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Preliminary communication

Parameter Optimization for a Potato Rod-type Conveyor Grading Device Based on the Discrete Element Method

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Abstract: Existing field potato grading devices are complex in structure and large in volume, designing a rod-type conveyor grading device. Relying on field measurement, size and field distribution laws of mature potatoes are obtained and their field distribution is modelled. Moreover, the conveyor grading device model is established using the discrete element method (EDEM). The single-factor test and multi-factor test adopting one evaluation index (grading accuracy) and four test factors (conveyor chain elevation angle, conveyor chain speed, rod clearance, and potato feed rate) were conducted. Finally, the effects of various test factors on the evaluation index are analyzed and test factors are optimized. According to the results of this study, the rod-type conveyor grading device had a grading accuracy of 93.32%. The relative error between experimental validation and simulation results was less than 8%, suggesting that the regressive mathematical model proposed in this paper and the optimization results obtained were reasonable.

Keywords: bench test; discrete element method; parameter determination; potato; simulation

1 INTRODUCTION

Potato is a perennial herb belonging to the genus Solanum of the family Solanaceae. It is characterized by factors such as drought resistance, high yield, barrenness resistance. With its further popularization as a staple food crop in China, potato is expected to become another major staple food crop following corn, rice, and wheat [1]. China is continuously increasing its potato yield, but it is not yet a world power in the potato processing trade, mainly because its grading technologies are still immature [2]. However, potato grading technology plays a very important role in the potato harvest process, because potatoes of different sizes are different in processing, selling and storage.

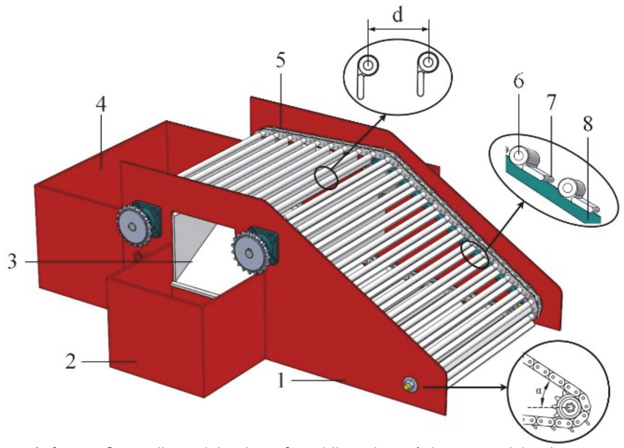
Depending on the time of grading, existing potato grading methods can be classified into grading after harvesting and grading upon harvesting. Grading potatoes after harvesting based on machine vision represents an important developmental direction of the post-harvesting automatic production lines of potatoes [3, 4]. Tao et al. [5] investigated a machine vision-based automatic detection system for potato shape grading developed through Fourier shape classification. The authors proposed a rule-based dynamic grading algorithm for potatoes. NavidRazmjooy et al. [6] graded potatoes according to industrial standards. They built a colour defect detection system with a colour grading accuracy of 96% and a size grading accuracy of 96.95%. Su et al. [7] developed a new image processing algorithm, which can successfully grade 90% of potatoes with a normal volume model and successfully identify 100% of deformed potatoes. To sum up, grading potatoes after harvesting offers a high grading accuracy. However, this approach does not apply to the situation in China. This is because potatoes are harvested by stages in China [8], and harvested potatoes are scattered on the ground for picking and later grading. In this case, too many mechanical operations not only increase mechanical damages to potatoes but also lower the production efficiency. Thus, field potato grading upon harvesting better suits China's national conditions. On that account, Wei et al. [9] designed a roller chain-type grading device mountable on potato combine-harvesters. Xiao et al. [10] designed a roller-type grading device for potato picking machines. These grading devices are all available for field potato grading. However, due to the large size of applicable model structures and the difficulties in climbing and turning, they are unsuitable for use in northwestern China. In addition, as an effective and mature numerical computation method, discrete element method is a numerical simulation method to deal with particle fluid problems, and the numerical simulation software EDEM based on discrete element method has been widely used in the field of agricultural engineering. For example, Niu et al. [11] used EDEM software to optimize the structure of potato seed metering device. Wei et al.[12] used EDEM software to analyze the influence of structural parameters and operating parameters of different wavy separating sieve on the separation mechanism of clods crushing and potato collision characteristics.

Taking into account the characteristics of conveyor devices, a conveyor grading device is designed in this paper which is mountable on small-sized potato picking machines in northwestern China [13, 14]. First, the size and field distribution laws of potatoes are obtained in field surveys. Next, a discrete element model for potatoes is established on this basis. A conveyor grading device is built using the discrete element method (EDEM), and potato conveying and grading processes are simulated. Finally, the conveyor grading device is optimized. In this way, a foundation for designing the conveyor grading device is laid.

