

Article

Design and Experiment of Toggle Lever-Type Potato Picker

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Abstract: To address the issues of significant soil blockage and high potato damage rates in current potato picking machines, this study developed a toggle lever-type potato picker designed to minimize potato damage and improve operational efficiency. Design calculations were performed for the picker components, and kinematic analyses were conducted for the toggle lever. Single-factor experiments were carried out to determine the variation in performance parameters of the potato picker under different experimental conditions. Discrete element simulations were performed to measure the peak soil height before the pick-up shovel and the peak force on potatoes during the pick-up process. A Box–Behnken response surface experiment was conducted using toggle lever speed, machine forward speed, and shovel angle as experiments factors. Subsequently, an analysis of variance was performed, and a mathematical regression model was established based on the experiments results. The findings revealed that at a toggle lever speed of 50 r/min, machine forward speed of 0.9 m/s, and shovel angle of 19°; the potato leakage rate was 2.32%, and the potato damage rate was 2.72%, thereby meeting the requirements stipulated by potato mechanized picking technology regulations.

Keywords: agricultural machinery; pick-up device; discrete element; EDEM; response surface



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1. Introduction

Potatoes are globally recognized as a vital food crop, with extensive planting areas and high production volumes. In 2015, China officially recognized potatoes as the fourth major staple food, following rice, wheat, and corn, at the “Symposium on the Development Strategy of Potatoes as Staple Food” [1–3]. According to 2021 statistics, China’s potato-planting area exceeded 4.63 million hectares, yielding over 90 million tons, which accounts for approximately one-fourth of the world’s total potato planting area and production [4,5]. The continuous expansion of potato planting areas and the gradual increase in production have made the level of mechanized potato picking a crucial factor influencing both yield and quality [6–8]. Currently, potato-picking methods in China primarily include segmented picking and combined picking techniques [9]. Due to China’s unique agronomic and geographical factors, segmented picking remains predominant in most regions. After excavation by potato diggers, the potatoes are spread on the ground and then manually picked and bagged [10], a labor-intensive and inefficient process that does not meet the demands of the potato industry. Therefore, there is a pressing need to develop machinery for potato picking.

Liu [11] integrated an active potato lifting device into the traditional shovel-type picker, effectively mixing the soil–potato mixture and resolving soil accumulation issues during the picking process. However, the interaction force between the lifting blades and the potatoes often resulted in potato skin damage, and changing the blade material did not fundamentally resolve this issue. Fan [12] developed a tine-type potato picker capable of completing the picking process, but it encountered issues with missed picks and potato damage. Shi’s [13] disc grid-type potato picking solution demonstrated high efficiency and achieved the desired picking goals, but it also tended to cause potato skin

damage. Yang [14] designed the 4UJ-1400 potato picker, using a forced pushing device to address missed picking issues. Despite its effective soil removal, the picker exhibited low efficiency. Jia et al. [15] developed a track-type self-sorting potato harvester that integrated self-propelling technology, automatic digging and sorting technology, and manual auxiliary sorting. However, it still faced challenges with missed picks and potato damage, and had not yet been widely adopted. Xiao et al. [16] designed a small potato picking and grading harvester incorporating a roller-type secondary grading device to facilitate picking, grading, and combined collection of potato blocks. However, the grading levels did not meet actual requirements, and the picking efficiency remained low.

In conclusion, as demonstrated by the preceding analysis, the structure and performance of the picker directly influence the overall efficiency of the potato picking machine. Therefore, to address the issues of pre-spade congestion and potato build-up in traditional spade-type potato pickers, this paper proposes the design of a new type of potato picker featuring a toggle lever. This design aims to ensure a low potato leakage rate and potato damage rate while enhancing the overall operational efficiency of the picker. Leveraging the new design, a combination of single-factor performance experiments, discrete element simulations, and field experiments is utilized to investigate the variation patterns of performance indicators of the picker with changes in operating parameters. The study analyzes the underlying reasons for these variation patterns and identifies the optimal parameter settings for the new picker. The research findings provide a theoretical basis and technical support for the development of potato picking machinery and equipment.

2. Materials and Methods

2.1. Overall Structure and Working Principle of the Toggle Lever-Type Potato Picker

The overall structure of the toggle lever-type potato picker is illustrated in Figure 1. The machine primarily consists of a picking shovel, guiding roller, toggle wheel, suspension device, chain drive mechanism, and hydraulic system. The hydraulic system comprises a hydraulic motor and hydraulic oil pipes.

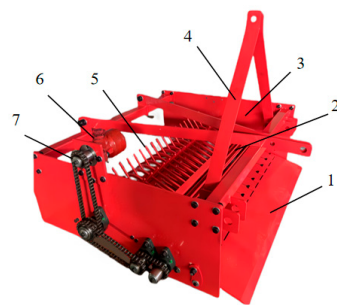


Figure 1. Overall Structure of the potato picker: (1) picking shovel; (2) guiding roller; (3) side plate; (4) suspension device; (5) toggle wheel; (6) hydraulic motor; (7) chain drive mechanism.

During operation, the hydraulic pump on the tractor drives the hydraulic motor, which transmits power to the toggle wheel and guides roller through the chain drive mechanism. As the machine operates, the picking shovel lifts the soil–potato mixture from the ground. Under the influence of the guiding roller, the soil–potato mixture moves backward. Finally, the toggle levers on the toggle wheel rotate and lift the potatoes, smoothly transitioning them to subsequent devices. Soil falls to the ground through the gaps between the toggle levers and the sieve bars, achieving soil separation.

