SIMULATION ANALYSIS AND OPTIMIZATION OF CONCAVE BAR POTATO-SOIL SEPARATION DEVICE
/
凹杆式薯土分离装置仿真分析与优化

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ABSTRACT
The limited separation efficiency of potato-soil separation equipment in the southern potato planting areas is attributed to the high viscosity of the soil. To enhance the performance of the lifting chain separation device, a concave bar was designed. Structural parameters influencing the efficiency of potato-soil separation by bars were determined through kinetic analysis during the separation and transportation of potato-soil mixtures. Both a potato simulation model and a sticky soil simulation model were developed. Simulation tests indicated that the concave bar outperforms the straight bar in separation efficiency. Key factors investigated include the angle of the concave side, the width of the concave bar, the depth of the concave bar, and the installation angle. Orthogonal simulations were conducted using separation efficiency and the maximum force on potatoes as evaluation metrics. The results demonstrated that with a concave side angle of 15°, a concave bar width of 450 mm, a concave bar depth of 60 mm, and an installation angle of 30°, the separation efficiency of the potato-soil mixture reached 79.7%, with a maximum force on potatoes of 35.218 N, achieving the highest separation efficiency. Based on these results, test devices were constructed, and field tests were performed. The field test results showed a damage rate of 1.58%, a potato epidermal injury rate of 1.03%, and a loss rate of 2.87%. These results comply with national standards and validate the reliability of the simulation findings.

摘要
南方马铃薯种植地区因土壤黏性大导致薯土分离装置分离效果差。为了提高升运链式分离装置的分离效率，设计一种凹形杆。在薯土分离和和运输过程中的力学分析的基础上，确定了影响筛分杆对薯土分离效果的的结构参数。构建了马铃薯模型和粘性土壤模型。通过仿真试验，明确了凹杆的分离效果优于直杆。选取凹杆边角、凹杆宽度、凹杆深度和安装倾角为试验因素，以薯土混合体分离效率与薯块最大受力为评价指标开展了仿真正交试验。结果表明，当凹杆边角为150°，凹杆宽度为450mm，凹杆深度为60mm，安装倾角为30°，此时薯土混合体分离效率为79.7%，薯块最大受力为35.218N，薯土分离效果最好。根据试验结果搭建试验样机，进行田间试验。田间试验结果统计得到伤薯率为1.58%，破皮率为1.03%，损失率为2.87%，符合国家标准，验证了仿真结果可靠性。

INTRODUCTION
China is a major potato-producing country, with an annual cultivation area exceeding 6 million hectares, demonstrating significant potential for industrial development. The potato has emerged not only as a key crop for enhancing farmers' income but also as a crucial component in the "all-encompassing approach" strategy, which aims to strengthen national food security (*Xin et al., 2023*). Soil properties vary significantly across different potato-growing regions in China. The Northeast is characterized by cohesive soils, the Northwest by sandy soils, and the South by sticky soils. The development of potato harvesting machinery is uneven across these regions, with higher levels of mechanization in the northern areas where production processes are more advanced. In contrast, the southern regions face challenges such as small and fragmented farmland plots and high soil moisture content during the rainy season, which result in lower levels of mechanized production (*Li et al., 2016*). The potato harvesters developed in China are primarily designed for agronomic practices such as mound or flat planting typical of the northern regions.

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Only a limited number of harvesting machines are suitable for winter potato harvesting in the South. Research on potato harvesting machinery in Europe and the United States began early, focusing mainly on self-propelled and traction types. Currently, the primary development trend in these regions is towards high-power combined harvesting machinery. Foreign potato harvesters have advanced significantly in areas such as automation control and the intelligentization of hydraulic systems. Some models are equipped with GPS navigation systems, enabling the monitoring of technical parameters through geographic information systems (*Wei et al., 2020; Zhao et al., 2021; Wei et al., 2019*). In Asia, small potato harvesting machines are produced in a few countries and regions, such as Japan and Korea. However, these machines face several challenges when used in China. They often have poor adaptability to the diverse arable land conditions and agronomic requirements across different regions of China. Additionally, they tend to be expensive, with high operating costs, limited after-sales service, and inadequate spare parts supply channels, which complicates their widespread adoption (*Qing, 2020; Li et al., 2016; Dou et al., 2019*).