2 METHODS AND MATERIALS

2.1 Rod-type Conveyor Grading Device

Fig. 1 shows the mechanical structure of a rod-type conveyor grading device available for the conveying, grading, and collection of potatoes. The device mainly consists of a frame, conveyor chain, conveyor rods, movable hinges, guide rails, guiding plates, and receiving boxes. Each conveyor rod on the conveyor chain is mounted with a freely rotational movable hinge. For potato grading, the lower front end of the conveyor chain is installed with guide rails, so that movable hinges stretch out horizontally. There are no guide rails at the rear end of the conveyor chain, so movable hinges are in a vertical state. As a result, the rear-end rod clearance is larger than the front-end. Under this design, small potatoes pass through rod clearance and enter receiving boxes on both sides through the guiding plate, while larger ones continue to move forward and arrive at the rear-end receiving box.



1. frame; 2. small receiving box; 3. guiding plate; 4. large receiving box; 5. conveyor chain; 6. conveyor rod; 7. movable hinge; 8. guiding rail.
Figure 1 Structure of rod-type conveyor grading device

Conveyor chain elevation angle and rod clearance are the main structural parameters of the rod-type conveyor grading device, and conveyor chain speed is its primary motion parameter. Besides, factors such as potato feed rate may also affect grading performance. To be specific, conveyor chain elevation angle and conveyor chain speed affect grading performance by influencing the motion time of potatoes on the conveyor grading device. Rod clearance affects it by influencing the size of potatoes passing through rod clearance. Potato feed rate affects it by influencing the mass of potatoes entering the conveyor grading device per unit time.

2.2 EDEM Simulation Model
2.2.1 Discrete Element Model for Potatoes

In this study, "Qingshu 9" potato was adopted as the research object, mainly because this variety is widely grown in Ningxia Province of China and has a high yield. A representative experimental field (with a gentle slope and low-viscosity loam or sandy loam) was selected in Baicheng Village, Xinying Township, Xiji County, Guyuan, Ningxia Province. Three experimental plots, each 30 m in length, were randomly picked by lottery. Three cells, every 3 m in length, were chosen by an equal interval from each experimental plot, resulting in nine cells. Five cells were randomly selected from them, and potatoes harvested from these cells and scattered on the ground were collected. The potatoes collected were cleaned up, and their length l, width w, thickness t, and mass were measured using a vernier caliper and a balance. Depending on their morphological characteristics, potatoes are roughly classified into two shapes, i.e., spherical shape and ellipsoidal shape [15]. In this study, sphericity S_p was introduced to classify potatoes into spherical potatoes ($S_p > 0.85$) and ellipsoidal potatoes ($S_p \le 0.85$) [16], where sphericity S_p is defined as:

$$S_p = \left(\frac{\frac{\pi}{6} lwt}{\frac{\pi}{6} l^3} \right)^3 = \left(\frac{wt}{l^2} \right)^{1/3} = \frac{(lwt)^{1/3}}{l} \tag{1}$$

Referring to the grades and specifications of potatoes stipulated in China's official document (*Grades and specifications of potatoes* (NY/T 1066-2006), 2006) and the data collected in the survey conducted in Guyuan, this study adopted 200 g as the mass threshold to divide potatoes into two grades. More specifically, small potatoes less than 200 g (often used for sowing and starch processing) and big potatoes equal to or more than 200 g (often used for supermarket sales and chip processing,), then the potatoes of each grade are classified according to their shape using sphericity S_p. To contribute to the convenience of building a discrete element model for potato particles in EDEM, long axis length $a = l$ and short axis length $b = (w + t)/2$ for ellipsoidal potatoes are introduced in this study, and diameter $d = (l + w + t)/3$ for spherical potatoes. Tab. 1 provides the detailed size information of potatoes obtained in this way [17].

Table 1 Measurements of potato samples

Type	Size range	Mean mass / g	Mean long axis length / mm	Mean short axis length / mm	Size distribution of short axis	Proportion
Spherical small potatoes	25~35	21.1		30.9	29.4~31.8	0.2%
	35~45	38.4		40.7	38.3~44.8	1.7%
	45~55	102.4		51.3	45.4~54.6	3.7%
	55~65	111.0		56.5	55.1~60.2	2.6%
Ellipsoidal small potatoes	25~35	32.2	51.3	31.6	30.4~34.7	0.6%
	35~45	74.5	73.7	41.2	35.2~44.8	9.7%
	45~55	125.8	86.0	49.7	45.3~54.8	21.5%
	55~65	165.5	91.4	57.4	55.1~61.5	5.7%
Ellipsoidal big potatoes	45~55	237.1	112.4	52.7	51.9~54.7	2.3%
	55~65	262.9	119.8	62.8	55.2~64.9	24.6%
	65~75	353.0	131.2	68.3	65.2~74.5	20.9%
	75~85	493.9	156.3	77.9	76.3~78.2	6.5%

