Analysis and parameter optimization of movement trajectory and impact characteristics during bagging process of potato combine harvester

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Abstract: Aiming at the problems of unclear potato movement trajectory and serious force impact, this study took the potato bagging device with buffer roller as the object of research. Through single-factor experiments, it analyzed how the roll diameter, conveyor speed, feed amount, and size of the potato collection bag affected the force of potatoes. Based on the EDEM-RecurDyn coupled simulation, it applied the Box-Behnken experimental method to conduct a three-factor orthogonal experiment on the operating parameters of the device, which took the maximum compressive force of the potato and the maximum kinetic energy as the experimental indices, and took the roller diameter, conveying speed, and feeding amount as the experimental factors. Establishing a quadratic polynomial regression model by using Design Expert software, the regression model was optimized to obtain the best combination of parameters as follows: roll diameter was 212 mm, conveying speed was 0.9 m/s, and feeding amount was 30 t/h. The verification experiment was conducted by using a potato impact recording device, and the results showed that under the condition of the optimal parameter combination, the maximum compressive force of the electronic potato was 238.854 N when bagging, which was close to the theoretical value after parameter optimization, with an error of 5.40%. The rate of damage to potatoes and skin-breaking rate were 0.98% and 1.86%, respectively. The research results can provide support for the study of the motion trajectory, impact force characteristics, and loss reduction of potatoes during subsequent bagging operations.

Keywords: agricultural machinery, potato bagging, EDEM-RecurDyn coupled simulation, force characteristics, potato impact recording device

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1 Introduction

Potato, which is abundant around the world and is one of the world's most important non-cereal foods, is an important commercial crop[1-3]. The potato planting area and yield in China has ranked first in the world for many years. With the support of market demand and national policies, the large-scale potato industry has rapidly developed. However, it has problems such as low yield per unit area and high cost of production[4,5]. Improving the mechanization level of potato harvesting is one of the most important factors to increase its yield per unit area and reduce the production cost. Potato collecting, as an important part of harvesting, directly affects its harvest quality[6-8].

The collection and transportation of potatoes is an important part of the combined harvesting of potatoes. However, during the potato transportation process, due to problems such as unstable operation of the combined harvester's mechanism, excessive drop height of potatoes, and the lack of a flexible buffer mechanism in the device, the potato tubers may suffer from damage such as skin scratches and flesh damaged due to squeezing and impact loads during transportation. It seriously affects the harvest quality and economic benefits of potatoes[9]. Therefore, it is urgently necessary to develop a potato bagging device with high bagging efficiency and a low rate of potato damage. Currently, the main methods of potato harvesting include transferring by conveyor arms, caching in storehouse on harvesters, and bagging without interrupting the harvesting process. The 4UL-170C potato combine harvester[10] developed by Xisen Tiancheng Company adopted the combination

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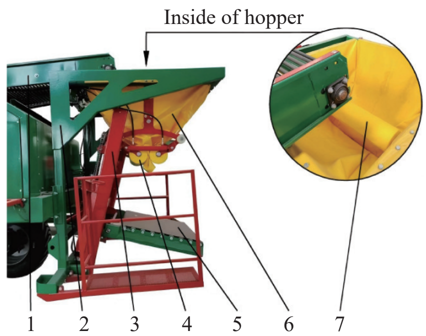
of conveying arms and hopper trucks to transport potatoes which had been harvested into storage for bagging. The conveying arm had an extension function which could adjust its posture according to the state of the materials in the transport truck to complete the potato loading function. The Keiler 2-RK22 potato combine harvester developed by ROPA in Germany[11] was equipped with a system for storing and unloading potatoes, which could meet the requirements of harvesting for a long time and in different environments in the field and automatically fill the silo by ultrasonic sensors. The Kwatro potato combine harvester developed by Dewulf company in Belgium, equipped with a height-adjustable conveying arm and a temporary storage bin for the harvested potatoes, significantly reduces the rate of damaged potatoes during the bagging process and ensures the continuity of the field harvesting process[12]. After being filled, the bag could be manually unloaded. With the development of computer simulation technology, the coupled simulation of Discrete Element Method (DEM) and Multi Body Dynamics (MBD) has been widely applied in the field of agricultural machinery structure optimization design, which can better simulate and analyze complex dynamics[13-16]. Li et al.[17] established a simulation model based on DEM-MBD coupling technology and conducted relevant experiments in order to solve the problems of serious damage and difficulty in removing impurities during potato harvesting. Chen et al.[18] established a coupled simulation model of the potato soil separation device and the interaction between potato and soil based on EDEM-RecurDyn, and the potato soil separation process of the potato harvester was simulated, which improved the efficiency of potato soil separation of the harvester. Wang et al.[19] established a potato transplant-soil composite model and the motion model of the disc-type clamping and pulling device based on the EDEM-RecurDyn coupling. The processes of straightening, clamping, and pulling out the seedlings were simulated and analyzed, and the influences of the forward speed, the angular velocity of the pulling tray, and the height of the pulling tray from the ground on the pulling performance of the device were clarified. For existing potato bagging devices, there are still problems such as unclear force during the bagging process which leads to serious skin damage. It is urgent to study the movement trajectory and collision characteristics of potatoes during the bagging process to effectively reduce damage and skin breaking of potatoes.

Based on previous research, this article takes the potato bagging device with buffer roller as the research object, combining the physical characteristics of potato particles and the operating characteristics of the bagging device. It establishes a dynamic model of the potato bagging device with buffer roller through EDEM and MBD coupled simulation technology. This study uses EDEM-RecurDyn to simulate the motion trajectory and collision characteristics of potato bagging process after cleaning, and analyzes the influence of buffer roller installation position, roller diameter, conveying speed, feeding amount, and potato bag size on the force of potatoes in order that the optimal parameters for the operation of the potato bagging device with buffer roller can be obtained. It is looking forward to providing a reference for the design of potato bagging devices for harvesting.

2 Materials and methods

2.1 Structure and working principle of potato bagging device

The potato bagging device mainly includes hopper, buffer roller, limiting roller, lifting slide table, slide rail, etc. The overall structural diagram of the potato bagging device with buffer roller is shown in Figure 1. The hopper is made of material that is flexible canvas. At present, the mainstream flexible cushioning materials include EVA foam, natural rubber, polyurethane sponge, etc. Among them, EVA foam is low-cost and easy to process, but has poor durability and is not suitable for high-intensity cushioning during the potato harvest process. Natural rubber has good resilience and strong durability, but it cannot effectively absorb impact from collisions. Compared with the above-mentioned materials, polyurethane sponge has the advantages of low cost, strong durability, and good energy absorption and buffering effect. Moreover, the small holes inside the sponge can store and absorb energy to reduce impact. Therefore, polyurethane sponge is selected as the covering material for buffer rollers and limit rollers. In working condition, the lifting slide table rises to the exit of the hopper, and the conveying device transports the cleaned potatoes into the hopper. The hopper is equipped with one buffer roller inside and two limiting rollers out of the hopper on both sides. When the potatoes enter into the hopper, they collide with the buffer roller to reduce impact damage while their falling trajectory is changed. Then, they undergo a secondary collision with the limiting rollers for buffering before entering into the collection bag on the lifting slide table. As the weight of potatoes in the bag increases, the lifting slide table slowly descends to control the height so that potatoes fall into the bag at the same level. After the potato bag is filled, two limiting rollers gather and clamp the hopper, forcing the exit of the hopper to close. The conveying device still continues transporting potatoes to the hopper, and the lifting slide table tilts towards the ground, forcing the bagged potatoes to slide down to the ground to complete the unloading process. After the new potato bag is hung, the two limiting rollers separate and the hopper exit opens, entering the next bagging process.



1. Conveying device 2. Rack 3. Slide rail 4. Limiting roller 5. Lifting slide table 6. Hopper 7. Buffer roller

Figure 1 Overall structural diagram of potato bagging device with buffer roller

2.2 Establishment of simulation model

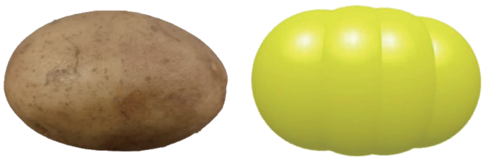
2.2.1 Creation of potato physical model

During simulation experiments, it is necessary to establish a physical model of the potato particle. Solidworks is used to draw potatoes with three-axis dimensions of 97.8 mm, 77.8 mm, and 60.4 mm[20], and they are imported into EDEM in igs. format. Then the physical parameters related to potatoes are set, and they are filled with four spheres for particle filling. The filling effect is shown in Figure 2.

2.2.2 Establishment of the simulation system

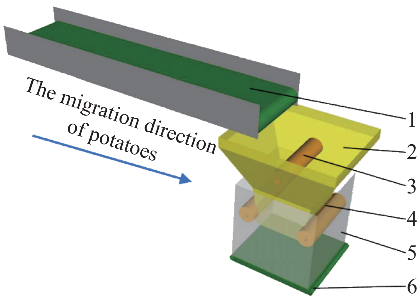
The potato bagging device model is simplified as shown in Figure 3 by using SolidWorks, and it is saved in x-t format to import into RecurDyn. A multi-body dynamics model is established by adding constraints, contacts, and other attributes. The various components of the potato bagging device are imported into EDEM as "wall" files through the RecurDyn built-in coupling interface.