Domestic potato harvesters are primarily classified into combined and segmented types, with small and medium-sized models being more advanced. The main types of potato-soil separation devices include bar type, vibration type, and cylinder type. In the southern regions, where the soil is often moist and sticky, the bar type separation device is preferred. This design is particularly effective for separating potatoes from sticky soil (*Zhou et al., 2021*). The problem of improving the quality of potato tuber separation by improving the digging working parts from the construction of potato harvesters is investigated (*Hrushetsky et al., 2019*). To reduce damage and improve the retrieval rate of whole potatoes, changes in the materials used for separation bars can be beneficial. For instance, incorporating rubber into metal bars and auxiliary devices has been explored (*Zi et al., 2016; Li et al., 2022*). On the basis of the analysis of the state of motion of potatoes and soil on the separating device, the mechanism of the separation process was understood and the separation devices were improved (*Xin et al., 2023; Nalobina et al., 2021*). Additionally, modifying the movement pattern of the bars by implementing a dual separation approach combining vibration and waveform has been shown to enhance potato-soil separation and minimize losses (*Zhong et al., 2020; Wei et al., 2019*). A curved bar design and a curved-straight bar exchange configuration have been developed to enhance potato-soil separation, improving effectiveness and reducing clogging. However, there has been limited research on how changing the shape of the bar affects separation efficiency, and there is currently no detailed theory regarding the optimal shape and mounting configuration of the curved bar (*Lv et al., 2015; Xing et al., 2024; Zhong et al., 2023; Ji et al., 2022*). Due to the scarcity of harvesters suited for sticky soils in southern regions (*Ji et al., 2022; Lv et al., 2017; Bei et al., 2021*), this paper focuses on optimizing the structural parameters and assembly methods of concave bars. Simulation models of potato-soil mixtures were developed to theoretically analyze the separation process. Key factors such as the angle of the concave side, width of the concave, and installation angle were studied. Orthogonal tests were conducted to evaluate separation efficiency and maximize potato recovery. The results confirmed the rationality and feasibility of the concave-bar potato-soil separation device.

Structure and theoretical analysis

Structure of the whole machine

In this paper, a potato-soil separation device is designed specifically for the sticky soils prevalent in southern regions. Due to the high soil adhesion characteristics, a lift chain separator was selected as the model for this study. The lifting chain potato-soil separation device is a critical component of a potato harvester, consisting of a frame, digging shovel, gearbox, transmission system, separation device, and vibration unit. It is known for its stable conveying performance, effective separation when paired with a vibration unit, straightforward structure, and strong adaptability. According to agricultural machinery design manuals, the length of the initial separation device typically ranges from 1.2 to 1.5 meters, with the inclination angle of the plane formed by the chain bar between 22° and 34°. In this study, a 30° angle was chosen to address the significant adhesion issues associated with southern sticky soil (*Wei et al., 2018*). To enhance the crushing and splitting of the potato-soil mixture, increasing the amplitude of vibration by adjusting the vibration unit could be considered. However, this approach might lead to increased damage to the potatoes (*Jin et al., 2020; Xie et al., 2020*). To address this issue, this paper proposes the use of concave bars. These bars are designed to induce fractures in the potato-soil mixture through an unbalanced force within a groove-like space, facilitating the crushing and separation of the mixture during the transfer process of the separation device. The structure of the entire machine is illustrated in Fig. 1.

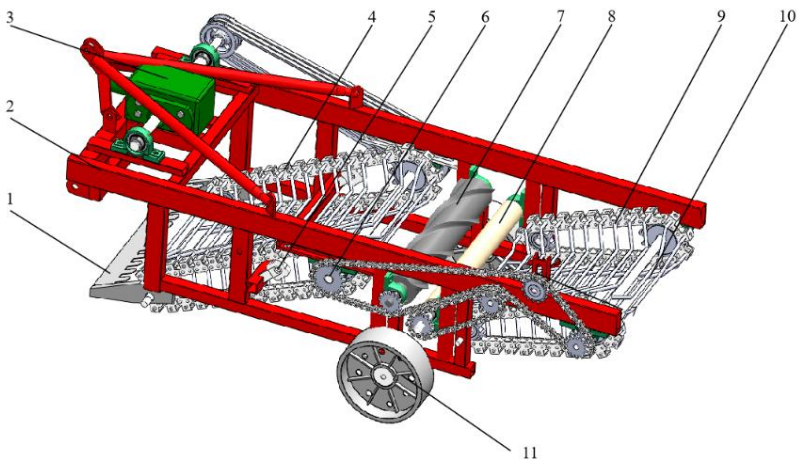

Fig. 1 - Structure of potato harvester in the form of concave bar

1- Digging shovel; 2 - Frame; 3 - Gearbox; 4- First separation device; 5 - Vibration unit; 6- Transmission system; 7- Cleaning roller; 8- Smooth roller; 9- Second separation device; 10- Concave bar 11- Walking wheel

The process of potato-soil separation can be summarized as follows: The tractor tows the potato harvester, which excavates the soil-potato mixture using the digging shovel. This mixture then enters the separation device. Within the device, the mixture is subjected to unbalanced forces in the grooves of the bars, causing it to break apart. The vibration unit generates impact collisions that help to overcome the adhesive forces between soil particles. This causes the internal structure of the soil to break down into smaller masses and particles. The separation device's design ensures that the broken soil and potatoes are separated, with the soil and potatoes falling to the ground through the gaps in the bars. Essentially, the process of crushing the soil transforms it from a continuous medium model into a discrete medium model, allowing for more efficient separation of soil and potatoes.