2.2. Design of Key Components and Determination of Parameters

2.2.1. Transmission Design and Selection of Hydraulic Motor

For the power transmission of the picker, a single-row chain drive system is designed, comprising three drive systems (Figure 2). The primary drive comprises hydraulic oil pipes, hydraulic motor, primary sprocket, and toggle wheel sprocket; the secondary drive

includes the toggle wheel sprocket and guiding roller sprocket; and the tertiary drive involves the guiding roller sprockets. Power is transmitted from the hydraulic pump to the hydraulic motor, driving the primary drive system. It then transfers to the secondary drive system via the toggle wheel sprocket and finally to the tertiary drive system through the guiding roller sprocket, completing the power transmission of the entire machine.

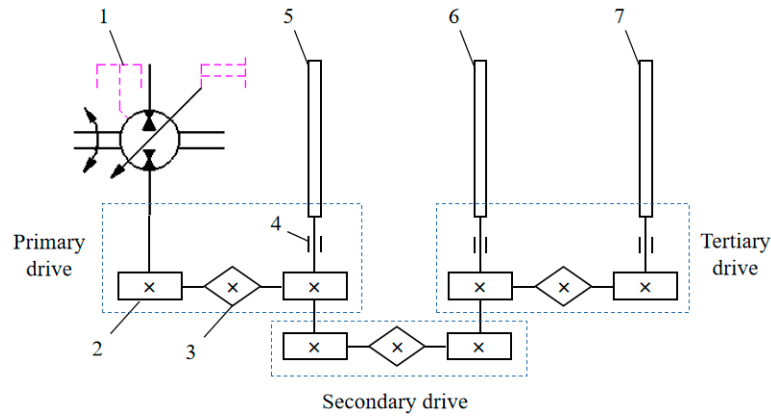


Figure 2. Schematic diagram of the transmission system: (1) hydraulic pump and hydraulic motor; (2) primary sprocket; (3) chain transmission; (4) transmission shaft; (5) toggle wheel; (6) and (7) guiding rollers.

The operating environment and conditions of the potato picker are complex and confined, requiring a hydraulic motor that is small, lightweight, has high output torque, and excellent stability. Consequently, the BMP series orbital hydraulic motor was selected as the power input device for the picker. This internal meshing orbital hydraulic motor features a low-speed, high-torque design, offering advantages such as a simple and compact structure, good starting characteristics, easy reversal, and smooth speed regulation. It effectively meets the complex operating conditions of the potato picker.

The equation for calculating the displacement of a hydraulic motor is:

$$V_t = \frac{2\pi T_t}{\Delta p \eta_m} \tag{1}$$

In the equation: V_t is displacement of hydraulic motor displacement, mL/r; T_t is maximum torque of the hydraulic motor, N·m; Δp is pressure difference between the inlet and outlet of the hydraulic motor, Mpa; η_m is mechanical efficiency of the hydraulic motor.

Referring to the working pressures of various commonly used mechanical equipment systems (Table 1), the working pressure of the hydraulic system for the picker is determined to be 16 MPa. The hydraulic motor’s maximum torque is 150 N·m, with a mechanical efficiency of 0.95. Substituting these values into Equation (1) yields a calculated displacement of the hydraulic motor as 62 mL/r. To ensure system operational stability, the displacement is set to $V_t = 80$ mL/r. According to the design requirements of the picker, the maximum output speed of the motor should not exceed 100 r/min. Consequently, the BMP-80 SA1P1Y5 hydraulic motor is selected.

Table 1. Table of Working Pressure of Common Mechanical Equipment Systems.

The Type of Mechanical Equipment	Precision Machining Machine	Semi-Precision Machining Machine	Rough Machining Machine Tool, Heavy-Duty Machine Tool	Agricultural Machinery	Hydraulic Press, Heavy Machinery, Medium to Large-Sized Excavator
Working pressure (Mpa)	0.8~2	3~5	5~10	10~16	20~32

2.2.2. Picking Shovel

The shovel angle is a crucial parameter [17,18] that influences both the depth of soil penetration during picking and the resistance encountered by the machine during operation. A suitable shovel angle ensures an optimal amount of soil–potato mixture enters the picker, thereby minimizing potato damage while enhancing picking efficiency. As depicted in Figure 3, the soil becomes loose after excavation by the potato digger, resulting in varied distribution of potatoes on the surface. Potatoes exposed on the surface after digging are termed “visible potatoes,” while those partially or entirely buried in the ground, primarily at a depth of 30–50 mm below the surface, are referred to as “hidden potatoes”.

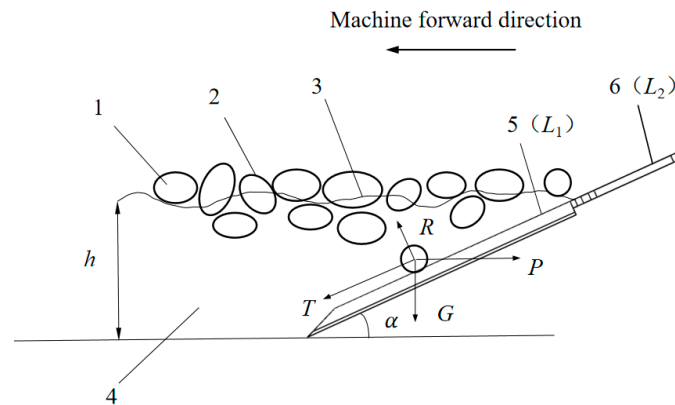


Figure 3. Force Analysis of the picking shovel: (1) visible potatoes; (2) hidden potatoes; (3) surface; (4) soil; (5) picking shovel; (6) transition plate.

