foam materials, respectively.

The inclination angle of Snow pears and materials in Table 6 was substituted into Equations (6) and (7), and \(\mu_1\) was 0.686, and \(\mu_2\) was 0.472. The static friction coefficients were set as the above parameters in EDEM, the maximum simulated inclination angle of Snow pear and materials were 33.58° and 23.98°, respectively, which were consistent with measured values. The errors between simulated values and measured value were 1.98% and 2.28%, respectively, which indicated that \(\mu_1\) and \(\mu_2\) were accurate and reliable.

Thus, the simulated values of static friction coefficient between other pear varieties and contact materials were shown in Table 7.
Table 7. Simulated values of static friction coefficient between typical pears and materials.

| Variety          | Contact Material | Static Friction Coefficient |
|------------------|------------------|----------------------------|
| Snow pear        | PVC              | 0.686                      |
|                  | EVA              | 0.472                      |
| Crisp pear       | PVC              | 0.651                      |
|                  | EVA              | 0.491                      |
| Huangguan pear   | PVC              | 0.627                      |
|                  | EVA              | 0.394                      |
| Qiuyue pear      | PVC              | 0.661                      |
|                  | EVA              | 0.574                      |

3.1.3. Rolling Friction Coefficient between Typical Pears and Materials

According to the Section 2.2.3, the experiments for each variety were carried out 30 times. The average of the maximum rolling distance was substituted into Formula (3), and rolling friction coefficient between typical pears and materials was obtained. The results were shown in Table 8.

Table 8. Measured values of rolling friction coefficient between typical pears and materials.

| Variety          | Contact Material | Rolling Distance/cm | Rolling Friction Coefficient |
|------------------|------------------|----------------------|------------------------------|
| Snow pear        | PVC              | 128.88               | 0.00629                      |
|                  | EVA              | 107.51               | 0.00742                      |
| Crisp pear       | PVC              | 128.27               | 0.00631                      |
|                  | EVA              | 103.91               | 0.00766                      |
| Huangguan pear   | PVC              | 125.09               | 0.00336                      |
|                  | EVA              | 119.79               | 0.00674                      |
| Qiuyue pear      | PVC              | 122.29               | 0.00666                      |
|                  | EVA              | 106.66               | 0.00748                      |

According to Tables 5 and 7, the collision recovery coefficient and the static friction coefficient were set, and the rolling friction coefficient was from 0.003 to 0.008 at an equal interval of 0.001 in EDEM. The experiments for each variety were carried out 30 times, and the average of the maximum rolling distance was recorded. Taking Snow pear as an example, the relationship between the rolling friction coefficient and the maximum rolling distance was shown in Figure 12.

![Figure 12. Fitting curve of rolling friction coefficient and rolling distance.](image-url)
Thus, by the method of origin, the fitting equations were shown as follows:

\[ L_1 = 659017857\mu_1^2 - 10650682\mu_1 + 529.98, \quad (R^2 = 0.99) \]  

\[ L_2 = 662982143\mu_2^2 - 10697546\mu_2 + 532.38, \quad (R^2 = 0.99) \]  

where, \( \mu_1, \mu_2 \) is rolling friction coefficient between Snow pears and PVC and EVA foam materials, respectively; \( L_1, L_2 \) is rolling distance of Snow pears and PVC and EVA foam materials, respectively, in cm.

The rolling distance of Snow pears and materials in Table 8 was substituted into Equations (8) and (9), and \( \mu_1 \) was 0.00597, and \( \mu_2 \) was 0.00706. The rolling friction coefficient were set as the above parameters in EDEM, the simulated inclination angle of Snow pear and materials were 130.24 cm and 108.97 cm, respectively, which were consistent with measured values. The errors between simulated values and measured value were 1.06% and 1.36%, respectively, which indicated that \( \mu_1 \) and \( \mu_2 \) were accurate and reliable.

Thus, the simulated values of static friction coefficient between other pear varieties and contact materials were shown in Table 9.