To improve the accuracy of discrete element modelling for potato particles, this study adopted multiple spherical particle aggregation models, which were built by overlapping and packing several spherical particles with different diameters. The overlapped and packed spherical particles were regarded as an independent entity in EDEM. A 3D potato model was created in Solidworks, imported into EDEM, and filled up with numerous spherical particles to obtain the simulation model. Simulated potatoes were classified into three types, i.e., spherical small potatoes, ellipsoidal small potatoes, and ellipsoidal big potatoes, as shown in Fig. 2. In the actual simulation, it was assumed that spherical small potatoes and ellipsoidal small potatoes were randomly distributed within the 0.9-1.1 times range of the basic model of each size and that ellipsoidal big potatoes were randomly distributed within the 0.95 - 1.05 times range. This arrangement could better depict the actual size distribution of potatoes.

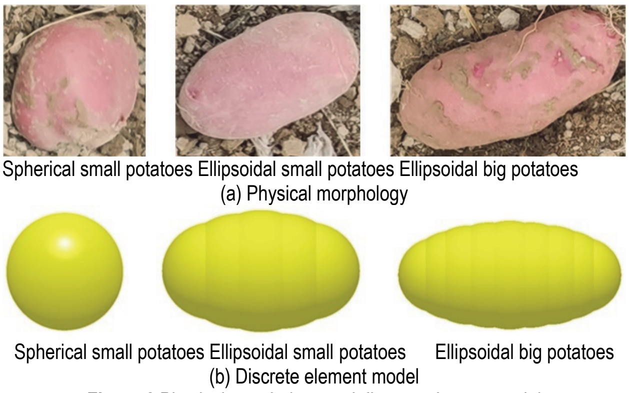


Figure 2 Physical morphology and discrete element model

2.2.2 Parameter Setting

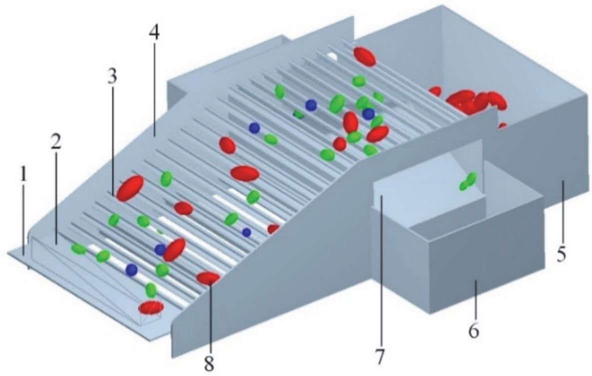
When potatoes are conveyed on the conveyor grading device, contacts are inevitable between potatoes, as well as between potatoes and the conveyor grading device. In consideration of this, this study selected the Hertz-Mindlin (no-slip) model in EDEM. According to relevant literature parameter determination method, Poisson's ratio, density, shear modulus and other parameters of "Qingshu 9" potato were measured, and the physical and contact mechanical parameters of materials used in this study were obtained. [12, 18, 19], as detailed in Tab. 2.

Table 2 Material, physical, and contact mechanical parameters

Parameter		Potato	Rod
Poisson's ratio		0.5	0.28
Density / kg·m^{-3}		1048	7800
Shear modulus / Pa		1.366×10^6	3.1×10^{11}
Contact mechanical parameters	Elastic restitution coefficient	Potato-potato contact	0.79
		Potato-rod contact	0.525
	Static friction coefficient	Potato-potato contact	0.452
		Potato-rod contact	0.445
	Rolling friction coefficient	Potato-potato contact	0.024
		Potato-rod contact	0.269

2.2.3 Simulation in EDEM

A simplified 3D model was created for the rod-type conveyor grading device in Solidworks and imported into EDEM. The fitting parameters of a single conveyor rod group (composed of conveyor rods and movable hinges) were set up in EDEM. The motion trajectory and running speed of the conveyor rod group were employed to calculate the initial running time and rotational angle of the conveyor rod group. On this basis, multiple conveyor rod groups were generated in succession to develop a conveyor grading screen structure model. The running time interval between two adjacent rods (counted from the initial point) in the built simulation model and geometric model was consistent with the actual production process. The potato particle factory generates potatoes with a certain amount of potato according to the size distribution and proportion in Tab. 1. Fig. 3 illustrates the working process of the conveyor grading device, where blue denotes spherical small potatoes, green denotes ellipsoidal small potatoes, and red denotes ellipsoidal big potatoes.



1. conveyor belt model; 2. potato particle factory; 3. conveyor rod; 4. side panel; 5. large receiving box; 6. small receiving box; 7. guiding plate; 8. potato particle.