When determining the soil penetration depth for the picking shovel, it is crucial to ensure the retrieval of both visible and hidden potatoes to prevent missed potatoes and reduce picking losses. Simultaneously, it is imperative to avoid excessively deep penetration, as it can cause soil congestion and accelerated wear of the picking shovel. Considering the above analysis and relevant literature [19], the soil penetration depth for the picking shovel should be maintained between 50 and 100 mm, with provisions for adjustable depth control.

The force conditions of potatoes during the picking process are shown in Figure 3. Based on these force conditions, the following relationship can be established:

$$\begin{cases} P \cos \alpha - T - G \sin \alpha = 0 \\ R - G \cos \alpha - P \sin \alpha = 0 \end{cases} \quad (2)$$

In the equation: P is the thrust of the soil–potato mixture on the potatoes, N; R is the supporting force of the picking shovel on the potatoes, N; G is the gravity acting of the potatoes, N; α is the angle of picking shovel, °; T is the frictional force of the potatoes, N.

Based on the above equations, the equation for calculating the shovel angle can be derived as follows (Equation (3)):

$$\alpha = \arctg \frac{P - \mu G}{\mu P + G} \quad (3)$$

After analyzing and calculating Equations (2) and (3) based on the expected functional requirements of the picking shovel, the optimal angle is determined to range between 17° and 23°. This range ensures smooth potato picking, minimizes potato damage, and prevents issues such as excessive picking resistance caused by an overly large shovel angle.

To facilitate the optimization of the shovel angle, this design establishes an adjustable range from 15° to 23°. The adjustment mechanism for the shovel angle is depicted in Figure 4. A fixed plate with grooves and three small holes, each welded to a nut, is provided. The fixed plate is attached to the exterior of the picker’s side plate and aligns

with the grooves on the side plate. Bolts pass through the welded nuts to secure both the side plate and the fixed plate. To adjust the shovel angle, the fastening bolts on the fixed plate must be loosened, allowing the entire shovel assembly to rotate around the axis. After adjusting to the desired angle, the bolts should be tightened to secure the assembly.

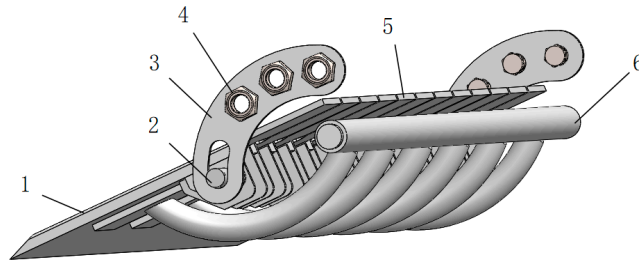


Figure 4. Shovel angle adjustment mechanism: (1) picking shovel; (2) supporting shaft; (3) fixed plate; (4) welded nut; (5) transition plate; (6) rotational axis.

During the picking process, the end of the picking shovel is prone to collisions with stones carried by the guiding rollers, leading to wear. To mitigate this issue, a movable transition plate is hinged behind the picking shovel. The soil–potato mixture is directed to the guiding rollers via the transition plate. The mobility of the transition plate allows it to prevent damage to the end of the picking shovel when encountering hard stones.

In this design, the picking shovel consists of two parts: the shovel blade and the transition plate (Figure 3). The length of the shovel blade is denoted as L_1 , and the length of the transition plate is denoted as L_2 .

According to Figure 3, the equation for calculating the length of the shovel blade can be derived as follows:

$$L_1 = \frac{h_1}{\sin \alpha} \quad (4)$$

In the equation: h_1 is picking depth, mm; α is the angle of picking shovel, °; v is machine forward speed, m/s; φ is the friction angle of soil on steel.

Substituting the shovel angle $\alpha = 15^\circ - 23^\circ$ into the above equation, we obtain a range of values from 127 to 386 mm. In actual picking operations, if the picking shovel is too long, it will increase soil resistance and cause soil blockage. Therefore, we choose the minimum value of 127 mm. Based on Figure 3 and the law of conservation of energy, we derive the calculation equation for the transition plate.

$$L_2 = \frac{v^2 \cos \varphi}{2g \sin(\alpha + \varphi)} \quad (5)$$

The total length of the picking shovel is:

$$L = L_1 + L_2 = \frac{h_1}{\sin \alpha} + \frac{v^2 \cos \varphi}{2g \sin(\alpha + \varphi)} \quad (6)$$

Substituting the data into the calculation, we obtain a range of values from 83 mm to 132 mm. Referring to the “Handbook of Agricultural Machinery Design”, we determine the length of the transition plate to be 100 mm to 150 mm. Considering the actual design situation, the final length of the transition plate is determined to be 107 mm. Therefore, the total length of the picking shovel is 307 mm.