### Table 9. Simulated values of static friction coefficient between other pear varieties and contact materials.

| Variety       | Contact Material | Rolling Friction Coefficient |
|---------------|------------------|------------------------------|
| Snow pear     | PVC              | 0.00597                      |
|               | EVA              | 0.00706                      |
| Crisp pear    | PVC              | 0.00602                      |
|               | EVA              | 0.00735                      |
| Huangguan pear| PVC              | 0.00323                      |
|               | EVA              | 0.00638                      |
| Qiuyue pear   | PVC              | 0.00627                      |
|               | EVA              | 0.00714                      |

3.2. Calibration of Contact Parameters between Typical Pears

3.2.1. Calibration of Collision Recovery Coefficient between Typical Pears

According to the Section 2.3.1, selecting pears of similar size and quality, the experiments for each variety were carried out five times. The average of the maximum rebound height was substituted into Formula (1), and collision recovery coefficient between typical pears was obtained. The results were shown in Table 10.

### Table 10. Measured values of collision recovery coefficients between typical pears.

| Variety       | Value of Maximum Rebound Height/mm | Value of Collision Recovery Coefficient |
|---------------|-----------------------------------|----------------------------------------|
| Snow pear     | 100.40~194.88                     | 0.501~0.698                            |
| Crisp pear    | 71.57~106.50                      | 0.423~0.516                            |
| Huangguan pear| 93.70~132.25                      | 0.484~0.575                            |
| Qiuyue pear   | 76.39~119.25                      | 0.437~0.546                            |

3.2.2. Pear Accumulation Angle

According to the Section 2.3.2 (1), the experiments of pear accumulation angle was carried out. It was obtained to process the image of pears with Matrix Laboratory software. There were four steps. The first one was to read the original image (Figure 13a), and the second one was to process gray scale and binarization (Figure 13b), and the third one was to extract the image boundary contour (Figure 13c), and the last one was linear fitting
(Figure 13d). The angle between the fitting line and the horizontal plane was the measured pear accumulation angle.

The average values were taken 10 times for each variety. The measured pear accumulation angle was obtained. The accumulation angles of Snow pear, Crisp pear, Huangguan pear and Qiuyue pear were 18.45°, 17.93°, 18.26° and 18.09°, respectively.

3.2.3. Optimal Value of Influencing Factors of the Pear Accumulation Angle

Considering the coefficient of collision recovery ($e$), the coefficient of static friction ($\mu_n$) and the coefficient of rolling friction between pears ($\mu_f$), the steepest ascent experiment was carried out to determine the optimal value of influencing factors of the pear accumulation angle. The collision recovery coefficient between pears was from 0.50 to 0.70 according to Table 10. The static friction coefficient of most agricultural materials is from 0.20 to 0.50 [34,35], and the rolling friction coefficient is from 0.01 to 0.05 [36,37]. Therefore, the design and the results of steepest ascent experiment were shown in Table 11. Among them, $\theta$ was the simulated value of the pear accumulation angle, and $\sigma$ was the error between the simulated value and the measured value.

Table 11. Design and results of the steepest ascent experiment.

| Number | Experiment Factors | Experiment Results |
|--------|--------------------|--------------------|
|        | $e$ | $\mu_n$ | $\mu_f$ | $\theta$(°) | $\sigma$/% |
| 1      | 0.50 | 0.10  | 0.01  | 16.98     | 7.97     |
| 2      | 0.54 | 0.20  | 0.02  | 18.14     | 1.69     |
| 3      | 0.58 | 0.30  | 0.03  | 19.35     | 4.88     |
| 4      | 0.62 | 0.40  | 0.04  | 20.52     | 11.22    |
| 5      | 0.66 | 0.50  | 0.05  | 22.75     | 23.31    |
| 6      | 0.70 | 0.60  | 0.06  | 23.43     | 26.99    |

As shown in Table 11, with the improvement of the static friction coefficient and rolling friction coefficient between pears, $\sigma$ decreased first and then increased. When the simulated
parameters were the second combination, \( \sigma \) is the smallest, at only 1.69%. Therefore, the optimal values of influencing factors of the pear accumulation angle was obtained, which were the first, the second and the third combination.

3.2.4. Error Optimization Model of the Pear Accumulation Angle

According to the above analysis, the coefficient of collision recovery \((e)\), the coefficient of static friction \((\mu_n)\) and the coefficient of rolling friction between pears affected the pear accumulation angle. By the method of orthogonal rotation combination, five-level simulation experiments of the pear accumulation angle were designed for each factor. The codes were shown in Table 12, and the results were shown in Table 13.