Figure 3 Conveyor grading device simulation model

2.2.4 Evaluation Index

Grading accuracy was adopted in this study to evaluate the grading performance of the rod-type conveyor grading device [20]. It is defined as the ratio of the total mass of correctly graded potatoes and the total mass of potatoes entering the grading. Generally speaking, the higher the grading accuracy, the better the grading device. It can be calculated from Eq. (2):

$$Y = \frac{m_l}{m_s} \times 100\% \tag{2}$$

where Y is grading accuracy; m_s is the total mass of potatoes entering the grading, kg; m_l is the total mass of correctly graded potatoes, kg.

A cuboid 1,040 mm × 520 mm × 20 mm in size was selected to measure the mass of the virtual potato particles in the rear-end receiving box. A cuboid 640 mm × 450 mm × 20 mm in size was used to measure the mass of the virtual potato particles in the left and right receiving boxes. As shown in Fig. 4, a_{ij}, b_{ij}, and c_{ij} are the mass values of the potatoes collected in the rear-end receiving box, the left receiving box, and the right receiving box, respectively (where i is the potato type, and j is the potato size). To be specific, i = 1 denotes spherical small potatoes; i = 2 denotes ellipsoidal small potatoes; i = 3 denotes ellipsoidal big potatoes. j = 1 denotes the first size; j = 2 denotes the second size; j = 3 denotes the third size; j = 4 denotes the fourth size. Parameters m_s and m_l can be calculated from Eq. (3) and Eq. (4), respectively.

$$m_s = \sum_{i=1}^{3}\sum_{j=1}^{4} a_{ij} + \sum_{i=1}^{3}\sum_{j=1}^{4} b_{ij} + \sum_{i=1}^{3}\sum_{j=1}^{4} c_{ij} \tag{3}$$

$$m_l = \sum_{j=1}^{4} a_{3j} + \sum_{i=1}^{2}\sum_{j=1}^{4} b_{ij} + \sum_{i=1}^{2}\sum_{j=1}^{4} c_{ij} \tag{4}$$

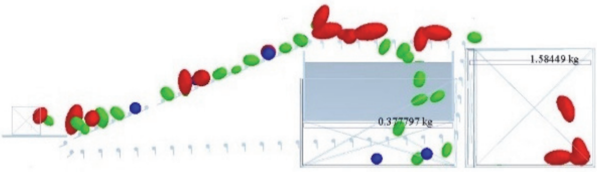


Figure 4 Mass measurement of potatoes entering the receiving box

3 RESULTS AND DISCUSSION

3.1 Single-factor Test

The main factors affecting the grading performance of the conveyor grading device are rod clearance, conveyor chain elevation angle, conveyor chain speed, and potato feed rate. Among them, rod clearance was set as 50 - 62 mm based on the potatoes sampled in Ningxia Province. The potato feed rate was obtained from the overall forward speed of the conveyor and the field distribution of potatoes. The five-section potatoes sampled from Ningxia Province presented a mean-field distribution of 3.3 kg/m. Referring to relevant literature [21, 22] and field measurement results, this study set conveyor chain elevation angle as 12° - 32°, conveyor chain speed as 0.8 - 2.4 m/s, and the overall forward speed of the conveyor as 0.6 - 1.4 m/s. On this basis, the range of potato feed rate was determined as 1.98 - 4.62 kg/s.

3.1.1 Effect of Conveyor Chain Elevation Angle on Grading Performance

The single-factor test was carried out by setting the parameters as follows: conveyor chain elevation angle = 12°, 17°, 22°, 27°, and 32°; conveyor chain speed = 1.6 m/s; rod clearance = 56 mm; potato feed rate = 3.3 kg/s. The relationship between conveyor chain elevation angle and grading accuracy was obtained from simulation results, as shown in Fig. 5a. With the increase of conveyor chain elevation angle, grading accuracy gradually declined. This was because a smaller conveyor chain elevation angle made it easier for potatoes to be conveyed upwards, while a larger conveyor chain elevation angle made it more difficult, resulting in lower grading accuracy. The highest grading accuracy (above 83.65%) occurred within the range of 12 - 22°.

3.1.2 Effect of Conveyor Chain Speed on Grading Performance

The single-factor test was carried out by setting the parameters as follows: conveyor chain speed = 0.8, 1.2, 1.6, 2.0, and 2.4 m/s; conveyor chain elevation angle = 22°; rod clearance = 56 mm; potato feed rate = 3.3 kg/s. The relationship between conveyor chain speed and grading accuracy was obtained from simulation results, as shown in Fig. 5b. With the increase of conveyor chain speed, grading accuracy first increased, and then decreased. This was because a lower conveyor chain speed meant a longer motion time of potatoes on the conveyor chain, which would be conducive to potato grading. On the contrary, an excessively high conveyor chain speed would obstruct potato grading. However, an extremely low conveyor chain speed would cause the congestion of potatoes, causing grading accuracy to first increase and then decrease. The highest grading accuracy (above 84.92%) occurred within the range of 0.8 - 1.6 m/s.