Theoretical analysis of potato transport process

Potatoes are cultivated in sticky soil environments, resulting in a lumpy potato-soil mixture when harvested by digging shovels. Separating this mixture efficiently using a straight-bar lifting chain proves challenging. To address this, the paper presents an optimized design featuring downward concave chain bars. As illustrated in Figure 2, the bars and their cross-sections were subjected to mechanical analysis to enhance the separation process.

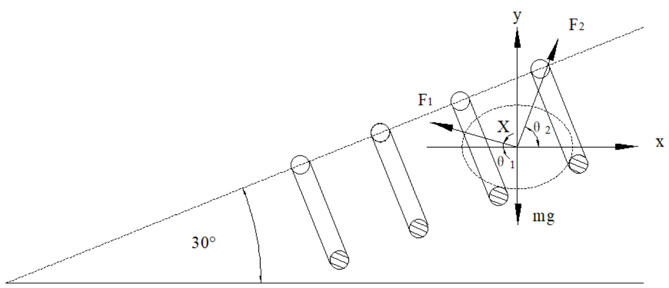

Fig. 2 - Mechanical analysis of potato

A coordinate system is established where the positive x-axis is directed opposite to the machine's forward direction, and the positive y-axis is oriented opposite to the direction of gravity. The equilibrium equation can then be derived based on this coordinate system, as follows:

$$F_1 \sin\theta_1 + F_2 \sin\theta_2 - mg = 0 \tag{1}$$

$$F_2 \cos\theta_2 - F_1 \cos\theta_1 = 0 \tag{2}$$

The simplification is as follows:

$$F_1 = \frac{mg\cos\theta_2}{\sin(\theta_1+\theta_2)} \tag{3}$$

$$F_2 = \frac{mg\cos\theta_1}{\sin(\theta_1+\theta_2)} \tag{4}$$

where:

F_1 is force of support of the front one bar on the potato, [N]; F_2 is force of support of the back one bar on the potato, [N]; θ_1 is angle between F_1 and the horizontal plane, [°]; θ_2 is angle between F_2 and the horizontal plane, [°]; mg is gravity of potato.

When the horizontal combined force on the potato is aligned with the positive x-axis, the potato will remain stable and not flow back during transportation. This stability is calculated as follows:

$$\sum F_x = F_2 \cos\theta_2 - F_1 \cos\theta_1 \geq 0 \quad (5)$$

Theoretical analysis of soil transport process

Large chunks of the potato-soil mixture are picked up by the digging shovels and conveyed to the concave bar. Due to varying coefficients of kinetic friction between the soil and potatoes against the bar, as well as the uneven forces exerted by the large soil lumps in the bar's grooves, the separation device can break and fragment. This results in the soil breaking into several particles and smaller lumps. When the mixture falls and collides with the bars, it generates significant and variable inertial forces. These forces can cause soil particles to fall through gaps in the bar and small soil pieces to break further. The sticky soil lump is idealized as a rectangular body for theoretical analysis. When a bar strikes this soil block, the instantaneous inertial force is much greater than the inertial force due to bar vibrations. Assuming the acceleration a perpendicular to the plane of the bar is the acceleration of the soil block, Figure 3 illustrates that to effectively crush the soil block, the crushing moment must exceed the moment of the internal forces' adsorption. The moment equation at point Q is given as follows:

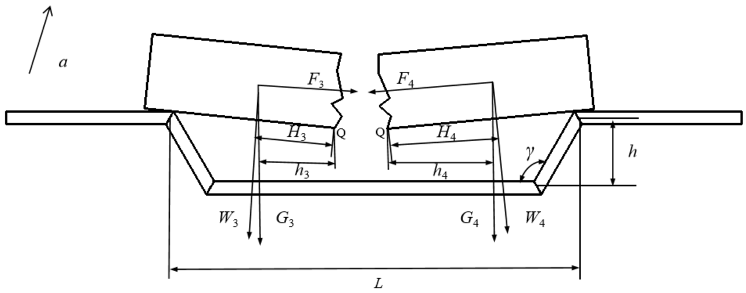

Fig. 3 - Mechanical analysis of soil

$$\begin{cases} G_3 h_3 + W_3 H_3 > F_3 H \\ G_4 h_4 + W_4 H_4 > F_4 H \end{cases} \quad (6)$$

where: G_3 and G_4 is gravity of the soil block, [N]; W_3 and W_4 is inertial force of the soil block, [N]; h_3 and h_4 is vertical distance of the gravitational force on the soil block to point Q, [mm]; H_3 and H_4 is vertical distance from the inertial force on the soil block to point Q, [mm]; L is width for concave bar, [mm]; h is depth for concave bars, [mm]; γ is angle of the concave side, [mm]; F_3 and F_4 is cohesion of the soil block, [N].