Table 12. Codes of simulation experiment factors.

| Code | Experiment Factors |
|------|--------------------|
|      | \(e\) | \(\mu_n\) | \(\mu_f\) |
| −1.682 | 0.47 | 0.03 | 0.003 |
| −1    | 0.50 | 0.1  | 0.01  |
| 0     | 0.54 | 0.2  | 0.02  |
| 1     | 0.58 | 0.3  | 0.03  |
| 1.682 | 0.61 | 0.37 | 0.037 |

Table 13. Results of orthogonal rotation combination experiment.

| Number | Parameter | \(\theta/\degree\) | \(Y(\sigma)/\%\) |
|--------|-----------|-------------------|-----------------|
| 1      | A(\(e\)) | 1                 | 18.46           | 5.37            |
| 2      | A(\(e\)) | −1                | 18.95           | 2.71            |
| 3      | 0         | 0                 | 18.13           | 1.73            |
| 4      | 0         | 1.682             | 18.65           | 1.08            |
| 5      | 0         | 0                 | 18.00           | 2.44            |
| 6      | 0         | 0                 | 17.94           | 2.76            |
| 7      | −1        | 1                 | 18.23           | 1.19            |
| 8      | 1         | 0                 | 19.09           | 3.47            |
| 9      | 1         | 1                 | 19.91           | 2.93            |
| 10     | 0         | 0                 | 18.26           | 1.03            |
| 11     | −1.682    | 0                 | 18.19           | 1.41            |
| 12     | 0         | 0                 | 18.12           | 1.79            |
| 13     | 1         | −1                | 16.94           | 8.18            |
| 14     | 0         | 1.682             | 18.35           | 0.54            |
| 15     | −1        | −1                | 17.97           | 3.58            |
| 16     | 0         | 0                 | 18.24           | 1.14            |
| 17     | 0         | 0                 | 18.29           | 0.87            |
| 18     | 0         | −1.682            | 16.79           | 9.00            |
| 19     | 0         | 0                 | 17.72           | 3.96            |
| 20     | −1        | −1                | 16.88           | 8.51            |

Using Design-Expert 8.0.6 to analyze the experimental data, the error regression model of the pear accumulation angle was as follows:

\[
Y = 1.46 + 0.46A - 2.10B - 0.84C + 0.13AB + 0.14AC + 1.23BC + 0.48A^2 + 1.52B^2 + 0.53C^2 \tag{10}
\]

According to the model, the \(p\) value was calculated by the F-test and the influence of each factor on the error of accumulation angle was analyzed, which was shown in Table 14.
Table 14. Analysis of Variance.

| Source | Sum of Squares | Degree of Freedom | Mean Square | F-Value | p-Value |
|--------|----------------|-------------------|-------------|---------|---------|
| Model  | 121.46         | 9                 | 13.50       | 14.90   | 0.0001 **|
| A      | 2.85           | 1                 | 2.85        | 3.14    | 0.1067  |
| B      | 60.09          | 1                 | 60.09       | 66.33   | <0.0001 **|
| C      | 9.57           | 1                 | 9.57        | 10.57   | 0.0087 **|
| AB     | 0.13           | 1                 | 0.13        | 0.15    | 0.7101  |
| AC     | 0.16           | 1                 | 0.16        | 0.18    | 0.6814  |
| BC     | 12.03          | 1                 | 12.03       | 13.28   | 0.0045 **|
| A²     | 3.25           | 1                 | 3.25        | 3.59    | 0.0873  |
| B²     | 33.27          | 1                 | 33.27       | 36.73   | 0.0001 **|
| C²     | 4.09           | 1                 | 4.09        | 4.51    | 0.0596  |
| Residual | 9.06       | 10                | 0.91        |         |         |
| Lack of Fit | 7.29  | 5                | 1.46        | 4.11    | 0.0734  |
| Pure error | 1.77    | 5                | 0.35        |         |         |
| Sum | 130.52         | 19                |             |         |         |

Note: ** indicates extremely significant difference (p < 0.01).

