DESIGN AND TESTING OF A COMPOSITE POTATO PICKUP DEVICE BASED ON EDEM
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基于 EDEM 的复合式马铃薯捡拾装置设计与试验

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ABSTRACT
To address the problems of low manual pickup efficiency and severe soil accumulation in existing shovel-type pickup devices used for segmented potato harvesting, a composite pickup device consisting of a grid-type segmented pickup shovel and a flexible lifting wheel was designed. A potato-soil-machine discrete element simulation model was established using EDEM to optimize structural parameters, including grid spacing, and to investigate the effects of operating parameters, including forward speed, digging depth, and lifting-wheel speed, on pickup performance. The simulation results showed that grid spacing was negatively correlated with the loss rate and positively correlated with the damage rate. An optimized grid spacing of 25 mm reduced the damage rate to 2.21% and the loss rate to 3.70%, while effectively reducing potato jamming. As the forward speed and lifting-wheel speed increased, the loss rate decreased, whereas the damage rate increased. Digging depth had a nonlinear effect on the loss rate, which initially decreased and then increased, reaching its minimum at a digging depth of 100 mm, whereas the damage rate continuously decreased with increasing digging depth. Field tests yielded an average loss rate of 3.88% and an average damage rate of 2.24%, meeting the operational requirements for potato harvesting.

摘要
针对马铃薯分段收获中人工捡拾效率低和现有铲式捡拾装置易壅土的问题，设计了一种由栅栏分段式捡拾铲与柔性拨薯轮组成的复合式捡拾装置。基于 EDEM 软件建立了薯-土-机离散元仿真模型,优化栅栏间距等结构参数并探究了前进速度、入土深度和拨薯轮转速等作业参数对捡拾性能的影响。仿真结果表明：栅栏间距与损失率负相关，与伤薯率正相关；优化后的 25 mm 栅栏间距使伤薯率降至 2.21%，损失率为 3.70%，显著减少了薯块卡滞现象；前进速度和拨薯轮转速增加时，损失率下降而伤薯率上升，入土深度对损失率呈先降后升的非线性影响，100 mm 时最优，对伤薯率则持续降低。田间试验平均损失率为 3.88%，伤薯率为 2.24%，满足马铃薯收获作业要求。

INTRODUCTION
Potato mechanized harvesting can be divided into combine harvesting and segmented harvesting. At present, segmented harvesting is still the predominant method in hilly areas with many small fields *(Wang et al., 2023)*. In segmented harvesting, the preliminary operations such as vine killing, digging, separation, and windrowing have achieved a relatively high level of mechanization. However, the pickup operation still relies heavily on manual labor, resulting in high labor intensity and low efficiency (*Dorokhov et al., 2022*). Therefore, developing a low-damage, high-efficiency potato pickup device is of great significance for improving the mechanization level of segmented potato harvesting and reducing labor costs.

Existing pickup devices can be mainly divided into two categories. The first category is shovel-type pickup devices represented by flat shovels, triangular shovels, and bionic shovels, which are currently widely used and usually adopt a single-stage flat structure. These devices have high forward resistance and severe soil accumulation, which easily cause potatoes to roll back into the furrow and increase the loss rate. However, they can achieve continuous feeding and high operational efficiency *(Beznosyuk et al., 2022; Yang et al., 2025; Mamatov and Karimov, 2023)*.

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The second category is rotary pickup devices represented by spring-tooth and disc types. They achieve intermittent grasping through rotating components, which avoids large amounts of soil being drawn in, enables targeted picking of potatoes, reduces operational resistance, and alleviates the burden of subsequent potato-soil separation. Nevertheless, these devices are prone to causing damage due to collisions with potatoes, and the forward speed and rotational speed cannot be too high; otherwise, missing picking may occur, limiting the overall operational efficiency *(Lu et al., 2023; Yang et al., 2024; Toure and Wei, 2023)*. Addressing the shortcomings of existing pickup devices, this study designed a composite pickup device consisting of a grid-segmented pickup shovel and a flexible lifting wheel. The device uses the grid structure of the pickup shovel to perform preliminary screening of the potato-soil mixture to alleviate soil accumulation, improves the pickup rate through the horizontal section of the segmented shovel surface, and reduces collision damage by means of the flexible lifting wheel's active rotary conveying action.

The discrete element method has been widely applied in research on potato-soil separation, digging resistance analysis, and structural optimization of equipment, as it can effectively simulate the complex interactions among potatoes, soil, and machinery. Based on this method, this study established a potato-soil-machine discrete element simulation model using EDEM software. The grid spacing of the pickup shovel was taken as a key parameter for optimization, and single-factor simulation experiments were conducted to systematically analyze the effects of forward speed, digging depth, and lifting wheel speed on picking performance. Finally, the operational performance of the device was verified through field experiments, confirming that the composite pickup device under optimized parameters meets the requirements for low-damage and low-loss potato pickup harvesting. This study provides a theoretical basis and technical reference for the optimal design of potato pickup equipment.

MATERIALS AND METHODS

Design of the composite pickup device

The specific structure of the composite pickup device is shown in Fig. 1. It mainly consists of a depth-limiting wheel, a height adjustment plate, a pickup shovel, a lifting wheel, a frame, etc. Its core is a composite structure in which the pickup shovel and the lifting wheel work synergistically: combining the advantages of continuous feeding and high efficiency of the traditional flat pickup shovel, while drawing on the targeted picking concept of the spring-tooth pickup device. By using the active conveying of the lifting wheel to replace the passive pushing of the shovel surface, effective pickup of potatoes is achieved.