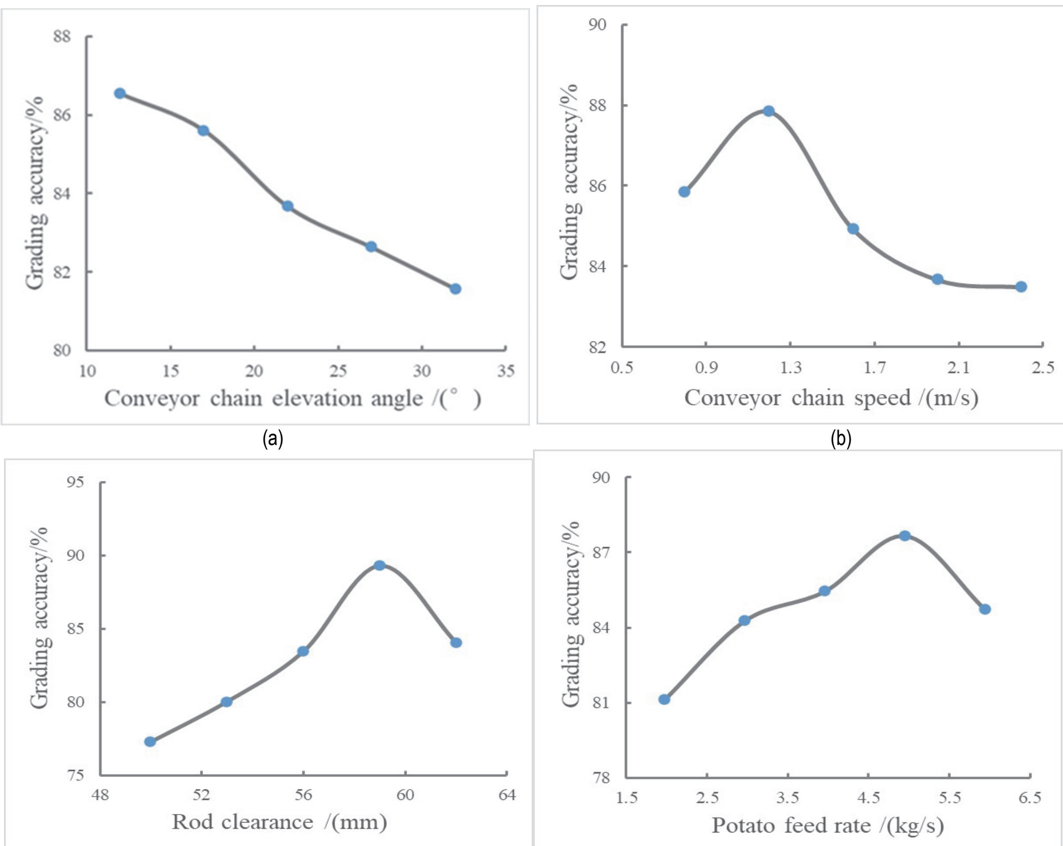


Figure 5 Effects of different factors on grading accuracy

3.1.3 Effect of Rod Clearance on Grading Performance

The single-factor test was carried out by setting the parameters as follows: rod clearance = 50, 53, 56, 59, and 62 mm; conveyor chain elevation angle = 22°; conveyor chain speed = 1.6 m/s; potato feed rate = 3.3 kg/s. The relationship between rod clearance and grading accuracy was obtained from simulation results, as shown in Fig. 5c. With the increase of rod clearance, grading accuracy first increased and then decreased, and peaked when rod clearance was 59 mm. This was because before rod clearance increased to the optimal value, ellipsoidal small potatoes and spherical small potatoes would enter the rear-end of the receiving box. After rod clearance increased to the optimal value, ellipsoidal big potatoes would enter the left and right receiving boxes through the guiding plate, causing grading accuracy to first increase and then decrease. The highest grading accuracy (above 83.49%) occurred within the range of 56 - 62 mm.

3.1.4 Effect of Potato Feed Rate on Grading Performance

The single-factor test was carried out by setting the parameters as follows: potato feed rate = 1.98, 2.64, 3.3, 3.96, and 4.62 kg/s; conveyor chain elevation angle = 22°; conveyor chain speed = 1.6 m/s; rod clearance = 56 mm. The relationship between the potato feed rate and grading accuracy was obtained from simulation results, as shown in Fig. 5d.With the increase of potato feed rate, grading accuracy first increased and then decreased. It peaked when the potato feed rate was 3.96 kg/s. This was because increased potato feed rate meant an increased mass of potatoes entering the conveyor grading device per unit time. Consequently, the grading accuracy is increased. However, when the mass of potatoes entering the conveyor grading device per unit time exceeded the maximum grading capacity of the device, grading accuracy would gradually decline. The highest grading accuracy (above 84.71%) occurred within the range of 3.3 - 4.62 kg/s.