2.2.3. Auxiliary Picking Device

In the actual operation of the potato picker, relying solely on the thrust of the soil–potato mixture to pick up the potatoes can result in soil blockage and potato stacking at the front end of the picking shovel [20–22]. Consequently, two guiding rollers and a toggle wheel are installed behind the picking shovel. The guiding rollers agitate the soil–

potato mixture during picking, facilitating the transportation of potatoes, and initiating the separation of the mixture. The toggle wheel effectively pushes the potatoes, ensuring a smooth transition to the subsequent device for efficient picking. The gap between toggle levers and sieve rods prevents squeezing and abrasion of the potatoes. The specific structure is shown in Figure 5.

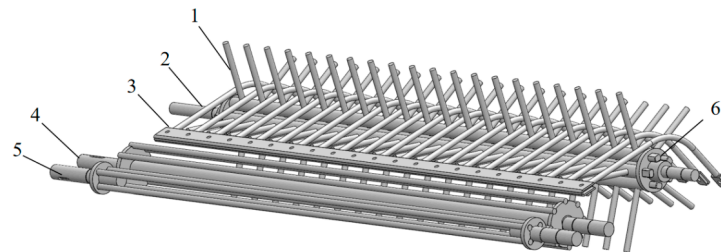


Figure 5. Auxiliary picking device: (1) toggle lever; (2) rotational axis; (3) sieve rods; (4) and (5) guiding rollers; (6) fixed disc.

To ensure the toggle wheel effectively pushes the potatoes, the effective working length of the toggle lever should be greater than the average length of the potato tubers to avoid missing potatoes during picking. The length of the toggle lever can be calculated according to Equation (7).

$$R = R_1 + R_2 + R_3 \quad (7)$$

In the equation: R is length of toggle lever, mm; R_1 is effective working length of toggle lever, mm; R_2 is radius of the fixed disc, mm; R_3 is diameter of the sieve rods.

With the effective working length of the toggle lever set to 100 mm, the radius of the fixed disc as 20 mm, and the diameter of the sieve rods as 10 mm, substituting these values into the calculation results in the length of the toggle lever being 130 mm.

To ensure the bending resistance and service life of the toggle lever, a diameter of 10 mm is selected. After digging, potatoes are irregularly scattered on the ground. To maximize the picking of potatoes from the ground, the clearance between adjacent toggle levers is set to 40 mm. The specific structure is shown in Figure 6.

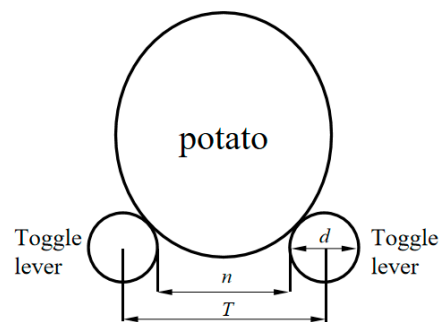


Figure 6. Schematic Diagram of toggle lever center distance.

From Figure 6, we can derive the equation for the center distance of toggle levers:

$$T = n + d \quad (8)$$

In the equation: T is center distance of toggle levers, mm; n is clearance between toggle levers, mm; d is diameter of toggle levers, mm.

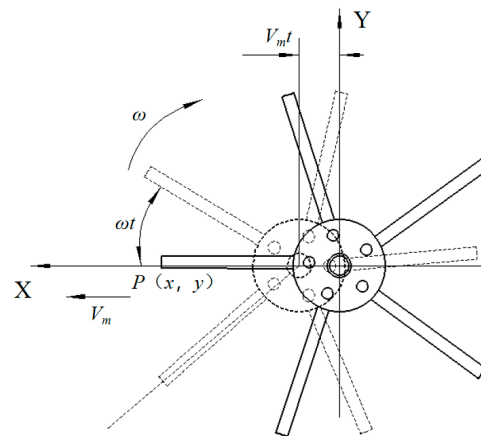
Substituting n and d into Equation (8), we find the center distance of the toggle levers to be 50 mm. The final technical parameters of the toggle lever-type potato picker are shown in Table 2.

Table 2. Table of picker technical parameter.

Program	Parameter
Machine working width (mm)	1050
Picking shovel adjustment angle range (°)	15–23
Picking depth (mm)	50–100
Pick-up shovel length (mm)	307
Finger length (mm)	130
Toggle lever center distance (mm)	50

2.3. Kinematic Characteristics Analysis of Toggle Lever

During operation, as the potato picker moves forward, the toggle wheel rotates around the main axis. Thus, the absolute motion of the toggle lever results from the combined forward motion of the entire machine and the rotational motion of the toggle wheel. A Cartesian coordinate system is established with the initial position of the rotation center of the toggle wheel as the origin. Here, the positive direction of the X-axis aligns with the forward direction of the picker, and the positive direction of the Y-axis points downward, as illustrated in Figure 7.

**Figure 7.** Schematic diagram of the motion process of toggle lever.

Since the potato picker moves forward at a speed of V_m and the angular velocity of the toggle wheel is ω , the motion trajectory equation for the endpoint $P(x,y)$ of the toggle lever over a time interval is given by:

$$\begin{cases} x = V_m t + R \cos \omega t \\ y = R \sin \omega t \end{cases} \quad (9)$$

In the equation: R is the length of toggle lever, m; ω is the angular velocity of toggle lever, rad/s; t is the time taken for the endpoint of toggle lever to rotate clockwise from the positive X-axis direction, s.