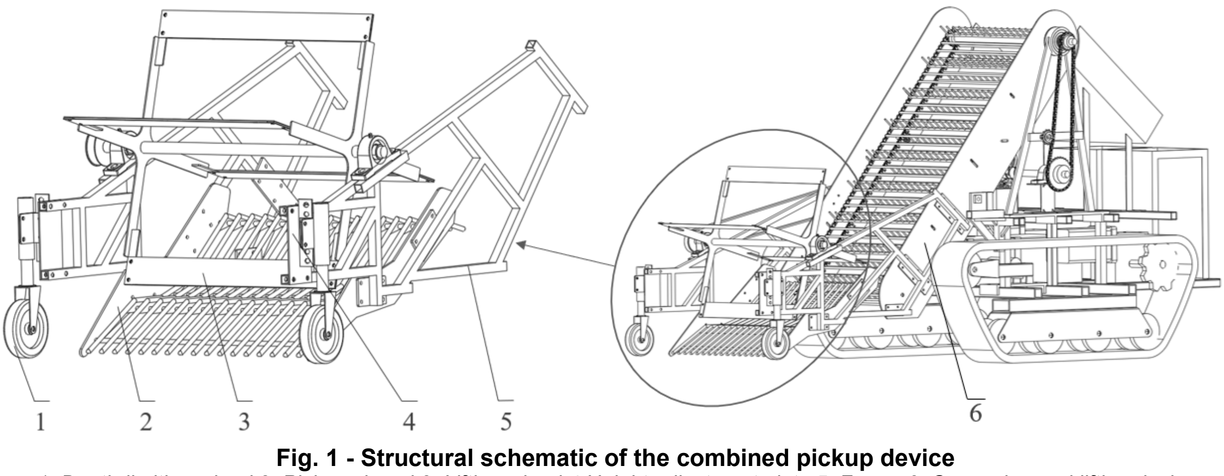


Fig. 1 - Structural schematic of the combined pickup device

1. Depth-limiting wheel 2. Pickup shovel 3. Lifting wheel 4.Height adjustment plate 5. Frame 6. Conveying and lifting device

Before operation, the depth-limiting wheel is adjusted to fit the side of the ridge. During operation, the potato-soil mixture is initially screened by the grid structure of the pickup shovel, and the potatoes remain on the shovel surface. The lifting wheel rotates to generate an active conveying force, smoothly pushing the potatoes off the shovel surface and onto the subsequent conveying and lifting device, finally completing the collection and bagging of potatoes. To adapt to terrain fluctuations, a compression spring is built into the depth-limiting wheel: when compressed, the spring drives the wheel to lift adaptively, buffering impacts and maintaining the working depth, thereby ensuring pickup quality. The main parameters of the composite pickup device are shown in Table 1.

Table 1

Main parameters of the composite pickup device

Item	Value
Overall dimensions (L×W×H) / (mm×mm×mm)	1039 × 818 × 906
Working width / mm	600
Applicable ridge width / mm	≤800
Applicable ridge height / mm	100–200
Number of ridges worked	1

Grid-segmented pickup shovel

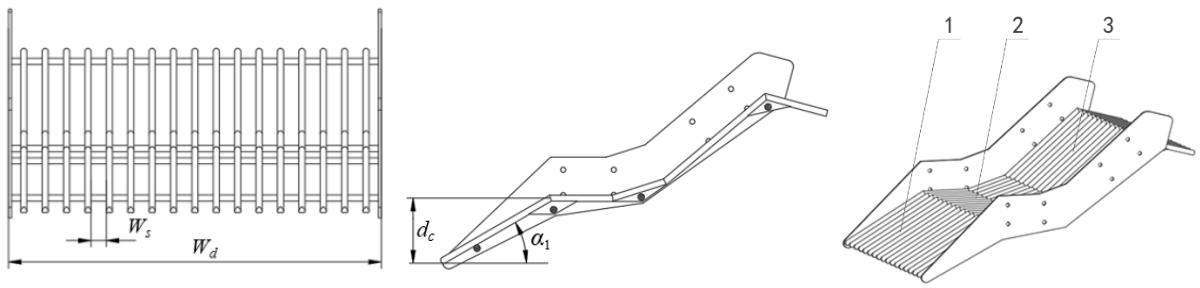
The pickup shovel is the core component of the pickup device. Structural innovations were made based on the traditional flat pickup shovel:

(1) The traditional shovel surface was optimized into a grid structure to preliminarily screen the potato-soil mixture and reduce traveling resistance.

(2) The single-stage shovel surface was reconstructed into a three-stage "inclined–horizontal–inclined" structure: the digging stage screens the soil and picks up underground potatoes (those buried beneath the soil surface); the horizontal stage forms a zero-inclination pickup platform to improve the pickup rate; a smooth transition section is added at the junction between the horizontal stage and the lifting stage to eliminate geometric discontinuities and enhance the low-damage performance of the device; the lifting stage works together with the lifting wheel to raise the potatoes to a certain height for subsequent conveying; and a guide section is provided at the end of the lifting stage to achieve impact-free connection with the conveying and lifting device.

According to the agrotechnical requirements for potato planting in hilly areas, the ridge width ranges from 600 to 800 mm. After digging, potatoes are scattered on the ridge surface with a distribution width of approximately 450 mm and a surface distribution depth of less than 40 mm *(Ahmad and Sharma, 2023)*. To ensure that the pickup shovel completely covers the potato distribution area, the shovel width W_d was designed as 600 mm. The resistance on the shovel surface increases with the entry angle, considering energy saving and soil penetration performance, the entry angle α_1 is generally taken as 20°- 30° *(Wei et al., 2023)*. To shorten the horizontal projection length of the pickup shovel, the upper limit of the entry angle, 30°, was chosen. The digging depth d_c of the pickup shovel should be controlled between 80 -120 mm. Based on this, the length of the first segment of the pickup shovel was set to 200 mm.