The simulation experiment imported each component of the potato bagging device into the EDEM through the built-in coupling interface of RecurDyn as the "wall" file. Because during the simulation movement of potatoes, each potato particle model moves and rotates under the action of force and torque when colliding and contacting the geometric body, the Hertz-Mindlin model is selected in EDEM to simulate the interactions between potato particles, between potatoes and 65Mn steel, sponge, and rubber. According to the actual harvest situation of potatoes, a virtual surface was set up at the starting end of the conveying device in the EDEM and a particle factory was added. The initial velocity direction is shown in Figure 3.



Potato The discrete element model of potato

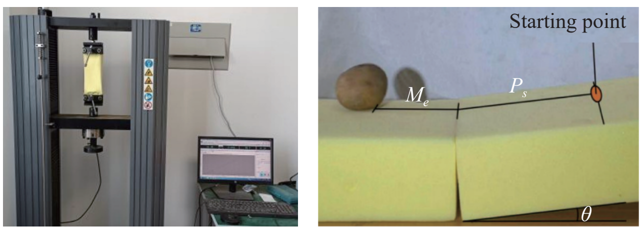
Figure 2 Potato and its discrete element model



1. Conveying device 2. Hopper 3. Buffer roller 4. Limiting roller 5. Potato collecting bag 6. Lifting slide table

Figure 3 Simplified model of potato bagging device

The material properties and contact parameters of potato, 65Mn steel, and rubber can be referred to in the References [21, 22]. However, there is relatively little research on the physical properties of polyurethane sponge and its contact parameters with potatoes. Therefore, their determination is shown in Figure 4.



a. Tensile test of polyurethane sponge b. Rolling friction coefficient test

Figure 4 Determination of the physical properties of polyurethane sponge

The sponge sample (250 mm×70 mm×10 mm) is installed between the upper and lower fixtures of the electronic universal testing machine, the tensile test speed is set to 2 mm/min, and it is ensured that the centerline of the sponge coincides with that of the fixture. After repeating five tests and taking the average of the test results, the maximum tensile force of the polyurethane sponge at fracture was 137.088 N, and the tensile change was 14.4 mm. The test process is shown in Figure 4a. The shear modulus of the polyurethane sponge is calculated to be 1.232 MPa, and the Poisson's ratio is 0.38.

$$\begin{cases} E_p = \dfrac{F_l/S_P}{\Delta L/L_P} \\ G_p = \dfrac{E_p}{2(1+\mu_p)} \end{cases} \tag{1}$$

where, E_p is the elastic modulus of polyurethane sponge, Pa; F_l is the maximum tensile force at break, N; S_p is the cross-sectional area of polyurethane sponge, mm²; ΔL is the tensile change of polyurethane sponge, mm; L_p is the initial length of polyurethane sponge, mm; G_p is the shear modulus of polyurethane sponge, Pa; μ_p is the Poisson's ratio of polyurethane sponge.

A potato with a vertical height of 300 mm from a sponge pad laid flat on the table was placed in free fall and collided with the sponge. The process of the potato's fall and rebound was recorded by a camera. The experiment was repeated five times, and the average maximum rebound height H_{ft} was finally recorded as 12 mm. The collision recovery coefficient between potatoes and sponges is calculated to be 0.2 by Equation (2).

$$e_{ps} = \frac{v_{fl}}{v_{jj}} = \sqrt{\frac{H_{ft}}{H_{xl}}} \tag{2}$$

where, e_{ps} is the collision recovery coefficient of potato and polyurethane; v_{fl} is the separation velocity of two colliding objects, m/s; v_{jj} is the approach velocity of two colliding objects, m/s; H_{ft} is the maximum rebound height of a potato, mm; H_{xl} is the initial height from which the potato drops, mm.

The potato is placed on a polyurethane sponge with one end fixed, and the tilt angle of the other end is gradually and slowly increased. When it is observed that the potato begins to slide, the raising of the angle of the inclined plane is stopped, and the angle between the inclined plane and the horizontal plane is measured at this time. The above steps are repeated five times to obtain an average critical angle of 16.5°. The static friction coefficient is calculated as 0.3 according to Equation (3).

$$\mu_s = \frac{mg\sin\theta_s}{mg\cos\theta_s} = \tan\theta_s \tag{3}$$

where, μ_s is the static friction coefficient between potatoes and polyurethane sponges; m is the mass of potato, kg; g is the acceleration due to gravity, m/s²; θ_s is the critical angle, (°).

The potato is rolled from the inclined sponge to the horizontal sponge with an inclination angle of 5°. The rolling distance P_s of potato on the inclined sponge is 200 mm, and the average value of the rolling distance M_e on the horizontal sponge after multiple tests is 116 mm, as shown in Figure 4b. According to Equation (4), the rolling friction coefficient μ_g can be calculated to be 0.21.

$$\mu_g = \frac{P_S\sin\theta}{P_S\cos\theta + M_e} \tag{4}$$

where, μ_g is the rolling friction coefficient between potato and polyurethane sponge; P_S is the distance the potato rolls on an inclined sponge, mm; θ is the inclination angle of polyurethane sponge, (°); M_e is the distance the potato rolls on a horizontal sponge, mm.

The physical properties of potatoes and various components of the potato bagging device are listed in Table 1, and the contact coefficients between various substances are listed in Table 2.

2.3 Selection and analysis of key parameters

2.3.1 The influence of the installation position of the buffer roller on the force of potatoes

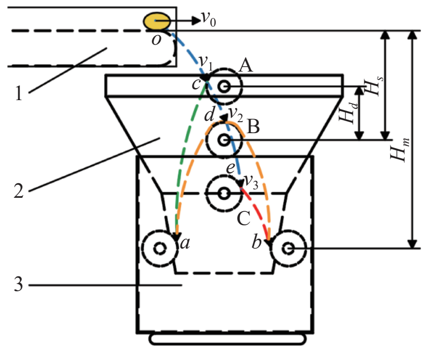
When bagging, the height difference between the conveying device and the limiting roller is fixed and unchanged[23-25]. When the height difference between the buffer roller and the conveying device is too large, it is easy to cause excessive impact such that potatoes fall from the buffer roller to the limiting roller, causing damage. Therefore, in order to minimize the damage during the falling of potatoes, it is necessary to further determine the relative height positions of the buffer roller and the conveying device, and the buffer roller and the limiting roller. The installation positions of the buffer roller are shown as numbers A to C in Figure 5.

Table 1 Physical properties of materials

Material	Poisson's ratio	Density/g·m⁻³	Shear modulus/MPa
Potato	0.40	1160	1.050
Rubber	0.30	1800	37.000
Sponge	0.38	60	1.232
65Mn steel	0.30	7850	310.000

Table 2 Contact parameters between materials

Contactant	Collision recovery factor	Static friction factor	Rolling friction factor
Potato and potato	0.7	0.48	0.025
Potato and rubber	0.7	0.40	0.250
Potato and sponge	0.2	0.30	0.210
Potato and 65Mn steel	0.8	0.45	0.270



1. Conveying device 2. Hopper 3. Potato collecting bag

Figure 5 Installation position of buffer roller

The height difference H_m between the conveying device and the limiting roller was 930.0 mm. Position B was located at the middle height between the conveying device and the limiting roller[26]. The height difference between position B and the conveying device, position B and the limit roller was H_s=1/2H_m=465.0 mm. Using position B as the starting point, the positions of A, B, and C are determined from top to bottom respectively. Position A was located at the middle height between the conveying device and position B, and position C was located at the middle height between position B and the limiting roller. The height difference between position A and the conveying device, i.e., the height difference between position A and the conveying device, and between position C and the limiting roller were both H_d=1/4H_m=232.5 mm. The parameters of the conveying device were pre-set based on the previous tests, the conveying speed of the conveying device was set to 1 m/s, and the roller diameter was set to 200.0 mm.

The collision model between potatoes and buffer rollers can be approximately regarded as the collision between two elastic spheres. According to the theories of Kuwabara and Kono (kk-model)[27], let the particle radii of the two contacts be R_a and R_b, respectively. Based on the Hertz-Mindlin model, the normal force F_n and the collision normal stress σ on potato particles between particles or between particles and material satisfies the following functional relationship:

$$\begin{cases} F_n = \dfrac{4E_aE_b\sqrt{\dfrac{R_aR_b}{R_a+R_b}}\delta_n^{\frac{3}{2}}}{3[E_b(1-\mu_a^2)+E_a(1-\mu_b^2)]} \\ \sigma = \dfrac{2}{\pi}\left(\dfrac{E_aE_b}{E_b(1-\mu_a^2)+E_a(1-\mu_b^2)}\right)^{\frac{1}{2}}\left(\delta_n\dfrac{R_aR_b}{R_a+R_b}\right)^{\frac{1}{2}} \end{cases} \quad (5)$$

where, δ_n is normal deformation amount, mm; E_a is elastic modulus of potatoes, Pa; E_b is elastic modulus of objects colliding, Pa; R_a is the radius of potatoes, mm; R_b is the radius of the object colliding, mm; μ_a is the Poisson's ratio of potatoes; μ_b is the Poisson's ratio of objects colliding.