As shown in Table 14, p < 0.01 showed that the error regression model of the pear accumulation angle was extremely significant. The fitting coefficient is 0.9306, which indicated the model had a high fitting degree. The static friction coefficient and rolling friction coefficient between pears had significant influence on the pear accumulation angle, while the collision recovery coefficient between pears had little influence. The main reason was that the pear’s size was bigger, which had caused the bigger voids and a rapid dissipation of energy. Therefore, the error model of pear accumulation angle can be simplified as follows:

\[
Y = 1.46 - 2.10B - 0.84C + 1.23BC + 1.52B^2
\]  

(11)

According to the above analysis, the collision recovery coefficient was set as intermediate level. In order to determine the optimal simulation parameters of, static friction coefficient and rolling friction coefficient between pears, the error optimization model of the pear accumulation angle was as follows:

\[
\begin{align*}
\min_Y & (B, C) \\
A & = 0.54 \\
\text{s.t.} & \begin{cases} 
-1.682 \leq B \leq 1.682 \\
-1.682 \leq C \leq 1.682 
\end{cases}
\end{align*}
\]  

(12)

When the collision recovery coefficient between pears was 0.54, and the static friction coefficient was 0.27, and rolling friction coefficient was 0.020, the error between the measured value and simulation value of accumulation angle was 0.73%. The same parameters were set in EDEM, the accumulation angle was 18.32°, which was consistent with the measured value. Using the method of combining direct measurement and virtual calibration, Mu Guizhi [38] determined the simulation parameters of sweet potato leaves, the error between the measured value and simulation value of accumulation angle was 0.972%. It was obvious that the error between the measured value and simulation value of pear accumulation angle was smaller than that of sweet potato leaves.

In the same way, the simulation parameters of other pear variety were obtained. The results were shown in Table 15.

According to [26], the collision recovery coefficient, the static friction coefficient and the rolling friction coefficient between Panax notoginseng seeds were 0.492, 0.202 and 0.083, respectively. In [27], the three coefficients between cotton seeds were 0.413, 0.695 and 0.214, respectively. Compared with them, the collision recovery coefficient between pears was similar, and the static friction coefficient and the rolling friction coefficient between
pears were smaller because the pears’ surface was smooth. So these results indicated the simulation parameters of pears were accurate and reliable.

Table 15. Simulation parameters of pears.

| Variety          | Collision Recovery Coefficient | Static Friction Coefficient | Rolling Friction Coefficient |
|------------------|--------------------------------| -----------------------------|------------------------------|
| Snow pear        | 0.54                           | 0.27                         | 0.020                        |
| Crisp pear       | 0.44                           | 0.24                         | 0.024                        |
| Huangguan pear   | 0.51                           | 0.31                         | 0.018                        |
| Qiuyue pear      | 0.48                           | 0.28                         | 0.027                        |

3.2.5. Verification of Simulation Parameters between Pears

According to the Section 2.3.2 (4), the experiment was carried out by the method of lifting bottomless barrel to verify the simulation parameters between pears. The average values were taken 10 times for each variety. The measured and simulated pear accumulation angles were obtained. The results were shown in Table 16.

Table 16. Verification of the pear accumulation angles.

| Variety          | Measured Value | Simulated Value | Error/% |
|------------------|----------------|-----------------|---------|
| Snow pear        | 15.53          | 15.75           | 1.42    |
| Crisp pear       | 15.04          | 15.29           | 1.68    |
| Huangguan pear   | 15.31          | 15.65           | 2.19    |
| Qiuyue pear      | 15.49          | 15.77           | 1.83    |

According to [39], the error of the accumulation angle of potato minituber between the physical experiment and the simulation experiment was about 2.06%, the errors of pears between the measured value and simulated value were all less than 2.5% as shown in Table 16, which indicated that the simulation parameters calibration based on DEM was accurate and reliable.

4. Conclusions

(1) Based on the intrinsic parameters of four kinds of pears (Snow pear, Crisp pear, Huangguan pear and Qiuyue pear), their simulation models were constructed by the method of DEM. The simulation parameters between pears and the contact material (PVC, EVA foam material) were calibrated by the methods of free fall collision, inclined sliding and rolling, respectively. The collision recovery coefficients of Snow pear, Crisp pear, Huangguan pear and Qiuyue pear with PVC material were 0.542, 0.516, 0.624 and 0.573, respectively; and the static friction coefficients were 0.686, 0.651, 0.627 and 0.661, respectively; and the rolling friction coefficients were 0.00597, 0.00735, 0.00638 and 0.00714, respectively. The collision recovery coefficients between Snow pear, Crisp pear, Huangguan pear and Qiuyue pear with EVA foam material were 0.652, 0.608, 0.678 and 0.641, respectively; and the static friction coefficients were 0.472, 0.491, 0.394 and 0.574, respectively; and the rolling friction coefficients were 0.00706, 0.00735, 0.00638 and 0.00714, respectively.