The three-axis size distribution of potatoes ranges from 30 to 160 mm *(Wang et al., 2023)*. To prevent small-sized potatoes from becoming embedded or stuck in the grid gaps, the grid spacing of the pickup shovel should be smaller than the minor axis of potatoes. In existing potato harvesting equipment, the grid spacing is mostly designed with reference to the bar spacing of the conveying and lifting chain or the separation conveyor chain, with typical values of 30 - 40 mm *(Bulgakov et al., 2021)*. During such conveying processes, potatoes mainly move with the conveyor chain under their own weight, without significant active pressing action between the potatoes and the grid; therefore, the grid spacing is mainly determined based on passing ability and soil sieving performance. Unlike conventional conveying structures, the pickup device designed in this study uses a lifting wheel to actively convey the potato tubers. When passing through the grid area, potatoes are subjected not only to gravity but also to the contact thrust applied by the lifting wheel, which may press them into the grid gaps. Consequently, the traditional grid spacing parameters are not directly applicable to the design of the present device. Considering the potato size distribution and existing equipment design experience *(Wei et al., 2023)*, the grid spacing W_s was preliminarily set to 30 mm, which will be further optimized through discrete element simulations. The specific structure and parameters of the grid-segmented pickup shovel are shown in Fig. 2.



(a) Front view of pickup shovel (b) Left view of pickup shovel (c) Axonometric view of pickup shovel

Fig. 2 - Structural diagram of the pickup shovel

1.Digging stage; 2.Horizontal stage; 3.Lifting stage

Flexible lifting wheel

Although the grid structure of the pickup shovel enables preliminary screening of the potato-soil mixture, thereby alleviating soil accumulation and reducing loss due to accumulation as well as forward resistance, it also brings a new problem: after soil and potatoes are separated, the potatoes lose the pushing effect of the soil, becoming stranded on the pickup stage of the shovel and difficult to effectively pushed forward and lifted. To address this issue, a lifting wheel is added above the pickup shovel. The lifting wheel is covered with a flexible material (canvas) and generates an active conveying force when rotating. When potatoes remain on the shovel surface, the paddles of the lifting wheel, with a relatively large contact area, smoothly push the potatoes off the shovel surface, avoiding the surface bruising and impact damage caused by the direct rigid collision of spring teeth or fingers in existing studies.

Although the lifting wheel draws on the active conveying concept of the spring-tooth pickup device, its mode of action is different: the spring-tooth pickup device relies on the spring teeth to directly grasp potatoes on the soil surface, and if the grasping fails, it results in missed pickups. In contrast, in the present design, potatoes continuously enter the shovel surface through the forward motion of the pickup shovel, and the lifting wheel only plays an auxiliary pushing role without undertaking the "grasping" function, thus not causing missed pickups. Therefore, the pickup efficiency is mainly inherited from the high-efficiency continuous feeding characteristic of the traditional flat shovel, achieving a balance between targeted potato picking and a high pickup rate.

To facilitate the smooth entry of potatoes into the subsequent elevator conveyor, the lifting wheel needs to push the potatoes up along the lifting section of the pickup shovel to a certain height. As shown in Fig. 3, from point A to point B for the potato, the relationship between the lifting wheel radius and the potato lifting height is given by the following formula:

$$H = \sqrt{2Rd - d^2} sin\beta + dcos\beta + R - Rcos\beta \tag{1}$$

where: H is the potato lifting height, mm;

β is the inclination angle of the third segment of the pickup shovel, (°);

d is the short-axis dimension of the potato, mm;

R is the minimum radius of the lifting wheel, mm.

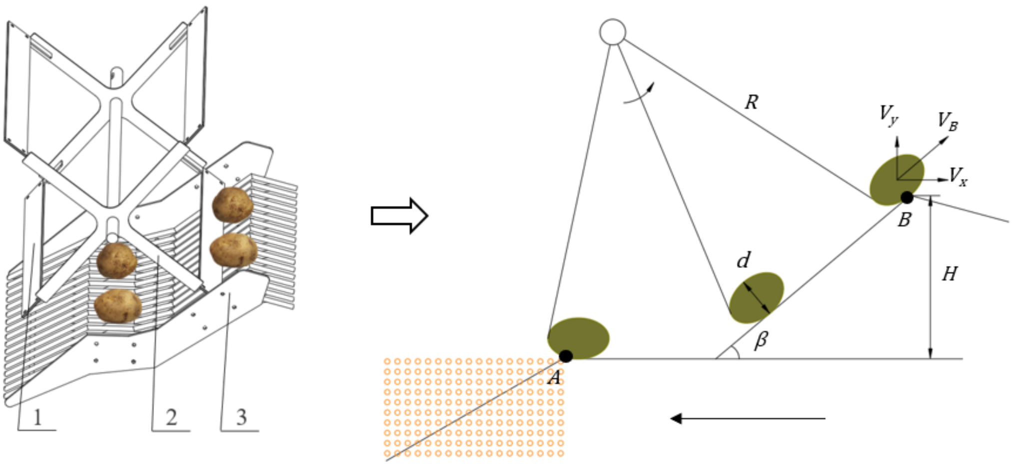


Fig. 3 - Schematic diagram of potato processing

1.Paddle; 2. Lifting wheel; 3. Pickup shovel

At the detachment position (point B), when the potato reaches the highest point with the lifting wheel, it is thrown out along the lifting stage of the pickup shovel and enters the subsequent conveying and lifting device. To facilitate the detachment of the potato from the lifting wheel paddle, the horizontal component of velocity V_X should be greater than the vertical component V_Y, i.e., $V_B cos\beta > V_B sin\beta$. From this, β should be less than 45°. To shorten the horizontal dimension of the pickup shovel and achieve better lifting effect, the inclination angle β of the lifting stage of the pickup shovel was preset to 40°.