During the potato throwing process, the system composed of the potato and the buffer roller satisfies the law of conservation of energy. That is, after the potato collides with the buffer roller, the kinetic energy E of the system is equal to the sum of the gravitational potential energy of the potato and the elastic potential energy generated by the collision, which can be expressed as:

$$E_1 = \frac{1}{2}m_av_0^2 - \frac{1}{2}m_a\left(\frac{\partial\delta_{n1}}{\partial t_b}\right)^2 = \int F_{n1}\mathrm{d}\delta_{n1} - m_agH + C \quad (6)$$

where, m_a is the mass of the potato, kg; t_b is the deformation time of the potato when it collides with the buffer roller, s; F_{n1} is the maximum normal force generated when the potato collides with the buffer roller, N; C is a constant; H is the vertical displacement of the potato's throwing motion, mm; δ_{n1} is the deformation amount of the collision between the potato and the buffer roller, mm.

For the entire movement process of throwing potatoes, after the potato collides with the buffer roller and then with the limit roller, the entire movement process still conforms to the law of conservation of energy. It can be concluded that the kinetic energy of E_2 is satisfied:

$$E_2 = \frac{1}{2}m_av_0^2 - \frac{1}{2}m_a\left(\frac{\partial\delta_{n2}}{\partial t_1}\right)^2 = \int F_{n1}\mathrm{d}\delta_{n1} + \int F_{n2}\mathrm{d}\delta_{n2} - m_agH + C \quad (7)$$

where, F_{n2} is the maximum normal force generated when the potato collides with the limit roller, N; t_1 is the deformation time of the collision and contact between the potato and the limit roller, s; δ_{n2} is the deformation amount of the collision between the potato and the limit roller, mm.

To calculate the maximum normal stress when the potato collides with the buffer roller and the limit roller respectively, it is assumed that the mass of the potato m_a is 0.25 kg, the dimensions of the three axes of the potato are 120 mm, 80 mm, and 60 mm, respectively, and the initial velocity v_0 of the conveying device is 0.8 m/s. It is assumed that after the potato collides with the buffer roller and the limit roller respectively, all the kinetic energy of the potato is converted into the elastic potential energy and gravitational potential energy of the system. By solving Equations (5) and (6) simultaneously and combining the physical properties of the material in Table 1, the ultimate normal stresses of potatoes when they collide with the buffer rollers located at positions A, B, and C after being thrown out of the conveyor belt can be calculated as 0.334 MPa, 0.348 MPa, and 0.36 MPa, respectively. The parameters of the buffer roller and the limit roller are exactly the same. By solving Equations (5) and (7) simultaneously and in combination with the physical properties of the material in Table 1, it can be known that the ultimate normal stresses of the potato when it collides with the buffer rollers installed at positions A, B, and C and then collides with the limit roller are 0.371 MPa, 0.365 MPa, and 0.366 MPa, respectively. It can be known from the calculation results of the ultimate normal stress after the potato collides with the buffer roller and the limit roller respectively that the buffer roller is installed at position B for the best effect.

2.3.2 Influence of the initial throwing velocity of potatoes on the buffering effect

The movement trajectory of the potato bagging and feeding process is shown in Figure 6. Among them, the key factors that affect the damage caused by the potatoes colliding and buffering with the buffer roller and then falling into the potato collection bag during the feeding process are the conveying speed and the feeding amount. When the speed of the potatoes colliding and falling or the contact force changes suddenly, it will cause the potatoes to break their skin and get damaged. Therefore, it is necessary to analyze and determine the range of the initial throwing velocity of the potato during the throwing process and after the collision with the buffer roller, providing theoretical support for the subsequent single-factor test and parameter optimization of the device structure.

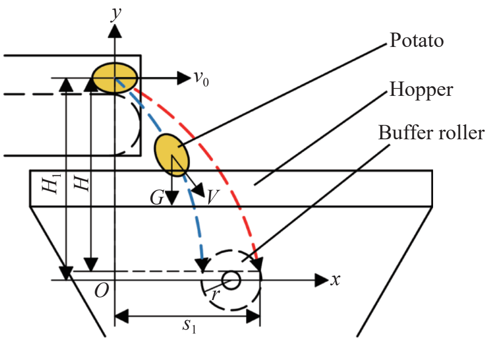


Figure 6 Installation position of buffer roller

During the throwing motion of potatoes, they are mainly affected by gravity. To ensure that potatoes always land on the buffer roller for buffering, a dynamic analysis of potatoes during the throwing process is conducted. Among them, the conveying speed is the key factor affecting whether potatoes can be thrown from the feeding device to the buffer roller of the hopper to achieve potato collection buffering. The dynamic analysis of potatoes during the throwing process is shown in Equation (8).

$$\begin{cases} H_s - R_b \le \dfrac{1}{2}gt^2 \le H_s \\ S_1 - 2R_b \le v_0\sqrt{\dfrac{2H}{g}} \le S_1 \end{cases} \tag{8}$$

where, g is gravitational acceleration, m/s^2; t is the movement time of the potato during the throwing process, s; S_1 is the farthest displacement of the potato thrown, mm; H is the vertical displacement of the potato being thrown and falling, mm; v_0 is the horizontal initial velocity of the potato, m/s.

The vertical distance H_s between the buffer roller and the conveyor belt is 465 mm, and the horizontal distance S_1 is 400 mm. The radius of the buffer roller R_b is 100 mm to ensure that the potatoes always land on the buffer roller. The vertical displacement H of the potatoes during the throwing process should be less than or equal to 465 mm, and the horizontal displacement should be greater than or equal to 200 mm and less than or equal to 400 mm. It can be known from Equation (8) that the initial velocity range of the potato should satisfy the maximum and minimum conditions of the collision velocity between the potato and the buffer roller.

$$0.67\ \text{m/s} \le v_0 \le 1.33\ \text{m/s} \tag{9}$$

The analysis of the motion of potatoes during the throwing process shows that in order to ensure that the potatoes always collide with the buffer roller during the throwing process, the range of the initial velocity v_0 should satisfy the range of Equation (9), thereby reducing the probability of potato drop damage.

3 Results and analysis

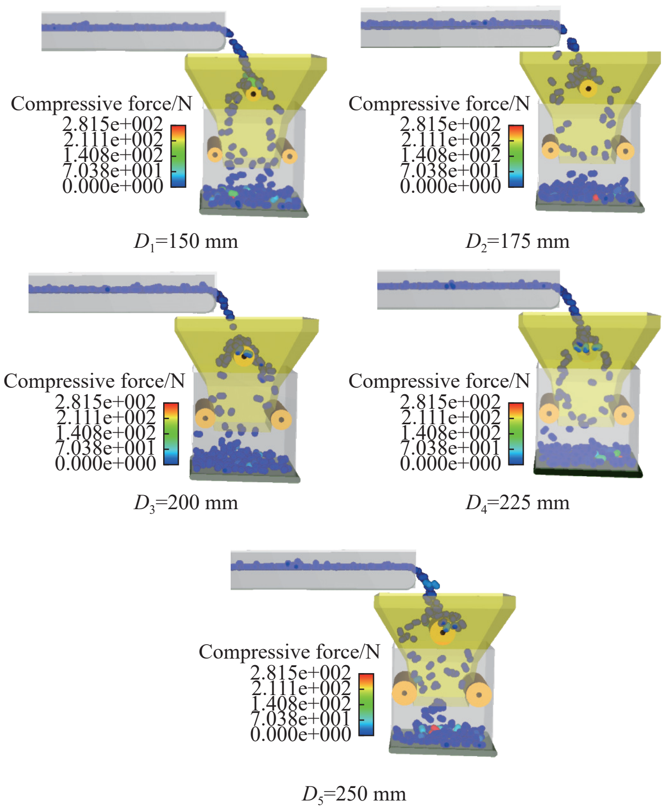
3.1 Single factor experiment

3.1.1 Influence of roller diameter on the force of potatoes

According to previous research[3], the diameter of the buffer roller and the limiting roller was one of the main factors affecting the force on potatoes. In order to obtain the influence of roller diameter on the force situation of potatoes, under the condition that the buffer roller was installed at position C, a feeding amount of 40 t/h and a conveyor speed of 1.0 m/s were selected based on the designed productivity of the machine, and the feeding amount and conveying speed were kept constant. To ensure the clarity of the obtained rules, based on the previous theoretical analysis, the diameter range of the buffer roller and the limiting roller was expanded. The selected roller diameters are 150 mm, 175 mm, 200 mm, 225 mm, and 250 mm. The maximum compressive force and the maximum kinetic energy were used as evaluation indicators to reflect the intensity of the collision impact generated by the potatoes during the bagging process. The relevant data obtained from the EDEM post-processing interface is listed in Table 3. The motion trajectories and force conditions of the potatoes under different roller diameters are shown in Figure 7.