The magnitude of the inertial forces W_3 and W_4 of the soil block are specified as follows:

$$\begin{cases} W_3 = -m_3 a \\ W_4 = -m_4 a \end{cases} \quad (7)$$

Bringing equations (6) and (13) into equation (12), as follows:

$$\begin{cases} 2A\pi^2 m_3 f^2 \cos(2\pi f t + a) h_3 + m_3 g H_3 > F_3 H \\ 2A\pi^2 m_4 f^2 \cos(2\pi f t + a) h_4 + m_4 g H_4 > F_4 H \end{cases} \quad (8)$$

It is the moment equation for crushing, as follows:

$$M_0 = 2A\pi^2 m_i f^2 \cos(2\pi f t + a) h_i + m_i g H_i \quad (9)$$

From the equation, the crushing capacity of the separation device is proportional to the square of the amplitude and frequency generated by the vibration unit.

Assuming that the height of the soil block is $2H$ and its length is L, it follows from the geometric relationship that:

$$\begin{cases} H = \dfrac{h}{2} \\ H_3 = H_4 = \dfrac{L}{4} \\ h_3 = h_4 = \cos(\gamma - \dfrac{\pi}{2}) h \end{cases} \quad (10)$$

Soil brokenness is directly proportional to soil strength, and adhesion is the main factor. The cohesion of the soil is as follows

$$F = c \cdot S \tag{11}$$

where:

c is soil bonding strength, [kPa]; S is area of soil breaks, [cm^2].

The quality of the soil is as follows:

$$m = \mu \cdot V \tag{12}$$

where:

μ is soil capacity, [g/cm^3]; V is volume of the soil block, [cm^2].

Bringing Eqs. (19), (20) and (21) into Eqs. (16) and (17). When the function of acceleration goes to the maximum, the maximum crushing moment generated by the separation device is as follows:

$$2A\pi^2\mu\frac{hL^2}{4}f^2\cos(2\pi ft+a)\cos(\gamma-\frac{\pi}{2})h+\mu\frac{hL^3}{16}g > c\cdot\frac{Lh^2}{8} \tag{13}$$

The inertia force distance indeed plays a crucial role in breaking the soil block, as it generates the dominant moment needed to overcome the block's resistance. When the block breaks, its displacement aligns with both the inertial force direction and the internal bonding force direction. The relationship between the concave's width, depth, and angle, and the crushing moment is positively correlated. This correlation implies that as these dimensions increase, the moment required for soil crushing also increases. Additionally, the energy required to break the soil block depends on its cohesive forces, which are significantly influenced by the soil's moisture content. More moisture typically reduces soil cohesion, making the soil block easier to break.

MATERIALS AND METHODS

Simulation model of potato

The study of potato, soil, and bar interactions, especially using Discrete Element Method (DEM), provides valuable insights. Potatoes and soil lumps have distinct mechanical properties: soil lumps exhibit excitation and depolymerization, while bars, particularly chain bars, show rigidity (*Zhong et al., 2020*). Analyzing how these properties affect collisions and fragmentation on concave bars helps understanding how different bar parameters influence the behavior of potato-soil mixtures. This can be critical for optimizing processes in agricultural and industrial applications.

Given the extensive variety of potato shapes, the study simplified the model by representing potatoes as multisphere aggregates. This approach facilitated the analysis by approximating the complex geometry of potatoes with a more manageable and computationally efficient model, as shown in figure 4.

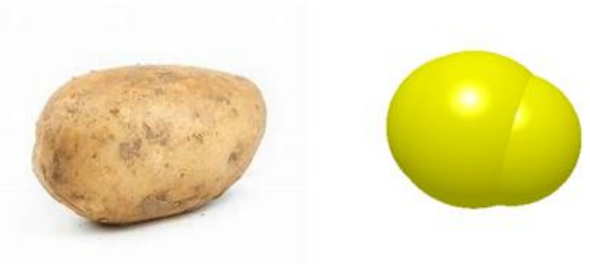

Fig. 4 - EDEM models of potato

For the study of potato triaxial minimum thickness dimensions, the potato model was configured with triaxial dimensions of 62 mm × 52 mm × 52 mm. The model generation time in the 'Particle Factory' software was set to 0.5 seconds, with a total of 20 models created. Potatoes and soils were distributed based on data from actual potato harvests. A monolayer distribution method was employed, wherein potatoes were randomly dropped onto a subsoil layer. Simulation parameters are detailed in Table 1 (*Zhong et al., 2020; Wen et al., 2018*).