As per Equation (9), the trajectory of toggle lever endpoint is contingent on the angular velocity of the toggle lever and the machine forward speed. To ensure that the lever initiates upward rotation from a horizontal position with a backward flicking action on the soil-potato mixture, the linear velocity of the lever endpoint should surpass machine forward speed. In this scenario, the trajectory of the lever endpoint resembles a trochoid curve (Figure 8), where the lever endpoint moves backward relative to the machine, effectively flicking the potatoes backward.

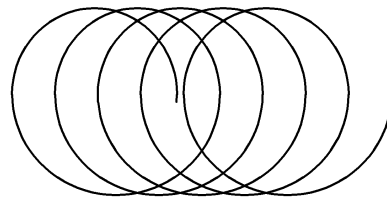


Figure 8. The trajectory of toggle lever endpoint.

Differentiating Equation (9) with respect to time yields the velocity equations of toggle lever endpoint $P(x,y)$ in the X-axis and Y-axis directions:

$$\begin{cases} V_x = V_m - R\omega\sin\omega t \\ V_y = R\omega\cos\omega t \end{cases} \quad (10)$$

Taking the first derivative of Equation (10) with respect to time, we can obtain the acceleration equations of toggle lever endpoint $P(x,y)$ in the X-axis and Y-axis directions:

$$\begin{cases} a_x = -R\omega^2\cos\omega t \\ a_y = -R\omega^2\sin\omega t \end{cases} \quad (11)$$

From Equation (11), we can deduce that the resultant acceleration of toggle lever endpoint P is: $a = R\omega^2$, indicating that the magnitude of the acceleration of toggle lever endpoint is only related to the length of toggle lever and the angular velocity of toggle lever's rotation.

Based on the results of potato collision contact force experiments [23], when the height of potato fall is between 20 and 40 mm, the depth of potato damage ranges from 0 to 1.9 mm. Therefore, the critical falling height for potato collision damage with the lever end should be between 20 and 40 mm. According to the law of conservation of energy:

$$mgh = \frac{1}{2}mv^2 \quad (12)$$

In the equation: v is the critical velocity for potato collision damage, m/s; h is the height of potato fall, m; m is mass of potato, kg.

The critical velocity for potato collision with toggle lever is calculated using Equation (12) as follows:

$$v_1 = \sqrt{2gh_1} = 0.626 \quad (13)$$

$$v_2 = \sqrt{2gh_2} = 0.89 \quad (14)$$

In the equation: v_1 is the minimum critical velocity for potato damage, m/s; v_2 is the maximum critical velocity for potato damage, m/s.

The relationship between the linear velocity and the rotational speed of toggle lever during uniform circular motion is given by:

$$v_b = 2\pi nr \quad (15)$$

In the equation: v_b is the linear velocity of the endpoint of toggle lever, m/s; n is the toggle lever speed, r/s; R is the length of toggle lever, mm.

The equation for calculating the rotational speed of toggle lever can be derived as follows:

$$n = \frac{V_b}{2\pi R} \quad (16)$$

Substituting the values of v_1 , v_2 and r , it can be obtained that the rotational speed of toggle lever to avoid potato collision damage falls within the range of 40.8 r/min to 58.2 r/min.

2.4. Key Performance Evaluation Indicators of Potato Picker

According to the requirements of DB64/T 1795-2021 “Technical code of practice for mechanized potato picking” [24], the key performance evaluation indicators for the toggle lever-type potato picker are selected as the potato leakage rate and potato damage rate.

Potato leakage rate: After the operation of the picker, the potatoes picked up by the machine and the potatoes missed by the machine are collected separately in the experiments area and weighed. Then, the percentage of missed potatoes in the total weight of potatoes in the experiments area is calculated according to Equation (17).

$$Y_1 = \frac{Q_2}{Q_2 + Q_3} \times 100\% \tag{17}$$

In the equation: Y_1 is potato leakage rate, %; Q_2 is mass of the missed potatoes, kg; Q_3 is mass of the potatoes picked up by the machine, kg.

Potato damage rate: The mass of the damaged potatoes is divided by the total mass of potatoes in the experimental area to calculate the percentage of damaged potatoes in total, according to Equation (18).

$$Y_2 = \frac{Q_5}{Q_2 + Q_3} \times 100\% \tag{18}$$

In the equation: Y_2 is potato damage rate, %; Q_5 is mass of damaged potatoes, kg.

2.5. The Design of Single-Factor Performance Experiment

2.5.1. Factors and Levels for Experiment

Based on theoretical analysis, the toggle lever speed that does not cause potato damage ranges from 40.8 r/min to 58.2 r/min. Therefore, the levels of toggle lever speed are selected as 40, 45, 50, 55, and 60 r/min. To ensure that the motion trajectory of the toggle lever forms a residual curve and effectively lifts the potatoes, the machine forward speed must be less than the linear speed of the toggle lever’s endpoint. Additionally, the machine forward speed should not be lower than 0.4 m/s to maintain operational efficiency. Hence, the levels of machine forward speed are selected as 0.5, 0.62, 0.75, 0.87, and 1 m/s. The levels of the shovel angle are chosen as 15°, 17°, 19°, 21°, and 23°. The levels of the experimental factors are summarized in Table 3.

Table 3. Table of factors and levels in single-factor performance experiment.