Table 3 Maximum compressive force and maximum kinetic energy of potatoes at different roller diameters

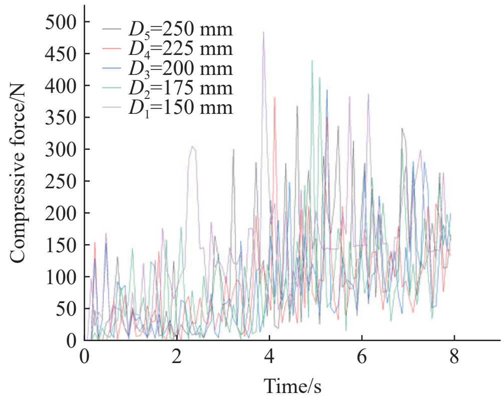
Roller diameters/ mm	Maximum compressive force/N	Maximum kinetic energy/J
150	483.90	2.91
175	439.21	2.77
200	281.51	2.27
225	381.50	2.37
250	393.25	2.65



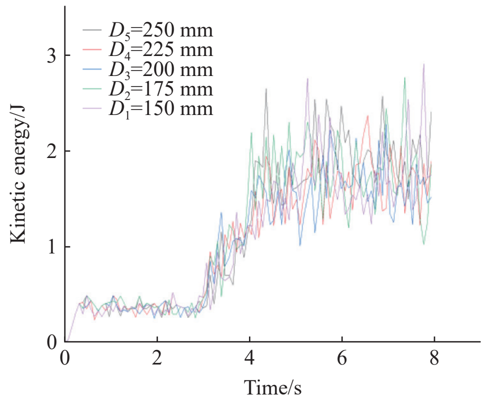
Note: D_1, D_2, D_3, and D_4 are different roller diameters, mm.

Figure 7 Motion trajectories and force simulation effects of potatoes at different roller diameters

The relationship between the maximum compressive force of potatoes and simulation time, as well as the relationship between the maximum kinetic energy of potato and simulation time, are shown in Figure 8. The overall trend showed that the maximum kinetic energy of potato increased rapidly from the third second and stabilized at 1.00-3.00 J after 4 s. This was because in the first three seconds, most of the potatoes were in a stationary state relative to the conveying device, and a small amount of energy was generated by the bumps and squeezes during the conveying process. After 3 s, they collided successively with the buffer roller, limiting roller, and lifting slide table. The speed increased continuously during the falling process, and the kinetic energy generated by the potatoes was relatively large, with a peak value of 2.91 J. In the first three seconds, the compressive force of the potatoes during the conveying process was relatively small, concentrated below 150.00 N. After 3 s, the potatoes entered the hopper and began to produce collision impacts. From the simulation results in Table 3, it can be seen that both the maximum compressive force and maximum kinetic energy initially decrease and then increase as the roller diameter increases. When the roller diameter was 150 mm, most of the potatoes, after colliding with the buffer roller, were unable to collide with the limiting roller and directly entered the potato collection bag. This resulted in a greater overall falling height of the potatoes, leading to the maximum compressive force and maximum kinetic energy being the highest, which were 483.90 N and 2.91 J, respectively. When the roller diameter was 175 mm, due to the increased thickness of the sponge covering on the buffer roller and the limiting rollers, the trajectory of the potatoes after colliding with the buffer roller shifted to both sides of the buffer roller compared to when the roller diameter is 150 mm. However, there were still more potatoes that could not collide with the limiting roller, resulting in a higher maximum compressive force and maximum kinetic energy of the potatoes, which were 439.21 N and 2.77 J, respectively. When the roller diameter was 200 mm, the thickness of the sponge increases, and the trajectory of the potatoes continued to shift to both sides of the buffer roller after colliding with the buffer roller. Most of the potatoes were able to collide with the limiting roller and fell into the potato bag. The limiting roller absorbed some of the kinetic energy, reducing the speed of the potatoes' subsequent falling. As a result, the maximum compressive force and maximum kinetic energy of the potatoes were smaller, with values of 281.51 N and 2.27 J, respectively. When the roller diameter was 225 mm, the sponge thickness continued to increase, allowing it to absorb more energy that was generated by the collisions of the potatoes. Due to the constraints of the hopper walls, the trajectory of the potatoes after colliding with the buffer roller gradually shifted upward. Most of the potatoes fell onto the side wall of the hopper above the limiting roller after colliding with the buffer roller, and then slid down to the limiting roller before entering the potato bag. During this process, the maximum compressive force and maximum kinetic energy of the potatoes were relatively small, at 381.50 N and 2.37 J, respectively. When the roller diameter was 250 mm, after the potatoes collided with the buffer roller, due to the large roller diameter, most of the potatoes were bounced to the side wall of the hopper slightly lower than the horizontal line of the buffer roller. After a secondary rebound from the side wall of the hopper, they fell into the collection bag. This resulted in a higher falling height of the potatoes when entering the bag. The maximum compressive force and maximum kinetic energy of the potatoes were relatively high, at 393.25 N and 2.65 J respectively, and a small number of potatoes were bounced out of the hopper.



a. Curve of maximum compressive force variation of potatoes



b. Curve of maximum kinetic energy variation of potatoes

Figure 8 Influence curve of roller diameter on the maximum compressive force and maximum kinetic energy of potatoes

In summary, it can be concluded that a roller diameter that is too small provides insufficient buffering effect for the potatoes, while a roller diameter that is too large may cause the potatoes to fail to fall onto the limiting roller and even have the potential to be bounced out of the hopper. Based on the simulation analysis results, the optimal roller diameter range was determined to be 175-225 mm.

3.1.2 Influence of conveying speed on the force of potatoes

The speed of the potato conveying device during harvesting is usually maintained at 1.0 m/s[26]. To obtain the influence of conveying speed on the force situation of potatoes during the potato collection process, a feeding amount of 40 t/h and a roller diameter of 200 mm were selected, and the feeding amount and roller diameter were kept constant. To ensure more accurate results, the range of conveyor speed variations was expanded based on theoretical analysis[3]. The selected conveyor speeds were 0.6 m/s, 0.8 m/s, 1.0 m/s, 1.2 m/s, and 1.4 m/s. The maximum compressive force and maximum kinetic energy were used as evaluation indicators to reflect the severity of the collision impact generated by the potatoes during the bagging process. The simulation duration was set to 8 s. According to the EDEM post-processing interface, relevant data was obtained as listed in Table 4.

Table 4 Maximum compressive force and maximum kinetic energy of potatoes at different conveying speeds

Conveying speed/m·s^{-1}	Maximum compressive force/N	Maximum kinetic energy/J
0.6	614.90	1.79
0.8	343.12	2.09
1.0	277.62	2.21
1.2	375.51	3.15
1.4	584.07	3.57

According to the data results in Table 4, it can be seen that the maximum kinetic energy of the potatoes is positively correlated with the conveying speed. As the conveying speed increased, the kinetic energy of the potatoes also increased. According to Figure 9b, it can be seen that during the conveying stage, the variation in kinetic energy of the potatoes was relatively stable. However, the trend of kinetic energy variation with time varied at different speeds. When the conveying distance was the same, the smaller the conveying speed, the later the kinetic energy would produce huge fluctuations. When the conveying speed was between 0.6 and 1.0 m/s, the potatoes collided with the buffer roller within 3-5 s, and the kinetic energy began to increase. When the conveying speed was between 1.0 and 1.4 m/s, the potatoes collided with the buffer roller within 2-3 s, and the kinetic energy began to increase.