Based on the measured distribution range of potato three-axis dimensions, the minimum short-axis dimension d of the potato was taken as 30 mm. To ensure the potato smoothly enters the subsequent conveying and lifting device, the minimum lifting height was set to 150 mm. From equation (1), the lifting wheel radius R ≥ 231 mm, so R = 300 mm was adopted.

Establishment of the discrete element model

Soil and potato particle models

Soil particles were modeled using spherical particles with a radius of 5 mm. To characterize the actual soil particle size distribution, based on the investigation results of soil particle size in hilly areas (<1 mm: 8.44%, 1- 2 mm: 23.12%, 2 - 5 mm: 37.68%, >5 mm: 30.76%) *(Issa et al., 2025; Chen et al., 2024)*, scaling factors of 0.1, 0.3, 0.5, and 2.0 times were set in the EDEM particle factory, corresponding to generated spherical particles with diameters of 0.5, 1.5, 2.5, and 10.0 mm, and the number generated was allocated according to the mass proportions.

Based on the measured average three-axis dimensions of potatoes, two types of simulation particle models were established: spherical-like and ellipsoidal. The spherical-like potato model had a short axis of 60 mm and a long axis of 66 mm; the ellipsoidal potato model had a short axis of 50 mm and a long axis of 85 mm. These were formed as discrete element models using multi-sphere aggregates. The two types of potato particle models are shown in Fig. 4. To reflect the size variation of tubers in the field, a random scaling factor of 0.6 -1.5 times was applied to the base models in the EDEM particle factory to generate particles covering the range of small, medium, and large tubers.

(a) Spherical-like potato (b) Ellipsoidal potato

Fig. 4 - Simulation model of potato particles

Referring to field conditions, a soil bin and potato ridge model were established: the soil bin length was 7000 mm, the ridge bottom width was 800 mm, the ridge surface width was 600 mm, and the ridge height was 150 mm. The particle factory for potatoes was placed at a height of 400 mm above the soil surface, allowing the potato tubers to fall freely and form a distribution close to the field scattering state. Based on the estimated actual potato yield, a total of 21 kg of potatoes was generated.

Simulation parameter settings

The basic characteristic parameters of the materials are shown in Table 2 *(Li et al., 2023; Wang et al., 2023; Pan et al., 2025)*. The Hertz–Mindlin (no slip) model was used for contacts between particles and the machine components, whereas the Hertz–Mindlin with JKR model was used for particle–particle contacts. The rolling friction model was the standard rolling friction model. The interaction parameters for contact are shown in Table 3 *(Yan et al., 2023; Pan et al., 2026; Foldager et al., 2022)*. The simulation time step was set to 20% of the Rayleigh time step, calculated to be approximately 1.2 × 10^{-5} s. The data save interval was set to 0.01 s *(Maraveas et al., 2025).*

Table 2

Basic simulation parameters

Parameter	Poisson's ratio	Density / (kg/m³)	Shear modulus / Pa
Potato	0.47	1047	1.99 × 10^{6}
Soil	0.25	1240	1.00 × 10^{6}
Steel	0.30	7800	7.00 × 10^{10}
Rubber plate	0.30	1800	3.85 × 10^{7}

Table 3

Interaction simulation parameters

Interaction pair	Coefficient of restitution	Coefficient of static friction	Coefficient of rolling friction
Potato-Potato	0.60	0.48	0.03
Soil-Soil	0.13	0.56	0.27
Potato-Soil	0.53	0.50	0.01
Potato-Steel	0.65	0.28	0.16
Soil-Steel	0.28	0.49	0.57
Soil-**Canvas**	0.12	0.66	0.54
Potato-**Canvas**	0.71	0.51	0.20

Evaluation indicators

Referring to the quality evaluation indicators for self-propelled potato combine harvesters in JB/T 14285-2022 "Potato Harvesting Machinery" *(JB/T 14285-2022, 2022)*, and considering the actual working conditions of pickup operations, the performance evaluation indicators for the device were determined as follows: loss rate ≤ 4%, damage rate ≤ 2.5%.

Previous studies typically take the potato extrusion force damage threshold as 100 N *(Yang et al., 2024*). However, multiple low-stress collisions may also cause cumulative tissue damage. To establish a more practical warning value, a preloading test was conducted on the potato variety used in this study (Qingshu No.9). The results showed that when the extrusion force reached approximately 60 N, slight surface indentations and softening began to appear on the tubers. Therefore, referring to existing damage thresholds and combining with the observations from the pre-test, a more conservative value of 60 N was adopted as the damage risk warning value, which is used to characterize potentially high-risk force events rather than the critical value for actual visible damage.

RESULTS AND ANALYSIS

Initial simulation and problem diagnosis under baseline operating parameters

In the initial design, the grid spacing of the pickup shovel was set to 30 mm. To diagnose whether there were any jamming or damage issues under this structural parameter, referring to typical potato harvesting operating conditions and the design experience of similar pickup devices *(Lu et al., 2023)*, a set of conventional operating parameters was selected as the baseline: forward speed of 0.40 m/s, digging depth of 100 mm, and lifting wheel speed of 20 r/min. A simulation of the pickup process was carried out under these operating conditions, as shown in Fig. 5.