Table 1

Simulation parameter of potato

Parameter	Numerical value
Poisson's ratio of potato	0. 5
Shear modulus of potato/ MPa	1.3
Density of potato	1100

Parameter	Numerical value
Potato-potato restitution coefficient	0.97
Potato-potato static friction coefficient	0.5
Potato-potato rolling friction coefficient	0.02

Simulation model of soil

Considering the characteristics of southern sticky soils, this paper employs the cohesive particle model, specifically the 'Hertz-Mindlin with Bonding V2' contact model, which incorporates bonding between soil particles. Soil particles in southern regions are noted for their high cohesion. When the particle radius is defined, the bonding radius of wet particles can be determined from the material density and moisture content using the formula for the contact radius of soil particles, as follows:

$$w_c = \frac{m_2}{m_1 + m_2} = \frac{\rho_2 v_2}{\rho_1 v_1 + \rho_2 v_2} \tag{14}$$

where:

w_c is soil moisture content, [%]; m_1 is quality of soil particles, [kg]; m_2 is quality of water, [kg]; ρ_1 is density of soil, [kg/m^3]; ρ_2 is density of water, [kg/m^3]; v_1 is volume of soil particles, [m^3]; v_2 is volume of water, [m^3].

For reference, the radius of soil particles is usually set to 3 mm. Based on actual tests, the moisture content of southern sticky soils is 26%. The contact radius of soil particles could be calculated as 3.75 mm. The simulation parameters are shown in Table 2 (*Zhong et al., 2020; Xie et al., 2020*).

Table 2

Simulation parameter of soil

Parameter	Numerical value
Poisson's ratio of potato	0. 5
Shear modulus of potato / MPa	1.3
Density of potato / kg/m^3	1100
Potato-potato restitution coefficient	0.97
Potato-potato static friction coefficient	0.5
Potato-potato rolling friction coefficient	0.02

Simulation model of separation device

To streamline the simulation process, this study disregards the effects of seedlings and vines on soil fragmentation and the movement characteristics of potato pieces. Additionally, air resistance during the falling process after material ejection is omitted. Components such as bars and other parts of the machine were constructed from 65Mn steel. Figure 5 illustrates the simulation model of the potato harvester, which features concave bars.

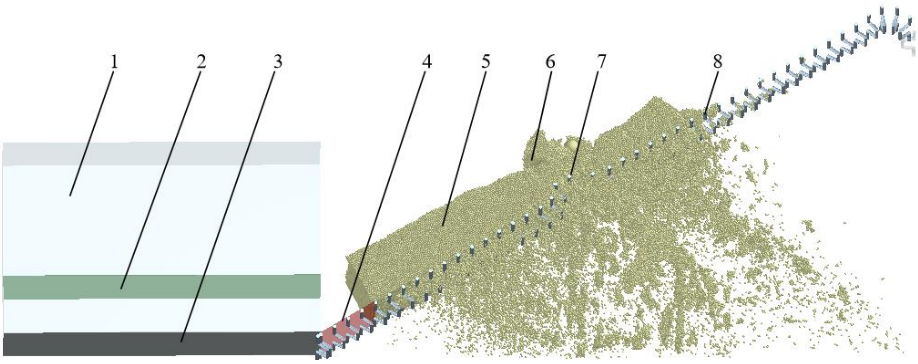

Fig. 5 - Simulation model

1- Factory; 2 - Plates for compacted soil; 3 - Conveyor belt model; 4- . Digging shovel; 5 - Soil; 6- Potato; 7- Vibration device; 8- Concave bar

Table 3 shows the soil and bar simulation parameters. The main parameters of the simulation are shown in Table 4 (*Zhong et al., 2020; Xie et al., 2020; Li et al., 2022*).

Table 3

Simulation parameters of separation device

Parameter	Numerical value
Potato-soil restitution coefficient	0.06
Potato-soil static friction coefficient	0.5
Potato-soil rolling friction coefficient	0.01
Potato-bar restitution coefficient	0. 5
Potato-bar static friction coefficient	0.4
Potato-bar rolling friction coefficient	0.1
Soil-soil of normal stiffness per unit area / ($N \cdot m^{-1}$)	1.4 × 10
Soil-soil the maximum normal strength / MPa	0. 235
Soil-soil of shear stiffness per unit area / ($N \cdot m^{-1}$)	1×10^6
Soil-soil the maximum shear strength/ (MPa)	0. 186
Poisson' s ratio of bar	0. 3
Shear modulus of bar/ (MPa)	3.1×10^5
Density of bar / ($kg \cdot m^{-3}$)	7800
Soil-bar restitution coefficient	0.16
Soil-bar static friction coefficient	0.6
Soil-bar rolling friction coefficient	0.35