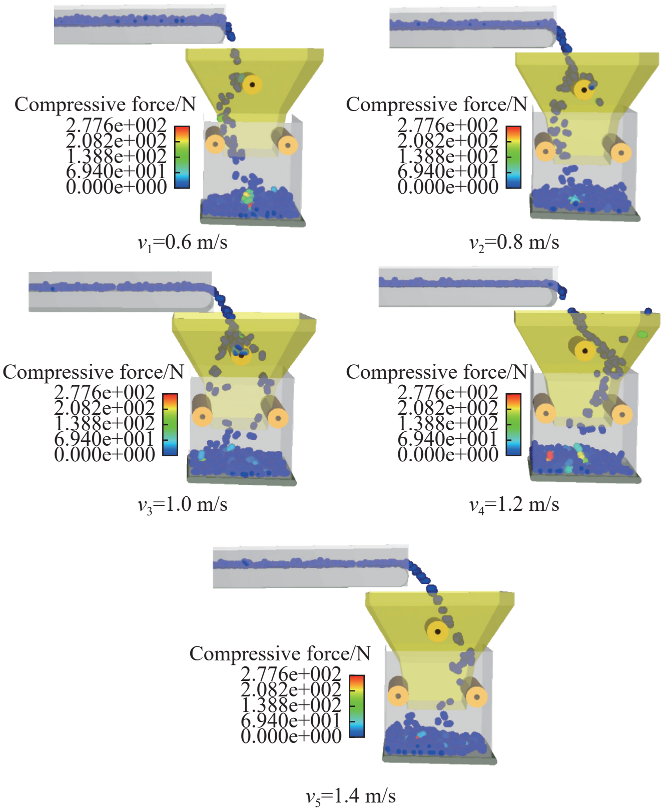
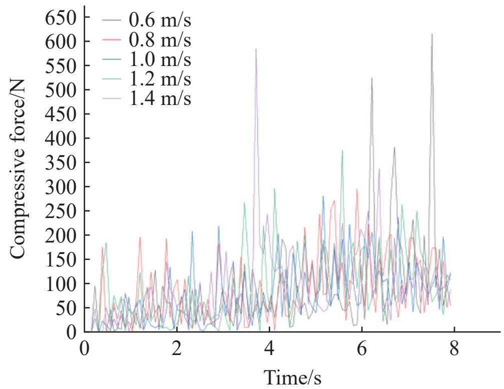
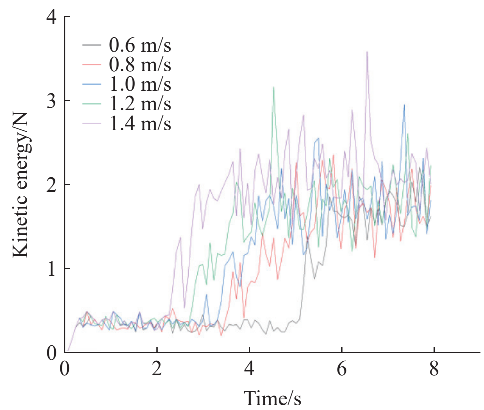


Figure 9 Motion trajectories and force simulation effects of potatoes under different conveying speeds

From the data in Table 4 and the simulation results in Figue 10, it can be seen that the maximum compressive force of potatoes first decreased and then increased with the increase of speed. The simulation results showed that at a conveying speed of 0.6 m/s, the maximum compressive force was able to reach 614.90 N. When most potatoes fell from the conveying device, due to the low speed, they only rubbed against the edge of the buffer roller in the hopper, resulting in a short buffering time and unclear buffering effect. When the conveying speed was 0.8 m/s, the maximum compressive force was able to reach 343.12 N. When the potatoes entered the hopper, most of them were able to collide with the buffer roller, and the collision points were mostly on the side close to the conveying device. Therefore, after colliding with the buffer roller, most of the potatoes fell from the side close to the conveying device to the limiting roller and then entered the potato bag. When the conveying speed was 1.0 m/s, the maximum compressive force was able to reach 277.62 N, which was 337.28 N lower than the conveying speed of 0.6 m/s and 65.50 N lower than the conveying speed of 0.8 m/s. The potatoes fell from the conveying device to the top of the buffer roller. During this process, the potatoes piled up on the buffer roller were evenly distributed to both sides of the buffer roller and fell downwards. After being buffered by two limiting rollers, the potatoes entered the potato bag, and the maximum compressive force was effectively reduced. When the conveying speed was 1.2 m/s, the maximum compressive force was able to reach 375.51 N. As the conveying speed increased, the collision points where most of the potatoes fell onto the buffer roller shifted to the side away from the conveying device. The acceleration of the collision between the potatoes and the buffer roller, the limiting rollers and the lifting slide table increased, thereby increasing the maximum compressive force on the potatoes. Due to the fact that the potatoes mainly piled up on one side and fell, the collision impact between the potatoes increased, which also increased the maximum compressive force on the potatoes. In addition, according to the simulation results, there was a phenomenon that a small amount of potatoes were bounced out of the hopper by the buffer roller. When the conveying speed was 1.4 m/s, the maximum compressive force was able to reach 584.07 N. Due to the increase in speed, most of the potatoes passed over the buffer roller when entering the hopper, and were unable to be buffered. The height of the potatoes falling into the potato bag was too high, resulting in a huge increase in the maximum compressive force. Based on the above analysis, the conveying speed range of potatoes was determined to be 0.8-1.2 m/s.



a. Curve of maximum compressive force variation of potatoes



b. Curve of maximum kinetic energy variation of potatoes

Figure 10 Influence curve of conveying speed on the maximum compressive force and maximum kinetic energy of potatoes

3.1.3 Influence of feeding amount on the force of potatoes

The feeding amount is one of the main factors affecting the force of potato bagging. To obtain the influence of feeding amount on the force situation of potatoes, we refer to the existing potato harvester feeding amount, which is mostly between 20-50 t/h. To obtain a more accurate rule, based on the above experiment, the roller diameter was determined to be 200 mm, the conveying speed was 1 m/s, and the feeding amounts were selected as 20 t/h, 30 t/h, 40 t/h, 50 t/h, and 60 t/h, respectively. The maximum kinetic energy and maximum compressive force were used as evaluation indicators to reflect the severity of the collision impact generated by the potatoes during the bagging process. According to EDEM post-processing interface, relevant data were obtained (Table 5).

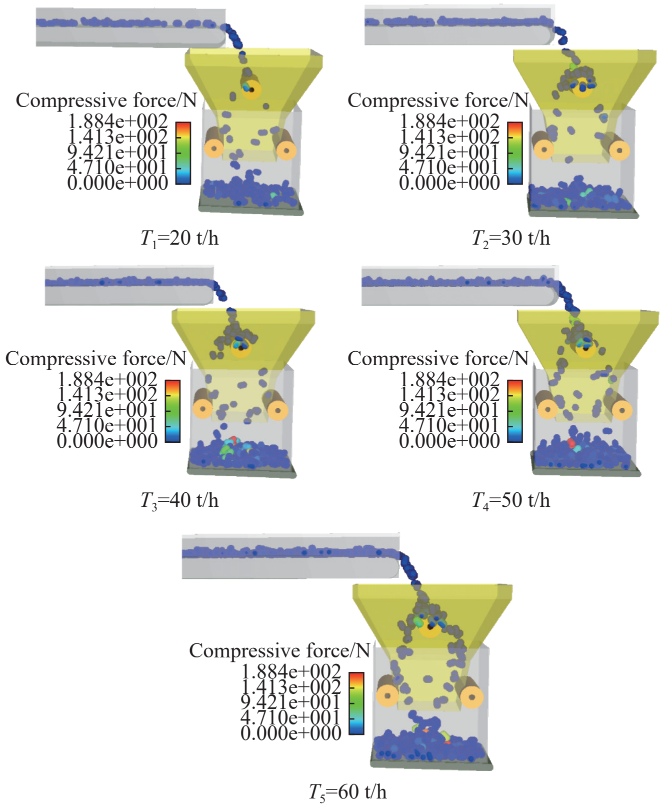
Table 5 Maximum compressive force and maximum kinetic energy of potatoes under different feeding amounts

Feeding amounts/ $t \cdot h^{-1}$	Maximum compressive force/N	Maximum kinetic energy/J
20	188.42	2.18
30	231.37	2.31
40	288.33	2.34
50	419.60	2.41
60	447.75	2.62

From the simulation results in Figure 11 and data in Table 5, it can be seen that the maximum kinetic energy and maximum compressive force of potatoes are positively correlated with the feeding amount. The influence curve of feeding amount on the maximum compressive force and maximum kinetic energy of potatoes is shown in Figure 12. When the feeding amount was 20 t/h, the potatoes scattered into the hopper, and the values of the maximum kinetic energy and maximum compressive force were the smallest, at 2.18 J and 188.42 N respectively. The collision frequency during the falling process of potatoes was relatively low. As the feeding amount increased to 60 t/h, the number of potatoes falling into the hopper increased per unit time, and the collision frequency and impact between potatoes increased. The values of the maximum kinetic energy and the maximum compressive force were 2.62 J and 447.75 N, respectively. When the potatoes collided with the buffer roller, under the buffering and support of the buffer roller, the potatoes would briefly stay directly above the buffer roller. As the feeding amount increased, the amount of potatoes piled up on the buffer roller in a short period of time became larger, resulting in significant instantaneous crushing and impact between the potatoes. Figure 12a shows that during the first half of the process of potatoes falling, there was a small peak in the maximum compressive force between the potatoes and the buffer roller. In the second half of the process, the potatoes fell into the potato bag, and some of the potatoes that entered the bag first collided with the lifting slide table. The potatoes that entered later collided with the potatoes that entered the bag first. As the feeding amount increased, there were cases where multiple potatoes hit the same potato, resulting in a larger peak in the maximum compressive force of a certain potato. On the premise of reducing bagging time to improve harvest efficiency, the feeding amount of potatoes per unit time should be minimized as much as possible. Based on the above analysis, the feeding amount was selected as 30-50 t/h.