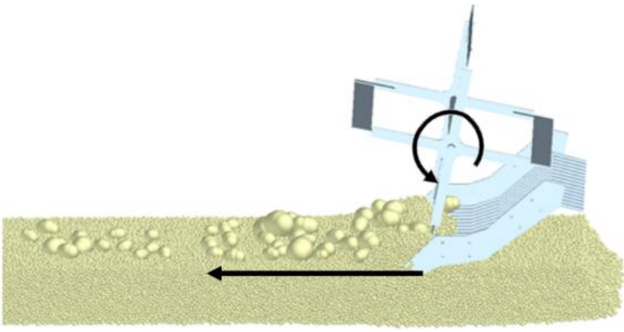


Fig. 5 - Simulation experiment of the pickup process

The time-history curve of the maximum extrusion force during the pickup process was extracted, as shown in Fig. 6. The maximum extrusion force on potatoes during pickup was recorded at intervals of 0.1 s. The red horizontal line in the figure indicates the damage risk warning value of 60 N.

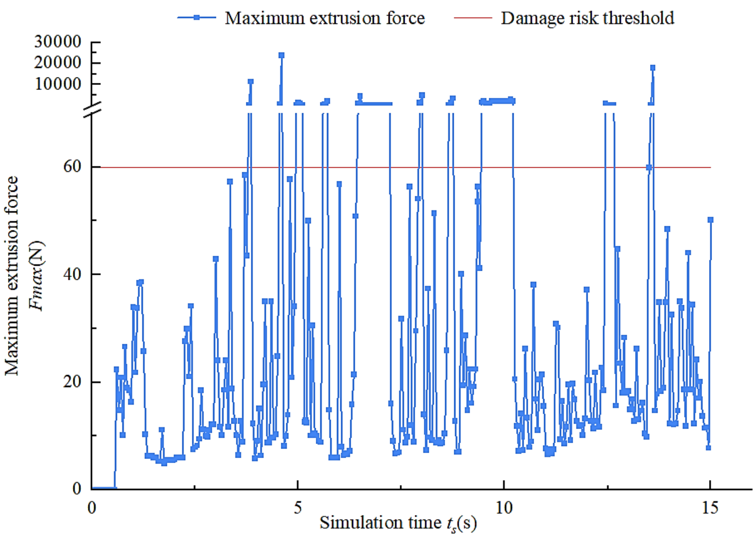
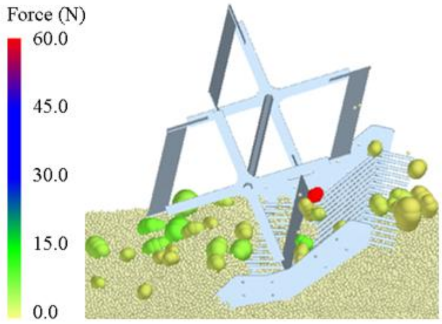
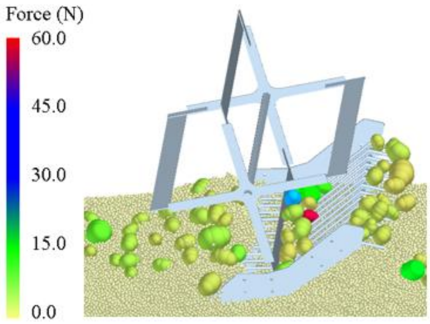


Fig. 6 - Time-history curve of extrusion force during potato pickup process (grid spacing 30 mm)

As shown in Fig. 6, during the 15 s pickup process, a total of 10 damage risk events with extrusion force exceeding 60 N occurred, with an average frequency of approximately once every 1.5 s. Among them, during the intervals of 6.4 - 7.2 s and 9.5 - 10.2 s, the high extrusion force states lasted for about 0.9 s and 0.8 s, respectively, and the risk events were mainly concentrated in the period of 3.8 - 13.6 s, indicating that under the initial grid spacing of 30 mm, the potatoes experienced a significant sustained compression phenomenon during the pickup process. To further analyze the causes of high extrusion forces, typical risk periods were selected for observation, and the results are shown in Fig. 7. It can be seen that during the periods of 6.4 -7.2 s and 9.5 - 10.2 s, potato jamming in the grid gaps occurred. After small-sized potatoes or the tips of potatoes became embedded in the grid gaps, they were constrained by the grid structure under the continuous conveying action of the lifting wheel, making it difficult to detach in time, thus forming a sustained compression state.



(a) Potato jam at simulation time 6.4-7.2 s



(b) Potato jam at simulation time 9.5-10.2 s

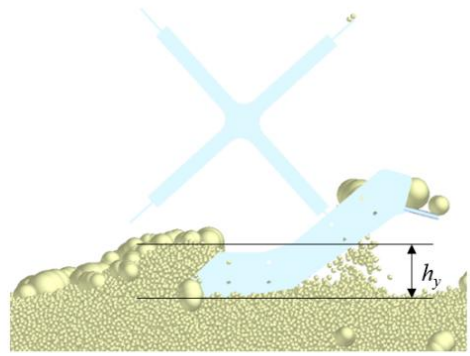
Fig. 7 - Abnormal conditions of potato during pickup process (grid spacing 30 mm)

The analysis suggests that although the 30 mm grid spacing can theoretically effectively prevent small-sized potatoes from falling through the gaps, due to the irregular shapes and random postures of the potatoes, their tips or local protruding parts are still prone to becoming embedded in the grid gaps. Once a potato tuber is embedded, under the continuous conveying action of the lifting wheel, it is easy to form a local "embedding–sustained compression" state, causing the extrusion force to remain at a high level for a certain period, with consecutive sampling points exceeding the 60 N risk warning value.