(2) The pear accumulation angle was obtained by experimental measurement. The steepest ascent experiment was carried out to determine the optimal value of influencing factors of the pear accumulation angle. Considering the coefficient of collision recovery, the coefficient of static friction and the coefficient of rolling friction between pears, five-level simulation experiments of the pear accumulation angle were designed for each factor by the method of orthogonal rotation combination. The regression model of the error between the measured value and the simulated value of the pear accumulation angle was established, and the influence of three factors on the pear accumulation angle was analyzed. The results showed that the collision recovery
coefficients of Snow pear, Crisp pear, Huangguan pear and Qiuyue pear were 0.54, 0.44, 0.51, and 0.48, respectively; and the coefficients of static friction were 0.27, 0.24, 0.31, and 0.28, respectively; and the coefficients of rolling friction were 0.020, 0.024, 0.018, and 0.027, respectively.

(3) The accumulation angle verification experiments were carried out by the method of bottomless barrel lifting. The results showed that the relative error between the simulated and measured accumulation angle of four kinds of pears were 1.42%, 1.68%, 2.19% and 1.83%, respectively, which indicated that the calibrated simulation parameters were reliable. The research can provide a basis for the design and parameter optimization of harvesting machinery of pears.

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**References**

1. **Wang, G.M.; Gu, C.; Qiao, X.; Zhao, B.Y.; Ke, Y.Q.; Guo, B.B.; Hao, P.P.; Qi, K.J.; Zhang, S.L.** Characteristic of pollen tube that grew into self style in pear cultivar and parent assignment for cross-pollination. *Sci. Hortic.* **2017**, *216*, 226–233. [CrossRef]

2. **Zhang, J.; Li, J.; Xue, C.; Wang, R.; Zhang, M.; Qi, K.; Fan, J.; Hu, H.; Zhang, S.; Wu, J.** The variation of stone cell content in 236 germplasms of sand pear (*Pyrus pyrifolia*) and identification of related candidate genes. *Hortic. Plant J.* **2021**, *7*, 108–116. [CrossRef]

3. **Winzer, F.; Kraska, T.; Elsenberger, C.; Kötter, T.; Pude, R.** Biomass from fruit trees for combined energy and food production. *Biomass Bioenerg.* **2017**, *107*, 279–286. [CrossRef]

4. **Musacchi, S.; Iglesias, I.; Neri, D.** Training Systems and Sustainable Orchard Management for European Pear (*Pyrus communis L.*) in the Mediterranean Area: A Review. *Agronomy* **2021**, *11*, 1765. [CrossRef]

5. **Seo, H.J.; Chen, P.A.; Song, J.** Model based on temperature parameters predicts optimal harvest date for ‘Whasan’ Asian pear. *Hortic. Env. Biotechnol.* **2020**, *61*, 807–814. [CrossRef]

6. **Zicheng, G.; Guoyou, P.; Lijun, L.; Kaijie, Z.; Xiaochen, W.; Chengcai, J.** Design of hand-operated piggyback jaw gripper type simplified picker for pear. *Trans. Chin. Soc. Agric. Eng.* **2019**, *35*, 39–45. (In Chinese)

7. **Kim, S.; Yang, S.; Cho, M.S.; Chung, S.J.** Understanding the drivers of liking for fresh pears: A cross-cultural investigation of Chinese and Korean panels and consumers. *J. Sci. Food Agric.* **2019**, *99*, 5092–5101. [CrossRef]

8. **Liu, X.; Tian, D.; Song, M.; Geng, D.; Zhao, Y.** Design and Experiment on Pneumatic Flexible Gripper for Picking Globose Fruit. *Trans. Chin. Soc. Agric. Mach.* **2021**, 52, 30–43. (In Chinese)

9. **Kong, X.; Liu, J.; Yang, T.; Su, Y.; Geng, J.; Niu, Z.** Numerical simulation of feed pellet breakage in pneumatic conveying. *Biosyst. Eng.* **2022**, *218*, 31–42. [CrossRef]