Levels	Factors		
	Toggle Lever Speed (r/min)	Machine Forward Speed (m/s)	Shovel Angle (°)
1	40	0.5	15
2	45	0.62	17
3	50	0.75	19
4	55	0.87	21
5	60	1	23

2.5.2. The Course of the Experiment

The performance experiments of the potato picker are conducted at the Soil Trough Laboratory of Inner Mongolia Agricultural University, where a soil trough vehicle powers the picker. The soil trough vehicle can adjust the forward speed and hydraulic system through the operation console to meet the experimental requirements. The soil trough is divided into three sections based on its length: the acceleration zone (5 m), the experimental zone (15 m), and the deceleration zone (10 m). The experimental procedure device is shown in Figure 9.

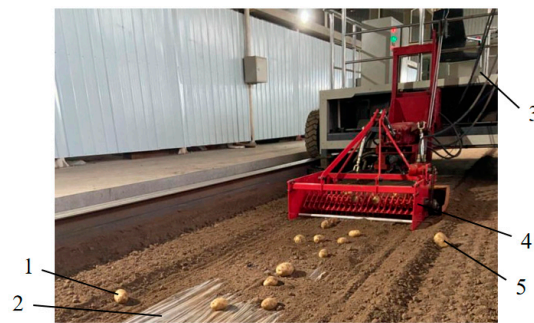


Figure 9. Single-factor experimental procedure device: (1) missed potatoes; (2) plastic film; (3) soil trough vehicle; (4) picker; (5) missed potatoes.

Before conducting the experiments, the hydraulic system of the potato picker was adjusted and pre-tested to ensure smooth operation during the formal trials. According to the agronomic requirements for potato cultivation in Inner Mongolia, the average yield per acre of potatoes reaches 2500 kg. Potatoes are planted in double rows on large ridges, with a ridge width of 800 mm and row spacing of 400 mm. Therefore, during the experiments, approximately 50 kg of potatoes were randomly spread in the working area of the potato picker, which measured 1500 mm in length and 1000 mm in width. The potato variety selected was Jizhangshu 12, which is widely grown in central and western Inner Mongolia. Using the LD-WSY soil environment detector, soil moisture content was measured to ensure it remained at 13%, aiming to closely replicate the field conditions during potato harvesting.

Before the start of each experiment, a bundle of plastic film was attached to the rear end of the potato picker's side plate, with one end of the film fixed at the initial position. As the soil trough vehicle moved forward, the film roll rotated and lay the film on the ground. Potatoes picked up by the machine fell onto the film or the edge of the film, while those not picked up were distributed on either side or below the film, facilitating the statistical analysis of the experimental results.

2.6. Discrete Element Simulation Experiment Design

2.6.1. Experimental Indicators

Through the process images of the single-factor performance experiments, it is evident that the main cause of potato leakage during the operation of the picker was excessive soil accumulation at the front end of the picking shovel. This accumulation led to congestion in front of the shovel and caused some potatoes to slide off to the sides of the machine. The primary reason for potato damage was that the collision force between the potatoes and the machine exceeded the critical force threshold for potato damage. Therefore, to thoroughly analyze the working mechanism of the potato picker, discrete element simulation experiments were conducted. These experiments use the same factor levels as the single-factor experiments, utilizing the peak force on potatoes during the picking process and the peak height of soil in front of the shovel as indicators, to analyze the influence of each factor on the indicators. This approach helps clarify the reasons for the changes in the performance indicators of the picker with variations in picker parameters.

2.6.2. The Course of the Experiment

Using EDEM 2021 software [25] and the Hertz–Mindlin with Bonding contact model [26,27], an optimized design was conducted based on actual potato dimensions. Using Solidworks 2016 software, an idealized ellipsoid model of a potato with dimensions of 100 mm × 70 mm (major axis × minor axis) was created and saved in .stl format.

In the EDEM 2021 software, two box geometries were created: one was set as a virtual type to act as a particle factory for generating particles, while the other was set as a physical type to serve as boundary conditions. After importing the idealized potato model into the EDEM 2021 software, both the peel and flesh interior regions were set as virtual types.

The particle size distribution was set to fixed distribution, and static generation mode was chosen during particle generation from the particle factory.

Initially, flesh particles (totaling 20,000) were generated by the particle factory. Once the flesh particles filled the box completely, compaction was performed using a moving plane geometry. Subsequently, the flesh interior region was set to physical type, while the box was set to virtual type, allowing excess particles to automatically leave the simulation domain under the influence of gravity.

The same method was applied to fill the peel particles. After filling all the particles and achieving stable system operation, bonding keys were added to bond the particles together. Finally, the main profile of the idealized potato model was removed, resulting in a double-layer bonded model of the whole potato. The model construction process is illustrated in Figure 10.