3.2 Multi-factor Test

Based on single-factor test results, the multi-factor test was performed using four test factors (conveyor chain elevation angle *A*, conveyor chain speed *B,* rod clearance *C*, and potato feed rate *D*) and one evaluation index (grading accuracy *Y*). The four-factor three-level quadratic rotating orthogonal center combination test was conducted, and the test table was created by Design-Expert 8.0.6 software. The test table was composed of 24 groups of analysis factors and five groups of zero-point estimation errors, i.e., 29 groups of test points in total. Each group was tested three times. Tab. 3 provides the codes of test factors and Tab. 4 the test results.

Table 3 Test factors and codes

Code	Factor			
	A / °	*B* / m/s	*C* / mm	*D* / kg/s
−1	12	0.8	56	3.30
0	17	1.2	59	3.96
1	22	1.6	62	4.62

Table 4 Test schemes and results

No.	Test factor				*Y* / %
	A / °	*B* / m/s	*C* / mm	*D* / kg/s	
1	−1	−1	0	0	89.14
2	1	−1	0	0	85.50
3	−1	1	0	0	89.93
4	1	1	0	0	87.75
5	0	0	−1	−1	88.40
6	0	0	1	−1	89.09
7	0	0	−1	1	87.33
8	0	0	1	1	84.53
9	−1	0	0	−1	93.27
10	1	0	0	−1	86.68
11	−1	0	0	1	88.04
12	1	0	0	1	86.78
13	0	−1	−1	0	85.87
14	0	1	−1	0	85.30
15	0	−1	1	0	85.37
16	0	1	1	0	88.31
17	−1	0	−1	0	90.57
18	1	0	−1	0	87.21
19	−1	0	1	0	90.30
20	1	0	1	0	88.31
21	0	−1	0	−1	86.15
22	0	1	0	−1	88.51
23	0	−1	0	1	83.76
24	0	1	0	1	86.57
25	0	0	0	0	90.36
26	0	0	0	0	90.75
27	0	0	0	0	90.95
28	0	0	0	0	91.00
29	0	0	0	0	92.35

3.2.1 ANOVA and Discussion

Test data were analyzed and fitted. Tab. 5 provides the ANOVA of grading accuracy *Y*. The significance test value of the model was $P < 0.0001$ ("$P < 0.01$" means the model is highly significant), and the lack of fit test value P = 0.5861 ("$P > 0.05$" means the absence of lack of fit), so the model had high goodness of fit within the ranges of its test parameters. The model had a coefficient of determination of R^2 = 0.9532, suggesting that it could satisfactorily explain the response values under the actions of different factors and predict the grading performance of the device. To be specific, the effects of *A*, *B, D, AD,* B^2, C^2, and D^2 on grading efficiency were highly significant ($P < 0.01$). The effects of *BC* and *CD* on grading efficiency were significant ($0.01 < P < 0.05$). The regression equation of grading accuracy *Y* is as follows:

$$\begin{aligned} Y &= 91.08 - 1.59A + 0.88B + 0.1C - 1.26D + 0.37AB \\ &+ 0.34AC + 1.33AD + 0.88BC + 0.11BD - 0.87CD \\ &- 0.22A^2 - 2.88B^2 - 1.83C^2 - 2.01D^2 \end{aligned} \quad (5)$$

The effects of test factors on the model were directly proportional to the magnitude of contribution rate *K*, as expressed by the following formula:

$$\theta = \begin{cases} 0 & F \le 1 \\ 1 - \dfrac{1}{F} & F < 1 \end{cases} \quad (6)$$

$$K_j = \theta_j + \frac{1}{2}\sum_{i=A}\theta_{ij} + \theta_j^{\,2}, j = A, B, C, D, i \ne j \quad (7)$$

where F is the value of each regression term in the regression equation, θ is the appraisal value of the F value by a regression term, and K_j is the contribution rate of a factor.

Table 5 ANOVA of regression model

Source	dF	Mean square	F	P
Model	14	10.88	20.39	< 0.0001**
A	1	30.15	56.49	< 0.0001**
B	1	9.33	17.48	0.0009**
C	1	0.13	0.24	0.6345
D	1	18.98	35.55	< 0.0001**
AB	1	0.53	1.00	0.3346
AC	1	0.47	0.88	0.3643
AD	1	7.10	13.31	0.0026**
BC	1	3.08	5.77	0.0307*
BD	1	0.051	0.095	0.7626
CD	1	3.05	5.71	0.0315*
A^2	1	0.31	0.57	0.4614
B^2	1	53.89	100.97	< 0.0001**
C^2	1	21.69	40.64	< 0.0001**
D^2	1	26.30	49.27	< 0.0001**
Residual	14	0.53		
Lack of fit	10	0.52	0.92	0.5861
Error	4	0.57		
Total	28			

Note: ** highly significant ($P < 0.01$); * significant ($0.01 < P < 0.05$).