3.1.4 Influence of the size of the potato bag on the force of potatoes

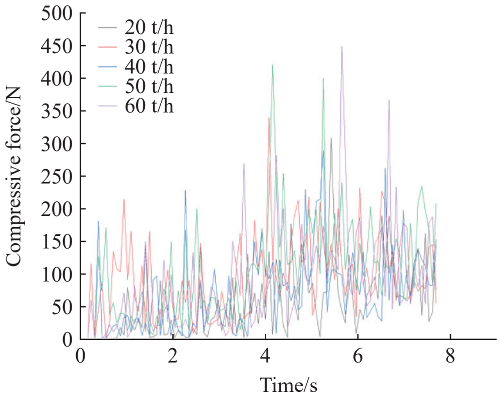
When the potatoes in the potato bag were filled, under the wrapping of the bag, the potatoes would be subjected to squeezing force from other potatoes in all directions. The squeezing force exerted on each potato was composed of multiple accumulated potatoes, and the size of the potato bag was the main factor affecting the force on the potatoes. The conveying speed of the conveying device was set to 1 m/s, the roller diameter to 200 mm, and the feeding amount to 40 t/h. Due to the fact that most of the potatoes in the potato bag were in a static state when filled, with little impact from falling, the potatoes at the bottom of the bag suffered the most severe crushing damage. Using the maximum compressive force as the evaluation index, the influence of the size of the potato bag on the force of the potatoes at the bottom of the bag was studied. Three sizes were selected: 800 mm×800 mm×800 mm, 1000 mm×1000 mm×1000 mm, and 1200 mm×1200 mm×1200 mm. The simulation results are listed in Table 6.



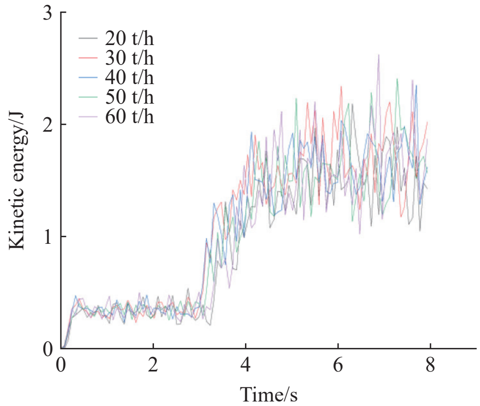
Note: T_1, T_2, T_3, T_4, and T_5 represent different feeding amounts, t/h.

Figure 11 Motion trajectories and force simulation effects of potatoes under different feeding amounts

According to the simulation results in Table 6, it can be seen that when the size of the potato bag was 800 mm×800 mm×800 mm, the filling time was 32 s, and the maximum compressive force of the potatoes at the bottom of the potato bag was 145.493 N. As the lifting slide table descended, the number of potatoes in the potato bag gradually increased. However, due to the slightly smaller size of the bag entrance, there was no extra bag wall to hold the potatoes that were knocked off. Therefore, there were a small number of potatoes that were knocked out of the potato bag by the falling potatoes from above when the potato bag was almost full. When the size of the potato bag was 1000 mm×1000 mm×1000 mm, the filling time was 55 s, and the maximum compressive force of the potatoes at the bottom of the potato bag was 203.312 N, which was 57.873 N higher than the maximum compressive force when the size of the potato bag was 800 mm×800 mm×800 mm. There was no situation where the potatoes were ejected from the potato bag. When the size of the potato bag was 1200 mm×1200 mm×1200 mm, the filling time was 96 s, and the maximum compressive force of the potatoes at the bottom of the potato bag was 233.344 N, which was 30.032 N higher than the maximum compressive force when the size of the potato bag was 1000 mm×1000 mm×1000 mm. There was no situation where the potatoes were ejected from the potato bag. Based on Figure 13, it can be observed that the larger the size of the potato bag was, the greater the maximum compressive force on the potatoes would be, and the more severe the compression on the potatoes at the bottom of the bag would be. This was because as the size and volume of the potato bag increased, it could accommodate more potatoes when filled, and each potato was subjected to the cumulative compressive force of multiple potatoes. To minimize the compressive force on the potatoes as much as possible and avoid the situation where the potatoes were ejected from the potato bag when it was almost full, the size of the potato bag was selected as 1000 mm×1000 mm×1000 mm.



a. Curve of maximum compressive force variation of potatoes



b. Curve of maximum kinetic energy variation of potatoes

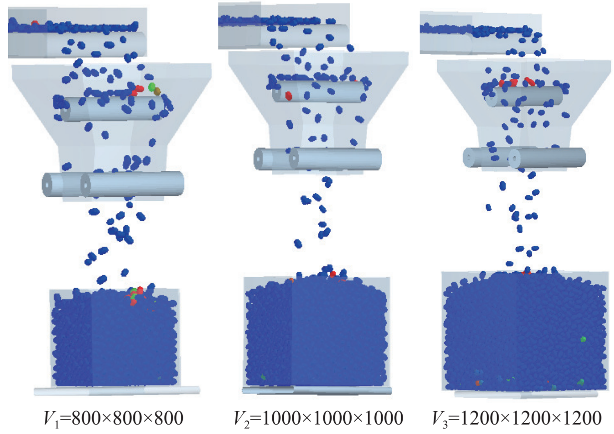
Figure 12 Influence curve of feeding amount on the maximum compressive force and maximum kinetic energy of potatoes

Table 6 Filling time and maximum compressive force of potatoes under different bag sizes

The size of potato bag/ mm×mm×mm	Filling time/s	Maximum compressive force/N
800×800×800	32	145.493
1000×1000×1000	55	203.312
1200×1200×1200	96	233.344

3.2 Orthogonal experiment

Through preliminary single-factor experiments, based on the analysis of the results, the position of the buffer roller and the size of the potato bag were determined and the range of values for roller diameter, conveying speed, and feeding amount were determined. To obtain the optimal combination value of roller diameter, conveying speed, and feeding amount, a three-factor three-level experiment was conducted by using the design method of Box-Behnken center combination. The experimental results were analyzed for variance and the significance of the experimental factors was tested. The response surface approximation model was used to optimize the parameter combination.



Note: V_1, V_2, and V_3 represent different potato bag sizes, mm×mm×mm.

Figure 13 Situation of potato bagging with different potato bag sizes

3.2.1 Design of the experimental plan

The experiment used roller diameter, conveying speed, and feeding amount as experimental factors, and maximum kinetic energy and maximum compressive force as experimental indicators. Orthogonal experiments were designed by using the software of Design-Expert, and the codes of the experimental factor are listed in Table 7.

Table 7 Codes of the experimental factor

Code	Factors of experiment		
	Roller diameter X_1/mm	Conveying speed X_2/m·s^{-1}	Feeding amount X_3/t·h^{-1}
−1	175	0.8	30
0	200	1.0	40
1	225	1.2	50

3.2.2 Result analysis and parameter optimization

Design-Expert was used to perform the analysis of quadratic regression equation on the experimental results and perform quadratic regression fitting. The experimental plan and results are listed in Table 8.

Table 8 Experimental plan and results

Serial number	Experimental factors			Maximum compressive force Y_1/N	Maximum kinetic energy Y_2/J
	X_1/mm	X_2/m·s^{-1}	X_3/t·h^{-1}		
1	200	1.0	40	255.30	2.13
2	200	1.0	40	281.51	2.27
3	200	1.0	40	277.62	2.21
4	200	0.8	50	478.15	2.71
5	200	1.2	50	552.80	3.29
6	175	1.0	50	452.33	3.58
7	175	1.0	30	412.37	2.59
8	200	1.0	40	290.25	2.33
9	200	1.0	40	288.33	2.29
10	225	1.0	30	221.69	2.15
11	200	1.2	30	420.19	2.58
12	225	1.2	40	508.22	3.32
13	175	0.8	40	495.54	2.73
14	200	0.8	30	389.55	1.52
15	225	0.8	40	443.32	2.03
16	225	1.0	50	521.10	3.41
17	175	1.2	40	477.22	3.08

The variance analysis of the regression model is listed in Table 9. The maximum compressive force Y_1 and maximum kinetic energy Y_2 were subjected to variance analysis. As listed in Table 9, for the maximum compressive force Y_1, the p-values of X_3, X_1X_3,

X_{12}, X_{22}, and X_{32} were all less than 0.01, indicating an extremely significant impact. X_1 and X_2 had a significant impact. The quadratic regression polynomial for the maximum compressive force Y_1 obtained by eliminating the insignificant term for variance fitting without loss of fit is

$$Y_1 = 278.6 - 17.89X_1 + 18.98X_2 + 70.07X_3 + 64.86X_1X_3 + 72.09X_1^2 + 130.39X_2^2 + 51.18X_3^2 \quad (10)$$

Table 9 Variance analysis of maximum compressive force Y_1 and maximum kinetic energy Y_2