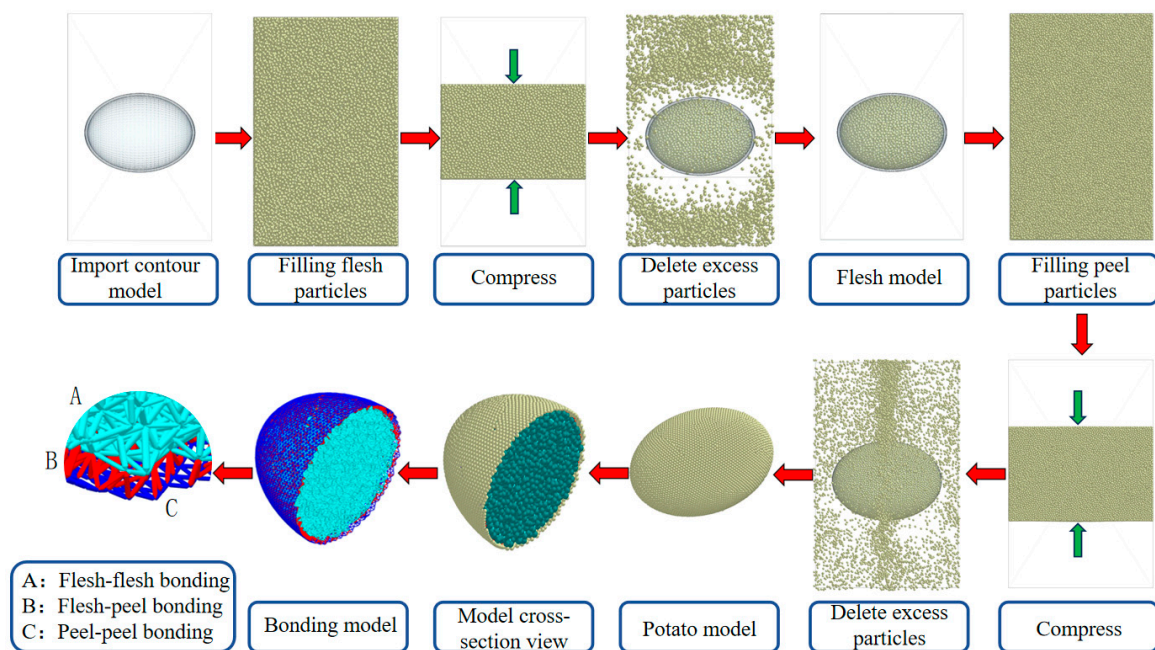


Figure 10. Potato whole stem modeling process.

Gai et al. [28] calibrated the bonding parameters of the potato model and verified the accuracy of these parameters. The bonding parameters are shown in Table 4.

Table 4. Table of bonding parameters.

Bonding Parameters	Value
Flesh particle-flesh particle unit area normal stiffness/tangential stiffness (N/m^3)	4.39×10^9
Flesh particle-flesh particle critical normal stress/tangential stress (Pa)	5.5×10^9
Peel particle-flesh particle unit area normal stiffness/tangential stiffness (N/m^3)	1.81×10^9
Peel particle-flesh particle critical normal stress/tangential stress (Pa)	2.2×10^9
Peel particle-peel particle unit area normal stiffness (N/m^3)	4.55×10^9
Peel particle-peel particle unit area tangential stiffness (N/m^3)	1.99×10^9
Peel particle-peel particle critical normal stress (Pa)	2.06×10^9
Peel particle-peel particle critical tangential stress (Pa)	4.55×10^9

To constrain the arrangement range of particles, a topless box with dimensions of 5000 mm in length, 1050 mm in width, and 300 mm in height was set up in EDEM 2021. Soil particles were generated in the area above the box, with a delay of 1 s to allow for soil stabilization. The soil parameters can be collated from the literature [18] as shown in Table 5.

Table 5. Table of soil parameters.

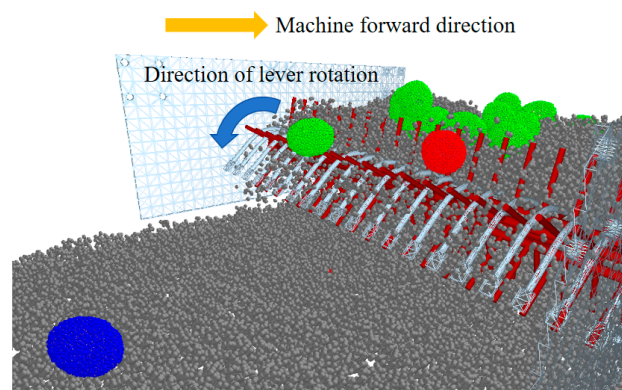
Soil Parameters	Values
Poisson's ratio (N/m^3)	0.2
Modulus of elasticity (MN/m^2)	13.5
Density (g/cm^3)	1.38
Coefficient of static friction	0.81
Coefficient of rolling friction	0.2095
Resting angle ($^\circ$)	35.53
JKR surface energy coefficient	0.356
Particle radius (mm)	2

In this experiment, 20 potato models were added, allowing them to freely fall onto the soil surface to create a potato-soil mixture of particles. The discrete element models for potatoes and soil were selected using the Hertz–Mindlin JKR model.

The 3D model of the potato picker was simplified and imported into EDEM 2021 software, as shown in Figure 11.

**Figure 11.** Simulation pre-processing model.

The duration of each set of simulations is set to 6 s. At the end of each experiment, the average peak force of three potatoes was calculated as the final result. The simulation process is shown in Figure 12.

**Figure 12.** Simulation process.

2.7. Experimental Design for Optimization of the Parameters of the Picker

To identify the significant factors and their interaction effects on the evaluation indicators, and to obtain the optimal working parameter combination for the harvester, a Box–Behnken response surface experimental method was employed. The experimental factors included the toggle lever speed, machine forward speed, and shovel angle, while the evaluation indicators were the potato leakage rate and potato damage rate. Mathematical regression models were established to analyze the influence of the interaction effects of the experimental factors on the evaluation indicators.

Based on the results of the single-factor performance experiments, reasonable intervals with low potato leakage rates and damage rates were selected. The encoding of each experimental factor is shown in Table 6. This experiment was conducted in the Soil Trough Laboratory of Inner Mongolia Agricultural University, following the same procedure as

the single-factor experiments. There were a total of 17 experimental groups, with each experiment repeated three times. The average value of the results from the three repeated experiments was calculated as the final experimental result.