The contribution rates of conveyor chain elevation angle, conveyor chain speed, rod clearance, and potato feed rate to grading accuracy were 1.44, 2.35, 1.80, and 2.83, respectively. That is, they can be ranked as follows in the descending order of contribution rate: potato feed rate > conveyor chain speed > rod clearance > conveyor chain elevation angle.

3.2.2 Response Surface Analysis

Using Design-Expert 8.0.6 software, response surfaces of grading accuracy Y are obtained, which are affected by significant and relatively significant interactions between conveyor chain elevation angle A, conveyor chain speed B, rod clearance C, and potato feed rate D (Fig. 6).

Fig. 6a shows the response surface between conveyor chain elevation angle and potato feed rate when conveyor chain speed and rod clearance were at center levels (B = 0, C = 0). As can be observed from the figure, given conveyor chain elevation angle, increased potato feed rate would cause grading accuracy to first increase and then decrease. This was because increasing the potato feed rate within a certain range would increase grading accuracy. However, when the potato feed rate exceeded the maximum grading capacity of the device, grading accuracy would gradually decline. In contrast, given potato feed rate, increased conveyor chain elevation angle would cause grading accuracy to gradually decline. This was because a larger conveyor chain elevation angle would make it more difficult for potatoes to be conveyed upwards, resulting in lower grading accuracy.

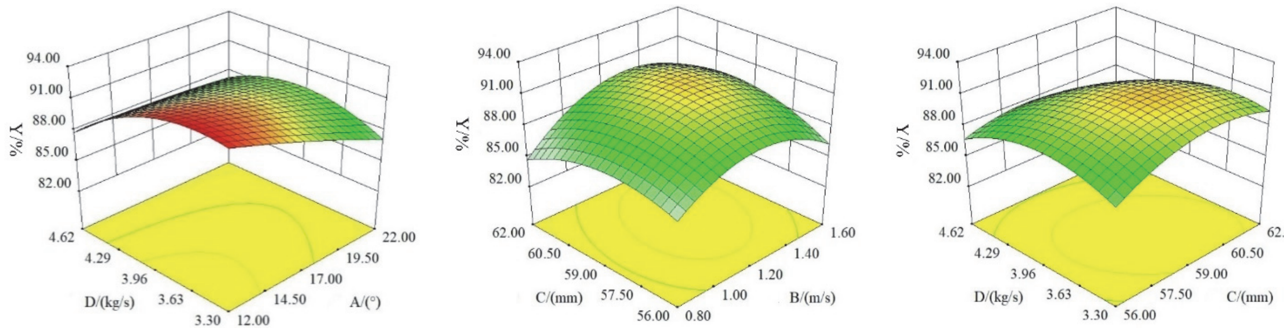


Figure 6 Response surfaces of grading accuracy being affected by interactive factors

Fig. 6b shows the response surface between conveyor chain speed and rod clearance when conveyor chain elevation angle and potato feed rate were at center levels (A = 0, D = 0). As can be observed from the figure, given conveyor chain speed, increased rod clearance would cause grading accuracy to first increase and then decrease. This was because grading accuracy would peak under the optimal rod clearance, and decline on both sides of the optimal rod clearance (before and after reaching the optimal rod clearance). In contrast, given rod clearance, increased conveyor chain speed would cause grading accuracy to first increase and then decrease. This was because increased conveyor chain speed meant a shorter motion time of potatoes on the conveyor chain, which would be inconducive to potato grading. However, an extremely low conveyor chain speed would cause the congestion of potatoes on the conveyor chain, causing grading accuracy to first increase and then decrease.

Fig. 6c shows the response surface between rod clearance and potato feed rate when conveyor chain elevation angle and conveyor chain speed were at center levels (A = 0, B = 0). As can be observed from the figure, given rod clearance, increased potato feed rate would cause grading accuracy to first increase and then decrease. This was because increasing the potato feed rate below the maximum grading capacity of the device would cause grading accuracy to rise. However, when the potato feed rate exceeded the maximum grading capacity of the device, grading accuracy would gradually decline. In contrast, given potato feed rate, increased rod clearance would cause grading accuracy to first increase and then decrease. This was because grading accuracy would peak under the optimal rod clearance, and decline on both sides of the optimal rod clearance (before and after reaching the optimal rod clearance).