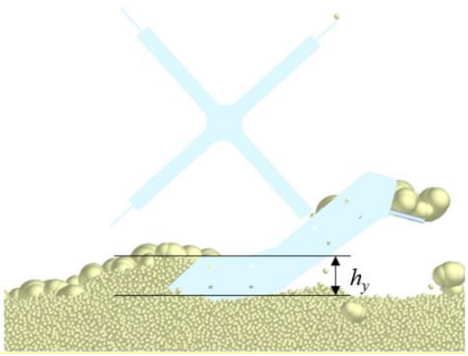
Combining the analysis of the extrusion force time-history curve and the particle motion state, it can be seen that the high extrusion force events did not occur randomly but showed a clear correspondence with potato jamming, exhibiting a certain regularity. This indicates that the initial 30 mm grid spacing is close to the minor axis size of some small-sized potato tubers, which easily induces tuber embedding and sustained compression. Therefore, it is necessary to further optimize the grid spacing parameter to reduce the risks of potato jamming and mechanical damage.

Single-factor optimization of grid spacing

Based on the clogging and potato damage risks observed in the initial simulation, a single-factor sensitivity analysis was conducted using grid spacing as the test factor. Five levels were selected: 20, 22.5, 25, 27.5, and 30 mm, among which 30 mm was the initial design value. The operating parameters were kept constant for all treatments: forward speed of 0.40 m/s, digging depth of 100 mm, and lifting wheel rotational speed of 20 r/min. Each treatment was simulated three times.



(a) Grid spacing of 20 mm



(b) Grid spacing of 30 mm

Fig. 8 - Soil accumulation under different grid spacings of the pickup device

The simulation results showed that grid spacing had a significant influence on soil screening performance and potato conveying behavior. As shown in Fig. 8, when the grid spacing was small (e.g. 20 mm), the soil passed slowly through the grid gaps, resulting in obvious soil accumulation at the front of the pickup shovel. Potatoes tended to accumulate on the shovel surface. As the device moved forward, the accumulated soil caused potatoes in front of the shovel to roll backward or fall back into the ridge bottom, preventing them from entering the pickup shovel smoothly and thereby increasing the loss rate. With increasing grid spacing (e.g. 30 mm), the soil screening capacity improved, the soil accumulation height h_y at the front of the pickup shovel decreased significantly, and the potato passing performance improved, resulting in a lower loss rate.

However, when the grid spacing became excessively large, although soil separation was improved, potatoes were more likely to become embedded in the grid gaps and jam between adjacent rods. Under the continuous conveying action of the lifting wheel, this led to sustained compression and an increase in potato damage rate. The variation trends of simulated damage rate and simulated loss rate under different grid spacings are shown in Fig. 9.

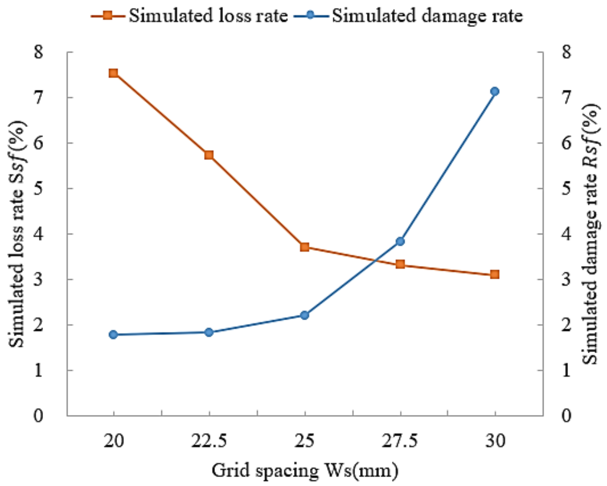


Fig. 9 - Simulated damage rate and simulated loss rate under different grid spacings

As shown in Fig. 9, with the increase of grid spacing, the simulated loss rate showed an overall downward trend, indicating that a larger spacing is beneficial for soil sieving and potato passage. When the grid spacing increased from 20 mm to 30 mm, the simulated loss rate decreased from 7.52% to 3.10%. At the same time, the simulated damage rate increased from 1.79% to 7.11%, indicating that excessive grid spacing significantly increases the risk of potatoes becoming embedded in the gaps and experiencing jamming and compression. Among the tested spacings, the damage rates at 20 mm and 22.5 mm were relatively low, but the loss rates reached 7.52% and 5.71%, respectively, indicating poor pickup performance. At 27.5 mm and 30 mm, the loss rates were low, but the damage rates increased significantly. A comprehensive comparison of the results shows that, under the premise that the damage rate does not exceed the design requirement of 2.5%, the grid spacing of 25 mm corresponds to the lowest loss rate of 3.70%, with a damage rate of 2.21%, demonstrating the best overall performance. Therefore, 25 mm was determined as the optimal grid spacing.

Force validation after optimization

Simulation was conducted again using the optimized grid spacing of 25 mm, and the time-history curve of potato extrusion force during the pickup process was extracted, as shown in Fig. 10. A total of 150 valid sampling points were obtained. Among them, only four isolated sampling points exceeded the 60 N damage warning threshold, occurring at 2.7 s (89.2 N), 5.6 s (90.0 N), 10.0 s (63.5 N), and 11.1 s (97.3 N), accounting for approximately 2.6% of the total sampling points. For the remaining 97.4% of the sampling points, the maximum extrusion force remained within the safe range.