Table 4

Main parameters

Parameter	Numerical value
Diameter of the bar / (mm)	11
Length of the bar / (mm)	630
Velocity of the bar / (m/s)	1.7
Distance between the centers of adjacent bars / (mm)	50
Time interval between movements of adjacent bars / (s)	0.02941
Angular velocity of the bar / (rad/s)	20.98765
Vibration frequency / (Hz)	5

A 630 mm × 1000 mm × 600 mm 'Factory' was constructed to characterize the potato-soil mixture. Within this 'Factory,' the potato factory and two soil particle factories were established. To accurately simulate the harvesting environment, the subsoil generation began at 0 seconds, with a total of 600,000 generations. The subsoil was fully generated before the creation of the potatoes. Following the completion of the topsoil layer, which involved generating 130,000 particles, the soil was compacted at 0.8 seconds, resulting in a 180 mm 'soil-potato-soil' mixture. To simulate the forward movement of the harvester, a 'moving plane' model was integrated into the floor and front settings of the 'Factory.' During the potato-soil separation process, soil clumps adhered to each other and collided with the concave chain bar, causing them to crush and disperse the potato-soil mixture throughout transportation.

Factors of orthogonal experiment

Based on research and practical production experience (*Jun, 2010*), Figure 6 illustrates the factors coded A, B, C, and D, which correspond to the angle of the concave side, the width of the concave, the depth of the concave, and the angle of installation, respectively. Table 5 presents the orthogonal experiment design, with separation efficiency and maximum force on potatoes used as evaluation indices.

Table 5

Coding with factors and levels

Level	Factor			
	A Angle of the concave side /°	B Width of concave /mm	C Depth of concave /mm	D Angle of installation/°
1	90	250	12	-30
2	120	350	36	0
3	150	450	60	30

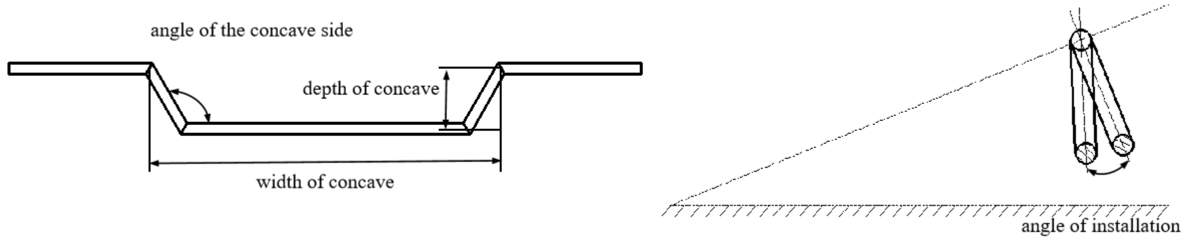

Fig. 5 - Schematic diagram of factors

Methodology for testing evaluation indicators

Separation efficiency is evaluated by collecting data from the 'particle factory' and from the position where the bar reaches its end. A mass sensor is set up at the end of the separation device to measure the soil mass. The separation efficiency is then calculated using the following formula:

$$E=1-\frac{M_r}{M_t} \tag{15}$$

where:

E is separation efficiency, [%]; M_r is remaining mass of soil at the end of the separation device, [kg]; M_t is total mass of soil after completion of soil generation in the “Factory”, [kg].

The method for determining the maximum force on the potato involves using a 'Grid Bin Group' to measure the force exerted on potatoes within the separation plane. Subsequently, 'Manual Selection' is employed to calibrate and measure the force on 20 individual potatoes, with data exported for analysis. The recorded 'Compressive Force' represents the maximum force applied to each potato. Observations of the potato-soil mixture on the sieving device revealed that potato movement was most active between 2.5 and 4 seconds, with the highest collision frequency during this interval. Assuming that collisions occur in the same area on the potato block within this period, the forces on the 20 potatoes are summed separately for this time frame, and the maximum value is selected. This maximum value is used to assess the force applied to the potato under these conditions and determine potential damage. According to potato damage experiments, a force greater than 200 N on the potato surface is likely to cause damage (*Wei et al., 2023; Li and Ji, 2022*). Thus, a threshold of 200 N is used to evaluate whether the potato has been damaged.

RESULTS

Concave vs. straight bars

Simulation experiments used EDEM's “Hertz Mindlin with bonding” contact model as a model for soil particle bonding. The “Grid Bin Group” was set to count the number of bond keys, and the data was exported as Figure 7.