3.2.3 Optimization Analysis

To achieve optimal grading performance, the constraint conditions of parameter optimization were determined according to the actual working conditions and grading performance requirements of the grading device. Parameter optimization was performed using Design-Expert 8.0.6 software under the following constraint conditions:

$$\begin{cases} \max Y(A, B, C, D) \\ s.t. \begin{cases} 12^\circ \le A \le 22^\circ \\ 0.8 \text{ m/s} \le B \le 1.6 \text{ m/s} \\ 56 \text{ mm} \le C \le 62 \text{ mm} \\ 3.30 \text{ kg/s} \le D \le 4.62 \text{ kg/s} \end{cases} \end{cases} \tag{8}$$

According to optimization results, the rod-type conveyor grading device had the optimal grading performance and a grading accuracy of 93.32% when conveyor chain elevation angle, conveyor chain speed, rod clearance, and potato feed rate were 12°, 1.24 m/s, 59.4 mm, and 3.52 kg/s, respectively.

3.3 Experimental Validation

To validate the grading performance of the conveyor grading device in practical work, the conveyor grading device was processed based on optimization results. A test bench was constructed and used at Northwest Agriculture & Forestry University in April 2021. The test bench is mainly composed of a conveyor grading device, conveyor belt, receiving boxes, drive motor, and test rack, as shown in Fig. 7. "Qingshu 9" potatoes, which were picked according to their sizes and proportions provided in Tab. 1, are mixed and investigated in this study. Potato feed rate and conveyor chain speed were set as 3.52 kg/s and 1.24 m/s, respectively. The mass of potatoes in each receiving box was measured on the test bench to obtain the grading accuracy of the device. The test was repeated five times and the results are provided in Tab. 6.

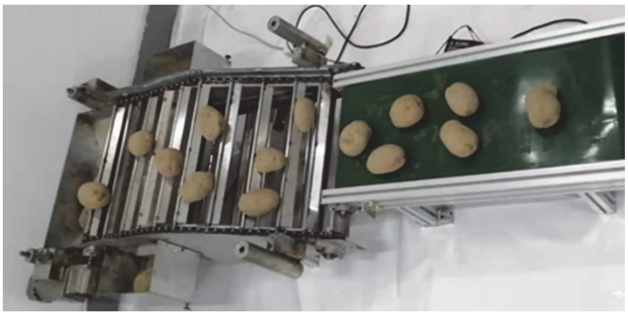


Figure 7 Test bench of rod-type conveyor grading device

Discrete element simulation results were compared with the test results in Tab. 6. As can be seen from test results, measured grading accuracy values ranged from 85.96 to 90.35, with a mean of 88.07. The relative errors between simulated and measured values ranged from 3.18% to 7.89%, with a mean of 5.62%. This demonstrated the pretty high accuracy of the developed EDEM model in simulating the rod-type conveyor grading device. The differences between simulated and measured values were attributable to several factors. The parameters of the potato model were extracted from relevant literature, and it was impossible to guarantee full consistency between the discrete element model for potatoes and the actual distribution of potatoes adopted in the test. All these factors might have contributed to the differences between simulation results and measured measurements.

Table 6 Test results

No.	Measured value	Relative error / %
1	85.96	7.89
2	88.34	5.34
3	89.14	4.48
4	90.35	3.18
5	86.57	7.23
Mean	88.07	5.62

4 CONCLUSION

(1) By conducting a single-factor test on conveyor chain elevation angle, conveyor chain speed, rod clearance, and potato feed rate using EDEM, the following optimal ranges are obtained: 17 - 22° for conveyor chain elevation angle, 0.8 - 1.6 m/s for conveyor chain speed, 56 - 62 mm for rod clearance, and 3.3 - 4.62 kg/s for potato food rate.

(2) In the multi-factor test, the four factors could be ranked as follows in the descending order of contribution rate to grading accuracy: potato feed rate > conveyor chain speed > rod clearance > conveyor chain elevation angle. In particular, interactions between the conveyor chain elevation angle, conveyor chain speed, potato feed rate, conveyor chain speed, conveyor chain elevation angle, potato feed rate, the square of conveyor chain speed, the square of rod clearance, and the square of potato feed rate exerted highly significant effects on grading efficiency. The interactions between the conveyor chain speed and rod clearance and the interactions between conveyor chain speed, rod clearance, and potato feed rate imposed significant effects on grading efficiency.

(3) The optimal parameters for optimizing the grading accuracy of the conveyor grading device are as follows: conveyor chain elevation angle = 12°, conveyor chain speed = 1.24 m/s, rod clearance = 59.4 mm, and potato feed rate = 3.52 kg/s. The optimal parameters were consistent with simulated values and bench test values, with relative errors of less than 8%.

The DEM model built in this study can satisfactorily simulate the working process of the conveyor grading device. However, considering that DEM simulation and experimental tests are customized for specific varieties of potatoes, caution should be taken when using this device for grading other varieties of potatoes upon harvesting.

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