Index	Source of variance	Sum of square	Freedom	Mean square	F value	p value
Y_1	Model	1.782×10^{-5}	9	1.9797.35	32.79	<0.0001
	X_1	2560.77	1	2560.77	4.24	0.0784
	X_2	2883.06	1	2883.06	4.78	0.0651
	X_3	39 281.24	1	39 281.24	65.06	<0.0001
	$X_1 X_2$	1731.39	1	1731.39	2.87	0.1342
	X_1X_3	16 828.58	1	16 828.58	27.87	0.0011
	$X_2 X_3$	484.22	1	484.22	0.80	0.4002
	X_1^2	21 879.85	1	21 879.85	36.24	0.0005
	X_2^2	71 581.64	1	71 581.64	118.57	<0.0001
	X_3^2	11 030.74	1	11 030.74	18.27	0.0037
	Residual	4226.10	7	603.73		
	Lack of fit	3443.39	3	1147.80	5.87	0.0602
	Pure error	782.71	4	195.68		
	Cor total	1.824×10^{-5}	16			
Y_2	Model	5.17	9	0.57	94.79	<0.0001
	X_1	0.14	1	0.14	23.60	0.0018
	X_2	1.34	1	1.34	221.78	<0.0001
	X_3	2.15	1	2.15	355.04	<0.0001
	$X_1 X_2$	0.22	1	0.22	36.43	0.0005
	X_1X_3	0.018	1	0.018	3.01	0.1266
	$X_2 X_3$	0.058	1	0.058	9.05	0.0178
	X_1^2	0.95	1	0.95	157.17	<0.0001
	X_2^2	0.020	1	0.020	3.23	0.1151
	X_3^2	0.19	1	0.19	30.84	0.0009
	Residual	0.042	7	6.064×10^{-3}		
	Lack of fit	0.018	3	6.042×10^{-3}	0.99	0.4811
	Pure error	0.024	4	6.080×10^{-3}		
	Cor total	5.22	16			

As is listed in Table 9, for the maximum kinetic energy Y_2, the p-values of X_1, X_2, X_3, X_1 X_2, X_{12}, and X_{32} were all less than 0.01, indicating an extremely significant impact. X_2 X_3 had a significant impact. The quadratic regression polynomial for the maximum kinetic energy Y_2 obtained by eliminating the insignificant term for variance fitting without loss of fit is:

$$Y_2 = 2.25 - 0.13X_1 + 0.41X_2 + 0.52X_3 + 0.23X_1X_2 - 0.12X_2X_3 + 0.48X_1^2 + 0.21X_3^2 \quad (11)$$

3.2.3 Analysis of the response surface

From the significance of the p-values of the variance analysis results in Table 9, it can be obtained that the primary order of the factors influencing the maximum collision normal pressure Y_1 is feeding amount>conveying speed>buffer roller diameter, and the primary order of the factors influencing the maximum kinetic energy Y_2 is feeding amount>conveying speed>buffer roller diameter. From the analysis of Figures 14a and 14b, it can be concluded that when the conveying speed is a horizontal value and the feeding amount value remains unchanged, the maximum impact normal pressure first decreases and then increases with the increase of the roller diameter. When the roller diameter value remains unchanged, the maximum impact normal pressure increases with the increase of the feeding amount. When the roller diameter is a horizontal value and the conveying speed value remains unchanged, the maximum collision normal pressure gradually increases with the increase of the feeding amount. From the analysis of Figures 14c and 14d, it can be seen that when the conveying speed is a horizontal value and the feeding amount remains unchanged, the maximum kinetic energy shows a trend of first increasing and then decreasing with the increase of the roller diameter. When the roller diameter remains unchanged, the maximum kinetic energy gradually increases with the increase of the feeding amount. When the roller diameter is a horizontal value and the conveying speed value remains unchanged, the maximum kinetic energy shows a slow upward trend as the feeding amount increases. From the analysis in Figure 13, it can be found that the optimal conveying speed range is between 0.9 and 1.1 m/s, the optimal roller diameter size is between 195 and 215 mm, and the optimal feeding volume range is between 30-40 t/h.

3.2.4 Optimization

Based on the analysis of the orthogonal test results, it can be known that when the conveying speed is too small, some potato chunks cannot collide with the buffer roller for buffering. At this time, the drop acceleration is too large, resulting in an increase in the maximum collision normal pressure. The conveying speed is too high, causing some potato chunks to jump over the buffer roller. At this time, the maximum collision normal pressure and maximum kinetic energy increase. As the diameter of the roller increases, the maximum collision normal pressure decreases, and the maximum kinetic energy first decreases and then increases. When the feeding amount is too large, the frequency of tube-to-potato collisions suddenly increases, resulting in an increase in the maximum collision normal pressure and maximum kinetic energy. To reduce the rate of potato damage and skin breakage during the actual bagging process of potatoes, the minimum values of the maximum compressive force and maximum kinetic energy of potatoes were selected as the optimization objectives. Combined with the regression models and boundary conditions of various experimental factors, the optimization constraints were selected as follows:

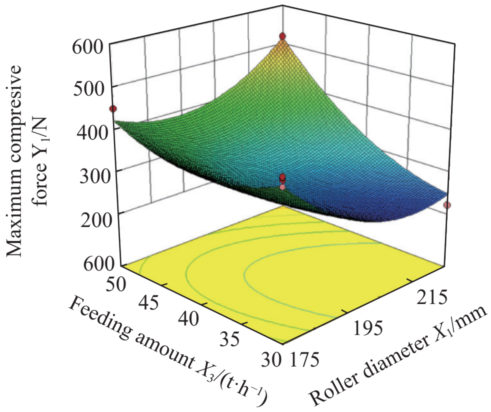
$$\begin{cases} \min Y_1(X_1, X_2, X_3) \\ \min Y_2(X_1, X_2, X_3) \\ 195\ \text{mm} \le X_1 \le 215\ \text{mm} \\ 0.9\ \text{m/s} \le X_2 \le 1.1\ \text{m/s} \\ 30\ \text{t/h} \le X_3 \le 40\ \text{t/h} \end{cases} \quad (12)$$

The objective function was optimized and solved through the optimization module of the Design-Expert software, and the optimal parameter combination was obtained as follows: roller diameter 211.803 mm, conveying speed 0.915 m/s, and feeding capacity 30 t/h. At this point, the maximum compressive force is 252.569 N and the maximum kinetic energy is 1.69 J.

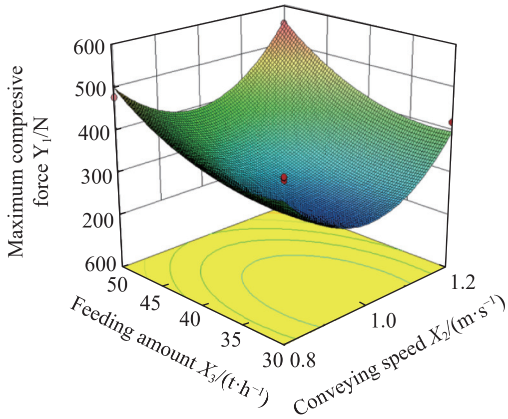
3.2.5 Verification experiment

To verify the accuracy of the simulation model and parameter optimization, a roller diameter of 212 mm, a conveying speed of 0.9 m/s, and a feeding amount of 30 t/h (actual operation took 8.3 kg/s) were selected according to the actual situation. The experimental instruments include: a test bench of potato bagging device with buffer roller, a potato impact recording device, and a weighing device. The potato impact recording device is equipped with an electronic potato with three-axis dimensions of 80 mm×

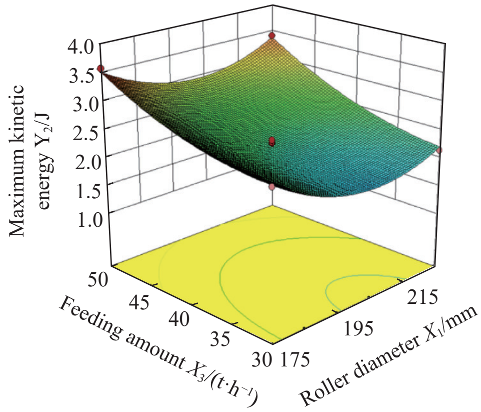
90 mm×60 mm and a PCIRD software developed by Techmark in the United States, used to collect potato collision information. The mass of the electronic potato is 270 g, and it can withstand a maximum collision acceleration of 450 G. The software of PCIRD provides communication between PC and IRD for processing and analyzing data.