10. **Wang, X.; Zhang, S.; Pan, H.; Zheng, Z.; Huang, Y.; Zhu, R.** Effect of soil particle size on soil-subsoiler interactions using the discrete element method simulations. *Biosyst. Eng.* **2019**, 182, 138–150. [CrossRef]

11. **Zeng, Z.; Chen, Y.** Simulation of straw movement by discrete element modelling of straw-sweep-soil interaction. *Biosyst. Eng.* **2019**, *180*, 25–35. [CrossRef]

12. **Ding, X.; Wei, Y.; Yan, Z.; Zhu, Y.; Cao, D.; Li, K.; He, Z.; Cui, Y.** Simulation and Experiment of the Spiral Digging End-Effector for Hole Digging in Plug Tray Seedling Substrate. *Agronomy* **2022**, *12*, 779. [CrossRef]

13. **Wang, X.; Yu, J.; Lv, F.; Wang, Y.; Fu, H.** A multi-sphere based modelling method for maize grain assemblies. *Adv. Powder Technol.* **2017**, *28*, 584–595. [CrossRef]

14. **Adilet, S.; Zhao, J.; Sayakhat, N.; Chen, J.; Nikolay, Z.; Bu, L.; Sugirbayeva, Z.; Hu, G.; Marat, M.; Wang, Z.** Calibration Strategy to Determine the Interaction Properties of Fertilizer Particles Using Two Laboratory experiments and DEM. *Agriculture* **2021**, *11*, 592. [CrossRef]

15. **Zhou, H.; Hu, Z.; Chen, J.; Lv, X.; Xie, N.** Calibration of DEM models for irregular particles based on experimental design method and bulk experiments. *Powder Technol.* **2018**, *322*, 210–223. [CrossRef]
16. Coetzee, C.J. Calibration of the discrete element method and the effect of particle shape. *Powder Technol.* **2016**, *297*, 50–70. [CrossRef]

17. Liu, F.; Li, D.; Zhang, T.; Lin, Z. Analysis and calibration of quinoa grain parameters used in a discrete element method based on the repose angle of the particle heap. *INMATEH-Agric. Eng.* **2020**, *61*, 77–86. [CrossRef]

18. Zeng, Z.W.; Ma, X.; Cao, X.L.; Li, Z.H.; Wang, X.C. Critical Review of Applications of Discrete Element Method in Agricultural Engineering. *Trans. Chin. Soc. Agric. Mach.* **2021**, *52*, 1–20. (In Chinese)

19. Chen, Z.; Wassgren, C.; Veikle, E.; Ambrose, K. Determination of material and interaction properties of maize and wheat kernels for DEM simulation. *Biosyst. Eng.* **2020**, *195*, 208–226. [CrossRef]

20. Zhang, S.; Tekeste, M.Z.; Li, Y.; Gaul, A.; Zhu, D.; Liao, J. Scaled-up rice grain modelling for DEM calibration and the validation of hopper flow. *Biosyst. Eng.* **2020**, *194*, 196–212. [CrossRef]

21. Li, X.; Du, Y.; Liu, L.; Mao, E.; Yang, F.; Wu, J.; Wang, L. Research on the constitutive model of low-damage corn threshing based on DEM. *Comput. Electron. Agric.* **2022**, *194*, 106722. [CrossRef]

22. Nguyen, T.X.; Le, L.M.; Nguyen, T.C.; Nguyen, N.T.H.; Le, T.T.; Pham, B.T.; Le, V.M.; Ly, H.B. Characterization of soybeans and calibration of their DEM input parameters. *Part. Sci. Technol.* **2020**, *39*, 530–548. [CrossRef]

23. Wenzheng, L.; Jin, H.; Hongwen, L.; Xueqiang, L.I.; Kan, Z.H.E.N.G.; Zhongcai, W.E.I. Calibration of Simulation Parameters for Potato Minituber Based on EDEM. *Trans. Chin. Soc. Agric. Mach.* **2018**, *49*, 125–135. (In Chinese)

24. Liu, Y.; Mi, G.; Zhang, S.; Li, P.; Huang, Y. Determination of Discrete Element Modelling Parameters of Adzuki Bean Seeds. *Agriculture* **2022**, *12*, 626. [CrossRef]