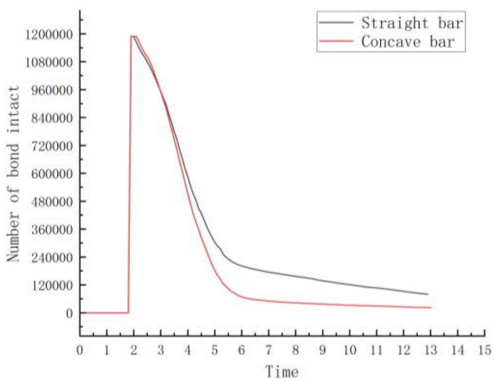

Fig. 7 - Bond Number of bond connections

From the figure, it is evident that after soil formation was completed at 1.8 seconds, bond connections between soil particles began to form. During transportation on the separation device, these soil clumps were broken apart, reducing the bond connections between particles. Over time, the rate at which these bonds decreased was more pronounced on separation devices with concave bars compared to those with straight bars. This observation indicates that the crushing capacity of concave bars is superior to that of straight bars.

Experimental results and analysis

Table 6 presents an analysis of variance (ANOVA) performed on the results of the orthogonal experiments to examine the impact of four factors—angle of the concave side bar, width of the concave, depth of the concave, and angle of installation—on separation efficiency and maximum force on the potato. Since factor A had the least effect on both indicators, it was used as the control group in the ANOVA.

Table 6

Results of orthogonal experiment and range analysis

Indicator	Serial number	Factor				Results	
		A	B	C	D	Separation efficiency (%)	Maximum force on potatoes (N)
	1	1	1	1	1	61.2	34.991
	2	1	2	2	2	72.0	41.694
	3	1	3	3	3	77.5	33.134
	4	2	1	2	3	74.9	42.125
	5	2	2	3	1	68.7	33.546
	6	2	3	1	2	73.3	33.681
	7	3	1	3	2	73.6	35.420
	8	3	2	1	3	77.0	45.674
	9	3	3	2	1	67.8	30.927
Separation efficiency (%)	K_1	210.7	209.7	211.5	197.7		
	K_2	217.0	217.6	214.7	218.9		
	K_3	218.3	218.6	219.8	229.4		
	k_1	70.2	69.9	70.5	65.9		
	k_2	72.3	72.5	71.6	73.0		
	k_3	72.8	72.9	73.3	76.5		
	R	2.5	3.0	2.8	10.6		
	Sequence	4	2	3	1		
Maximum force on potatoes (N)	K_1	109.819	112.536	114.346	99.464		
	K_2	109.351	120.914	114.745	110.794		
	K_3	112.021	97.742	102.100	120.933		
	k_1	36.606	37.512	38.115	33.155		
	k_2	36.450	40.305	38.248	36.931		
	k_3	37.340	32.581	34.033	40.311		
	R	0.890	7.724	4.215	7.156		
	Sequence	4	1	3	2		

Table 7

Results of variance analysis

Indicator	Origin	Sum of squared deviations	Mean square	F-value	P-value
Separation efficiency (%)	width of concave	0.002	< 0.001	1.444	0.409
	depth of concave	0.001	< 0.001	1.080	0.481
	angle of installation	0.017	0.009	15.903	0.059
Maximum force on potatoes (N)	width of concave	91.777	45.889	67.713	0.015
	depth of concave	34.445	17.223	25.414	0.038
	angle of installation	76.895	38.447	56.733	0.017

Table 7 indicates that the factors had weakly significant effects on separation efficiency. Due to the orthogonal design, there was no correlation between factors, resulting in a large p-value for the non-significant factor C. Table 8 presents the revised ANOVA obtained by excluding factor C. This is because the sum of squared deviations for the remaining factors remains constant when one factor is removed. The results revealed that the angle of installation was significant ($p < 0.05$), indicating that it has a substantial effect on the screening efficiency of potato-soil mixtures. Polar analysis showed that the factors affecting separation efficiency are ranked as follows: D > B > C > A. The installation angle has the most significant impact on efficiency, while the angle of the concave side bar has the least. The optimal parameters for achieving the best separation efficiency are a 150° angle for the concave side bar, a concave width of 450 mm, a concave depth of 60 mm, and an installation angle of 30°.

Table 8 revealed that the width of the concave, the depth of the concave, and the angle of installation all had significant effects ($p < 0.05$) on the maximum force exerted on potatoes. The data from polar analysis showed that the factors influencing the maximum force are ranked as follows: B > D > C > A. The width of the concave bar had the greatest impact, while the angle of the concave side bar had the least influence. Thus, the optimal parameters for minimizing the maximum force on potatoes are a 120° angle for the concave side bar, a concave width of 450 mm, a concave depth of 60 mm, and an installation angle of -30°.