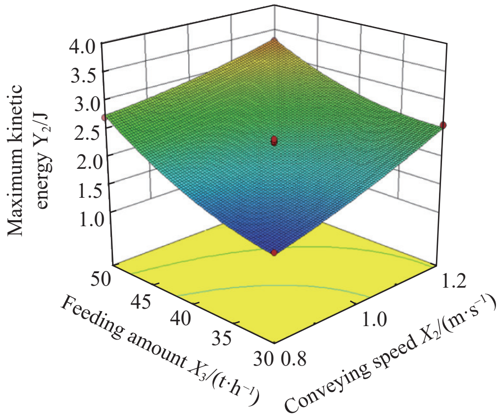
a. Y_1=f(X_1, 1, X_3)



b. Y_1=f(200, X_2, X_3)



c. Y_2=f(X_1, 1, X_3)



d. Y_2=f(200, X_2, X_3)

Figure 14 Impact of the interaction of experimental factors on evaluation indicators

The collision characteristic and trajectory of the electronic potato is equivalent to that of actual potato. The electronic potatoes and cleaned potato clusters are mixed and placed on the conveyor device, with optimized parameters set for five sets of experiments. The potato impact recording device is used to measure the peak collision acceleration and take the average value, while observing the bagging operation status of the machine. The experimental scenario is shown in Figure 15.

a. The test bench of potato bagging device with buffer roller b. Potato bagging c. The impact recording device of potato

Figure 15 Potato impact recording device and data collection process

The device is started, the conveying speed is adjusted to 0.9 m/s, and the operation status of the equipment is observed. After the conveying speed stabilizes, the electronic potato and potato clusters are mixed together and placed at the start of the conveying device. When the potatoes entered the hopper, they collided with the buffer roller, and scattered evenly towards both sides of the buffer roller. After colliding with the limiting roller, they entered the potato bag. The bagging process was relatively smooth, and the falling trajectory of the potatoes was consistent with the simulation results. After bagging, any cracks on the surface and leakage of internal tissue fluid of the potatoes were considered as damage to the potatoes. The damaged area of the epidermis reaching 0.2 cm^2 was considered as skin rupture[27-29]. The experimental results are listed in Table 10.

Table 10 Results of verification experiment

Experimental group sequence	Peak collision acceleration/ G	Average of the peak collision acceleration/ G	Damage rate of potatoes/ %	Average of the damage rate of potatoes/ %	Skin breakage rate/%	Average of the skin breakage rate/%
1	86.86		0.65		1.31	
2	90.99		0.86		1.87	
3	98.08	90.27	1.28	0.98	2.47	1.86
4	93.23		0.98		2.52	
5	82.19		1.11		1.12	

According to Newton's second law, the peak collision acceleration in Table 10 can be converted into the maximum compressive force experienced by the electronic potato during bagging. The converted value was 238.854 N, which was close to the theoretical value after parameter optimization with an error of 5.4%. Through researching the information, it was found that the compressive force between potatoes and mechanical components was positively correlated with the rate of potato damage, and the kinetic energy was positively correlated with the rate of skin breakage. The average potato damage rate and skin breakage rate measured in the experiment were 0.98% and 1.86%, respectively, which meet industry standards and were lower than those of most existing potato bagging devices. This indicates that the optimized potato bagging device can reduce the force on potatoes and minimize damage and skin breakage of potatoes during bagging.

4 Discussion

This article took the potato bagging device with buffer roller as the research object, and used EDEM-RecurDyn coupled simulation to simulate the motion trajectory and collision characteristics of cleaned potatoes during bagging, in order to obtain the optimal structural and operating parameters, with the aim of minimizing the collision force on potatoes during bagging and reducing skin breakage and damage. Previously, research on potato bagging operations mostly focused on the design and study of potato technology and device functions[30], lacking analysis of the collision characteristics of potatoes during the bagging process. This article focuses on the study of the motion trajectory and collision characteristics of potatoes during bagging operations. Potatoes fell from the conveying device into the hopper, and were successively buffered by the buffer roller and the limiting rollers before entering the potato bag. During this process, roller diameter, conveying speed, feeding amount, etc. all had a significant impact on the force on the potatoes. Compared to previous theoretical research, this article used a coupled simulation method of discrete element and multibody dynamics to more intuitively and clearly simulate the falling trajectory and force situation of potatoes during bagging under different influence factors. It combined simulation analysis with the experiment of the potato impact recording device, and closely linked the maximum compressive force and the peak collision acceleration. The results showed that the results of the simulation analysis and the verification experiment results of the potato impact recording device were close, with an error of only 5.4%. The potato damage rate and skin breakage rate were 0.98% and 1.86%, respectively, which met the relevant industry standards.

When the potato collides with the buffer roller, the sponge undergoes elastic deformation under the impact force, thereby absorbing kinetic energy. The thicker the sponge, the more kinetic energy it absorbs. However, the simulation results showed that the maximum kinetic energy of potatoes first decreased and then increased with the increase of roller diameter, which was inconsistent with the expectation that the maximum kinetic energy of potatoes would constantly decrease with the increase of roller diameter. The possible reason for this may be that as the diameter of the roller increased, not only did the falling trajectory of potatoes move upward after colliding with the buffer roller, but a small portion of potatoes were also ejected out of the hopper, resulting in an increase in height during the second drop of potatoes. Under the conservation of mechanical energy, potential energy was converted into kinetic energy, so the kinetic energy was relatively large.

From the simulation results, it can be seen that when the roller diameter was 200 mm, the maximum compressive force and maximum kinetic energy of potatoes were minimized. Based on the simulation results of the conveying speed on the force of potatoes, the maximum kinetic energy was positively correlated with the conveying speed, which was in line with the expected results. However, the impact of conveying speed on the maximum compressive force of potatoes was more unexpected. It was assumed that the maximum compressive force would be larger when the conveying speed was 0.6 m/s. As previously analyzed, if the conveying speed was too small, the initial kinetic energy of the potato falling might not be sufficient to support collision between the potato and the buffer roller, which might cause it to rub against the edge of the buffer roller and fall, or it might not be able to contact the buffer roller, resulting in an increase in the compressive force when the potato entered into the bag. However, the maximum compressive force could reach 614.9 N, which was much greater than the maximum compressive force when the conveying speed was 1.4 m/s. This was an unexpected result. After observing the simulation process multiple times and reviewing all the processes of potato harvesting operations, it was found that when potatoes were harvested in the field, a change in the conveying speed of potatoes did not necessarily mean a change in the advance speed of the machine. In other words, the feeding amount of potatoes entering the bagging process remained unchanged. During the simulation, only the conveying speed was changed, but the generation speed of potato particles remained unchanged. In this case, the conveying distance remained unchanged, the conveying speed decreased, and more potatoes were stored on the conveying device, which was equivalent to an increase in the feeding amount of potatoes entering the potato bag, resulting in a significant increase in the maximum compressive force. In addition, the influence of feeding amount and bag size on the force of potatoes was more in line with expectations.

The most direct way to determine the damage situation of potatoes is to obtain the damage rate and skin breakage rate of potatoes during the harvesting process. However, the simulation experiment in this article cannot intuitively see the situation of potato damage and skin breakage rate. In recent years, the critical value of the stress of the potato damage can be found in relevant literature[31], which provides some inspiration. The falling trajectory of potatoes in the verification experiment was in good agreement with the simulation results. The measured potato damage rate and skin breakage rate were positively correlated with the maximum compressive force and maximum kinetic energy, and the indicators are both lower than most existing potato bagging devices. Next, we can further study the critical damage on the compressive force of potatoes. When the compressive force of potatoes is greater than or equal to a certain value, potatoes exhibit internal cracks and tissue fluid outflow, which are considered as damaged potatoes. The compressive force of potatoes can be closely related to the potato damage rate and skin breakage rate, which is the focus of future research.

5 Conclusions

1) This article focused on the problems of unclear movement trajectory of potatoes and severe collision force during the bagging process. Based on previous theoretical research, the potato bagging device with buffer roller was taken as the research object. Through theoretical analysis, it was determined to use the Hertz-Mindlin model to simulate the interaction between potato particles and other collision materials. The influence of roller diameter, conveying speed, feeding amount, and potato bag size on the force of potatoes during bagging operation was analyzed through single-factor experiments by using the EDEM-RecurDyn coupled simulation. The motion trajectory of potatoes under various experimental factors and the reasons for different motion trajectories were analyzed one by one, and each parameter through orthogonal experiments was optimized.

2) Through single-factor experiment by using RecurDyn-EDEM coupled simulation, and based on the motion trajectory and maximum compressive force of potatoes, the range of the roller

diameter was determined to be 175-225 mm, the range of the conveying speed was determined to be 0.8-1.2 m/s, the range of the feeding amount was determined to be 30-50 t/h, and the size of the potato bag was determined to be 1000 mm×1000 mm×1000 mm.

3) A three-factor three-level orthogonal experiment was conducted with roller diameter, conveying speed, and feeding amount as experimental factors, and maximum compressive force and maximum kinetic energy as evaluation indicators. By analyzing the interaction effects of various factors on the evaluation indicators through the response surface method and optimizing key parameters, the optimal parameter combination was determined to be: roller diameter of 211.803 mm, conveying speed of 0.915 m/s, and feeding amount of 30 t/h. The potato impact recording device was used for the verification experiment, and the results of the experiment showed that under the optimal parameter combination, the average maximum compressive force on electronic potato during bagging was 238.854 N, which was close to the theoretical value after parameter optimization, with an error of 5.40%. The average potato damage rate and skin breakage rate were 0.98% and 1.86%, respectively, which met the relevant industry standards.

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