Compared with the initial 30 mm grid spacing, the optimized 25 mm grid structure no longer showed continuous jamming events involving multiple consecutive sampling points exceeding the threshold. The peak extrusion force was controlled below 100 N, and the overall loading level was significantly reduced. This indicates that the optimized grid spacing effectively alleviated sustained compression of potatoes during the pickup process.

The analysis suggests that after reducing the grid spacing, potatoes were less likely to become embedded in the grid gaps. The contact mode gradually changed from "embedded compression" to "surface sliding contact", thereby reducing the probability of continuous high-load events. In addition, the average extrusion force remained at a relatively low level after optimization, indicating that the interaction between the lifting wheel and potatoes was mainly characterized by transient contact and flexible conveying, without obvious accumulation or sustained compression.

These results demonstrate that the 25 mm grid spacing not only ensures effective soil screening and smooth potato passage, but also effectively suppresses tuber embedding and jamming, significantly reducing the risk of mechanical damage. Therefore, it can be considered an optimal structural parameter that achieves a good balance between low loss rate and low damage rate.

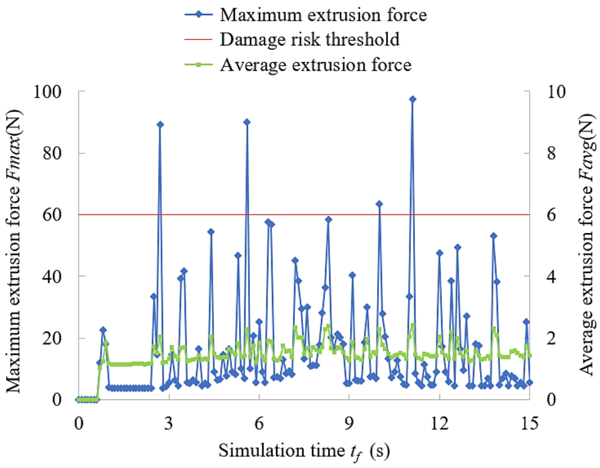
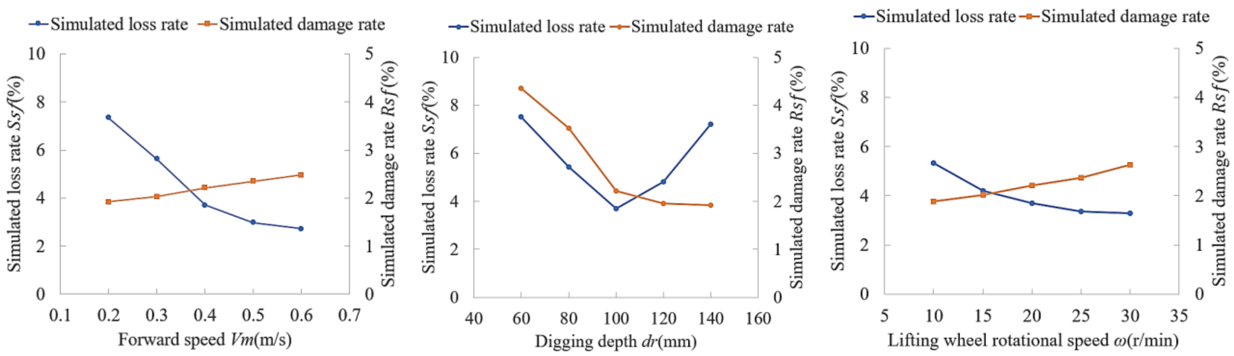


Fig. 10 - Time-history curve of extrusion force during the potato pickup process (optimized grid spacing 25 mm)

Single-factor analysis of the influence of operating parameters on pickup performance

On the basis of determining the optimal grid spacing (25 mm), single-factor simulation tests were carried out to further investigate the influence trends of the overall forward speed, digging depth of the pickup shovel, and lifting wheel speed on the pickup performance. The value ranges of forward speed and digging depth were set with reference to relevant studies on shovel-type pickup devices *(Yang et al., 2024)*, while the value range of lifting wheel speed was determined based on the operating parameters of a spring-tooth pick up device with a similar radius *(Lu et al., 2023*). Accordingly, the forward speed was preliminarily set at 0.2 - 0.6 m/s, the digging depth at 60 - 140 mm, and the lifting wheel speed at 10 - 30 r/min. When testing one factor, the other two factors were kept at their intermediate levels (forward speed 0.40 m/s, digging depth 100 mm, lifting wheel speed 20 r/min). Each parameter combination was simulated three times, and the average values were taken. The influence trends of forward speed, digging depth, and lifting wheel speed on the simulated loss rate and simulated damage rate are shown in Fig. 11(a), (b), and (c), respectively.



(a) Effect of forward speed on pickup performance
(b) Effect of digging depth on pickup performance
(c) Effect of lifting wheel speed on pickup performance

Fig. 11- Effect of operating parameters on picking performance

Analysis of the experimental results yields:

(1) Effect of forward speed: As the forward speed increased from 0.20 m/s to 0.60 m/s, the simulated loss rate decreased significantly (from 7.35% to 2.72%), while the simulated damage rate increased slowly (from 1.92% to 2.48%). A higher forward speed gives the potato-soil mixture sufficient inertia to be transported backward quickly, reducing soil accumulation and buildup, thereby lowering the loss rate.