Table 8

Consolidated results of variance analysis

Indicator	Origin	Sum of squared deviations	Mean square	F-value	P-value
Separation efficiency (%)	width of concave	0.002	< 0.001	1.389	0.348
	angle of installation	0.017	0.009	15.290	0.013*
Maximum force on potatoes (N)	width of concave	91.777	45.889	67.713	0.015*
	depth of concave	34.445	17.223	25.414	0.038*
	angle of installation	76.895	38.447	56.733	0.017*

Table 9 indicated that two sets of parameter schemes were simulated to determine the optimal combination. The results showed that with an angle of 150° for the concave side bar, a concave width of 450 mm, a concave depth of 60 mm, and an installation angle of 30°, the separation efficiency reached 79.7%. Additionally, the maximum force on the potatoes did not exceed 200 N in both combinations, ensuring that the potatoes remained undamaged.

Table 9

Simulation results with optimal parameters

Composition	Separation efficiency [%]	Maximum force on potatoes [N]
$A_3B_3C_3$ D_3	79.7	35.218
$A_2B_3C_3$ D_1	77.9	32.787

Field experiment

The field experiment utilized a towed harvester with bars set to a 150° angle for the concave side bar, a concave width of 450 mm, a depth of 60 mm, and an installation angle of 30°. Conducted at Yingchang Agricultural Machinery Cooperative in Liuyang City, China, the potatoes (Jiaxing 2 variety) were grown in row crops with a soil moisture content of 22.4%. The loss rate, damage rate and potato epidermal injury rate were measured in the field experiment are. The detailed measure methods are as follows:

Lost potatoes are buried potatoes and non-dug potatoes. The loss rate was calculated as follows:

$$T_1 = \frac{W_1 + W_2}{W} \times 100\% \tag{16}$$

where: T_1 is lost rate, [%]; W_1 is mass of buried potatoes, [kg]; W_2 is mass of non-dug potatoes, [kg]; W is total mass of potatoes, [kg].

Damaged potatoes are the damaged part of all potatoes. The damage rate was calculated as follows:

$$T_2 = \frac{W_3}{W} \times 100\% \tag{17}$$

where: T_2 is damage rate, [%]; W_3 is mass of damaged potatoes, [kg].

Potatoes of epidermal injury are the part of all potatoes with broken skin. The potato epidermal injury rate is calculated as follows:

$$T_3 = \frac{W_4}{W} \times 100\% \tag{18}$$

where:

T_3 is potato epidermal injury rate, [%]; W_4 is mass of potatoes of epidermal injury, [kg].

Figure 8 illustrates the results of the field harvesting experiment, and Table 10 presents the data. The results showed that the damage rate was 1.58% and the potato epidermal injury rate was 1.03%, and the loss rate was 2.87%, which met the standard requirements (NY/T 648-2015).


Fig. 8 - Field harvest experiment and results

Table 10

Results of field tests

Groups	Mass of damage potato [kg]	Mass of potato epidermal injury [kg]	Mass of loss potato [kg]	Total mass [kg]	Damage rate [%]	Potato epidermal injury rate [%]	Loss rate [%]
1	0.12	0.09	0.27	8.75	1.37	1.03	3.09
2	0.19	0.1	0.25	9.18	2.07	1.09	2.72
3	0.15	0.08	0.32	9.07	1.65	0.88	3.53
4	0.11	0.1	0.19	8.85	1.24	1.13	2.15
Average					1.58	1.03	2.87
Standard requirements					≤2	≤3	≤4

CONCLUSIONS

Due to the high soil moisture content prevalent in southern potato cultivation environments, separating potatoes from the soil during harvesting presents significant challenges. To address this issue, a concave lifting chain device was employed, and the structural parameters of the concave chain bars were optimized. The results of this approach are summarized as follows:

(1) A potato-soil mixture model was developed using EDEM software. A simulation model of a concave bar-type potato-soil separation device was constructed to investigate the effects of various structural parameters on the separation process. The influence of these parameters on the potato-soil separation was elucidated through theoretical analysis.

(2) A comparative simulation experiment was conducted using both the concave bar-type and straight bar models for potato-soil separation. The number of bonds in the soil model was quantified for each model. The analysis of the results indicated that the soil-breaking capacity of the concave bar-type separation device was superior to that of the straight bar model.

(3) Orthogonal simulation experiments were conducted to identify the optimal parameter combinations for the concave bar potato-soil separation device through comprehensive analysis. The field experiment, conducted under the conditions of a 150° angle for the concave side bar, a concave width of 450 mm, a concave depth of 60 mm, and an installation inclination angle of 30°, demonstrated that the relevant test indices met national standards.

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