25. Hao, J.J.; Wei, W.B.; Huang, P.C.; Qin, J.H.; Zhao, J.G. Calibration and experimental verification of discrete element parameters of oil sunflower seeds. *Trans. Chin. Soc. Agric. Eng.* **2021**, *37*, 36–44. (In Chinese)

26. Yu, Q.X.; Liu, Y.; Chen, X.B.; Sun, K.; Lai, Q.H. Calibration and Experiment of Simulation Parameters for Panax notoginseng Seeds Based on DEM. *Trans. Chin. Soc. Agric. Mach.* **2020**, *51*, 123–132. (In Chinese)

27. Bai, S.; Yuan, Y.; Niu, K.; Zhou, L.; Zhao, B.; Wei, L.; Liu, L.; Xiong, S.; Shi, Z.; Ma, Y.; et al. Simulation Parameter Calibration and Experimental Study of a Discrete Element Model of Cotton Precision Seed Metering. *Agriculture* **2022**, *12*, 870. [CrossRef]

28. Hou, Z.F.; Dai, N.; Chen, Z.; Qiu, Y.; Zhang, X.W. Measurement and calibration of physical property parameters for Agropyron seeds in a discrete element simulation. *Trans. Chin. Soc. Agric. Eng.* **2020**, *36*, 46–54. (In Chinese)

29. Hao, J.J.; Long, S.F.; Li, H.; Jia, Y.L.; Ma, Z.K.; Zhao, J.G. Development of discrete element model and calibration of simulation parameters for mechanically-harvested yam. *Trans. Chin. Soc. Agric. Eng.* **2019**, *35*, 34–42. (In Chinese)

30. Yu, F.H.; Zhou, C.Q.; Yang, X.; Guo, Z.H.; Chen, C.L. Design and Experiment of Tomato Picking Robot in Solar Greenhouse. *Trans. Chin. Soc. Agric. Mach.* **2022**, *53*, 41–49. (In Chinese)

31. JIANG, K.; Liping, C.E.H.N.; ZHANG, Q. Design and Experiment on Flexible Clamping and Conveying Mechanism of Vegetable Grafting Robot. *Trans. Chin. Soc. Agric. Mach.* **2020**, *51*, 63–71. (In Chinese)

32. Wen, X.; Yuan, H.; Wang, G.; Jia, H. Calibration Method of Friction Coefficient of Granular Fertilizer by Discrete Element Method and Verification of Seed-metering experiment. *Trans. Chin. Soc. Agric. Mach.* **2020**, *51*, 115–122. (In Chinese)

33. Wang, Z.; Lin, S. Tests and FE analysis for dynamic responses of packaged products underrandom vibration environment. *J. Vib. Shock.* **2017**, *36*, 223–229. (In Chinese)

34. Shi, L.; Sun, W.; Zhao, W.; Yang, X.; Feng, B. Parameter determination and validation of discrete element model of seed potato mechanical seeding. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 35–42. (In Chinese)

35. Zhang, S.; Zhang, R.; Chen, T.; Fu, J.; Yuan, H. Calibration of Simulation Parameters of Mung Bean Seeds Using Discrete Element Method and Verification of Seed-metering experiment. *Trans. Chin. Soc. Agric. Mach.* **2022**, *53*, 71–79. (In Chinese)

36. Scheffler, O.C.; Coetzee, C.J.; Opara, U.L. A discrete element model (DEM) for predicting apple damage during handling. *Biosyst. Eng.* **2018**, *172*, 29–48. [CrossRef]

37. Kafashan, J.; Wiacek, J.; Ramon, H.; Mouazen, A.M. Modelling and simulation of fruit drop experiments by discrete element method. *Biosyst. Eng.* **2021**, *212*, 228–240. [CrossRef]

38. Guizhi, M.; Xieteng, Q.; Wanzhi, Z.; Zhaofin, L.; Tingting, Z.; Shuwen, W. Parameter Measurement and Calibration in Discrete Element Simulation of Broken Sweet Potato Seedlings. *Am. J. Biochem. Biotechnol.* **2021**, *17*, 256–266.

39. Yu, C.; Duan, H.; Cai, X.; Xu, T.; Yao, F.; Chen, Z.; Yan, F. Discrete element simulation parameters-based measurement of materials for potato minituber. *J. Huazhong Agric. Univ.* **2021**, *40*, 210–217. (In Chinese)