However, a higher speed also increases the relative collision speed between potatoes and the pickup shovel, leading to a slight increase in the damage rate. When the forward speed exceeded 0.50 m/s, the damage rate approached the design upper limit of 2.5%, and the decrease in loss rate leveled off, indicating that further increasing the forward speed has limited marginal effect on improving pickup performance.

(2) Effect of digging depth: The simulated loss rate exhibited a U-shaped curve with increasing digging depth, first decreasing and then increasing. It was highest at 60 mm (7.52%), lowest at 100 mm (3.70%), and then rose to 7.20% at 140 mm. The simulated damage rate, in contrast, continuously decreased (from 4.36% at 60 mm to 1.92% at 140 mm). When the digging depth was too shallow (60 mm), the end of the digging stage of the pickup shovel was prone to emerge from the soil surface, causing potatoes to stagnate and roll off, resulting in a high loss rate. Moreover, the shallow depth meant less soil and more direct collisions, leading to a higher damage rate. As the digging depth increased, the buffering effect of the soil was enhanced, and the damage rate continued to decrease. However, when the depth exceeded 100 mm, soil accumulation worsened, causing the loss rate to rise again.

(3) Effect of lifting wheel speed: As the lifting wheel speed increased from 10 r/min to 30 r/min, the simulated loss rate continuously decreased from 5.34% to 3.28%, while the simulated damage rate continuously increased from 1.89% to 2.63%. Increasing the speed effectively alleviated soil accumulation and enhanced the active conveying capacity, thereby reducing missed pickup losses. However, excessively high speeds increased the frequency and velocity of collisions between the paddles and the potatoes, leading to a higher damage rate.

Field experiment and simulation comparison

Experimental conditions

The field experiment was conducted in November 2025 at the potato experimental field of the College of Agricultural Engineering, Jiangsu University (Fig. 12). Measurements showed that the ridge bottom width was 800 mm, the ridge surface width was 600 mm, the ridge height was 150–200 mm, and the soil was loam. Before the experiment, the soil moisture content and bulk density were measured: moisture content was determined by the oven-drying method, and bulk density by the cutting ring method, with five sampling points and three repetitions for each. The results showed an average soil moisture content of 14.2% and an average bulk density of 1.28 g/cm³. The test variety was "Qingshu No. 9". Potatoes were manually and randomly placed on the ridge surface according to their field distribution state, with some buried 5–6 cm into the soil to simulate exposed and buried potatoes. The test area length was 10 m, and the total mass of potatoes placed was approximately 30–35 kg. After the test, the picked and missed potatoes were separately collected and weighed, and the damaged potatoes were also picked out and weighed.

Fig. 12 - Field test of potato pickup harvesting

Experimental results and comparison with simulation

Field tests were conducted using the optimized parameter combination (grid spacing of 25 mm, forward speed of 0.40 m/s, digging depth of 100 mm, lifting wheel speed of 20 r/min), and the results are shown in Table 4.

Table 4

Field experiment results of potato pickup harvesting

Indicator	1	2	3	4	5	Mean ± SD
Loss rate Y_1 (%)	3.45	4.24	3.76	4.15	3.82	3.88 ± 0.32
Damage rate Y_2 (%)	2.18	2.31	2.22	2.34	2.15	2.24 ± 0.08

From Table 4, it can be seen that the average loss rate in the field test was 3.88% and the average damage rate was 2.24%, indicating that the designed composite pickup device can meet the operational requirements for potato pickup and harvesting under the optimized grid spacing. Meanwhile, the test results are in good agreement with the simulated predicted values (loss rate 3.70%, damage rate 2.21%), with relative deviations of 4.97% and 1.4%, respectively, further verifying the reliability of the EDEM simulation model and the damage warning method. The deviations mainly stem from the presence of soil clods, stones, and slightly higher surface unevenness in the field compared to the simulation settings, which caused localized soil accumulation and a very small number of missed potatoes. In summary, the composite pickup device with a grid spacing of 25 mm can achieve both low loss and low damage operational requirements.

CONCLUSIONS

(1) To address the problems of low manual picking efficiency, susceptibility to soil accumulation, and high damage rate of existing pickup devices during segmented potato harvesting, a composite potato pickup device consisting of a grid-segmented pickup shovel and a flexible lifting wheel was designed. This device enables preliminary screening of the potato-soil mixture and active conveying, effectively reducing soil accumulation and mechanical damage to potatoes.

(2) A potato–soil–machine discrete element simulation model was established using EDEM to optimize the grid spacing and conduct single-factor simulation analyses. The results showed that increasing the grid spacing was beneficial for reducing the loss rate but increased the risk of potato embedding and jamming, leading to a higher damage rate. After comprehensive comparison, a grid spacing of 25 mm was determined as the optimal value, corresponding to a simulated loss rate of 3.70% and a simulated damage rate of 2.21%. The single-factor simulation analyses also indicated that as the forward speed and lifting wheel speed increased, the simulated loss rate showed an overall decreasing trend while the simulated damage rate gradually increased. Digging depth exhibited a non-linear effect on pickup performance: the simulated loss rate first decreased and then increased with increasing digging depth, whereas the simulated damage rate decreased overall.

(3) Field tests were conducted using the optimized grid spacing (25 mm) and operating parameters. The results showed an average loss rate of 3.88% and an average damage rate of 2.24%, both better than the industry standard requirements (loss rate ≤ 4%, damage rate ≤ 2.5%), verifying that the designed composite pickup device under the optimized parameters can meet the operational requirements of low loss and low damage.

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