Table 6. Table of factors and levels of the experiment.

Levels	Toggle Lever Speed (r/min)	Machine Forward Speed (m/s)	Shovel Angle (°)
−1	45	0.75	17
0	50	0.87	19
1	55	1	21

2.8. The Field Experiment Design

According to the technical regulations for mechanized potato picking, the potato picker should achieve a potato leakage rate of $\leq 5\%$ and a potato damage rate of $\leq 6\%$. Therefore, field experiments were carried out to verify whether the optimal working parameters of the picker meet these technical regulations.

The field experiment was conducted in September 2023 at the Potato Experimental Field of Inner Mongolia Agricultural University (Figure 13). The field was arranged in a ridge double-row planting pattern with a ridge width of 800 mm, and the potato variety was Jizhang Potato 12. Three days prior to the experiment, the field underwent desiccation treatment. The experimental process was conducted in accordance with the DB64/T 1795-2021 “Technical code of practice for mechanized potato picking” [24]. Potatoes were first dug up using the 4SW-170 potato digger, then naturally air-dried for one hour. Subsequently, a Dongfanghong 704 tractor was used to tow the potato lifting finger-type picker for the experiments.



Figure 13. Field experiment of picker.

3. Results and Discussion

3.1. Analysis of the Results of the Single-Factor Performance Experiments

The performance variations of the picker under different experimental factors are shown in Figure 14. As shown in Figure 14a, the potato damage rate increases with the toggle lever speed. According to the theoretical analysis of the toggle lever in Section 2.3, the acceleration at the tip of the toggle lever is related to its rotation speed. With a fixed length of the toggle lever, the faster the toggle lever speed, the greater the absolute acceleration, resulting in a higher force exerted on the potatoes. This increased collision intensity between the potatoes and the lifting fingers is likely to cause skin damage. Similar analyses were conducted by Wu et al. [29,30], who found that when the core working component of a machine is a rotating structure, the impact on the target increases with rotational speed, making damage more likely.

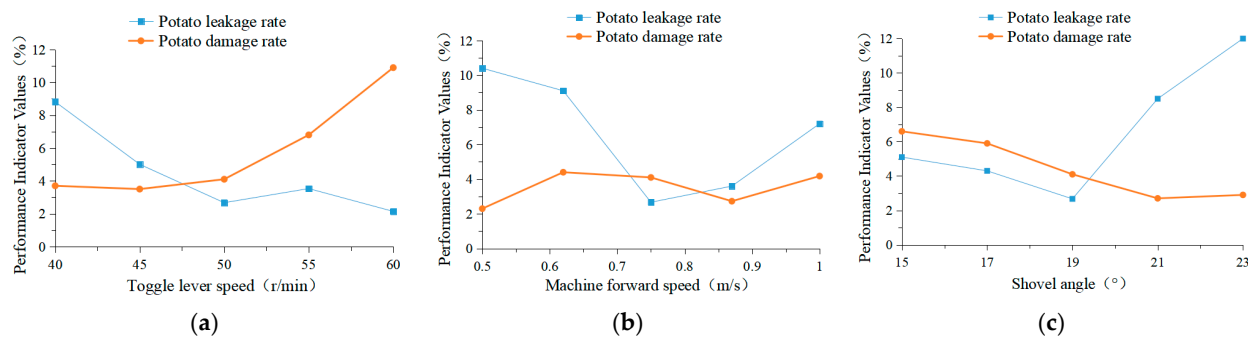


Figure 14. Results of single-factor performance experiments. (a) Influence of toggle lever speed on picker performance; (b) influence of machine forward speed on picker performance; (c) influence of shovel angle on picker performance.

Figure 14b shows that the potato damage rate does not vary significantly with changes in the machine forward speed. This finding differs from the results of Xie, which indicated that machine forward speed affects the material feed rate and, without sufficient soil protection, potatoes are more prone to skin damage [31]. However, in this experiment, potatoes were protected by soil at different forward speeds, resulting in a minimal impact of forward speed on the potato damage rate.

As shown in Figure 14c, the potato damage rate decreases with an increase in the shovel angle. According to Wang's research [18], the angle of the shovel directly affects the operational efficiency of the potato harvester. A larger shovel angle increases the amount of material fed into the shovel per unit time, thickening the soil layer on the picker, thereby enhancing the protective effect of the soil on the potatoes and reducing the potato damage rate.

From Figure 14a, it can be observed that the potato leakage rate decreases as the toggle lever speed increases. This result differs from the findings of Fan [12], where the tine-type picker showed a trend of first decreasing and then increasing under this factor. This difference arises because the working principles of the tine-type potato picker and the toggle lever-type picker are different. As the toggle lever speed increases, the disturbance effect on the soil-potato mixture intensifies, reducing the mixture height, allowing the potatoes to be smoothly picked up and transferred to subsequent devices, thereby reducing the potato leakage rate.

The potato leakage rate shows a trend of first decreasing and then increasing with the increase in the machine forward speed and shovel angle (Figure 14b,c). The main reason for this is that the machine forward speed and shovel angle affect the feeding rate of the soil-potato mixture. When the machine forward speed and the shovel angle are at an optimal level, the potatoes can be smoothly picked up, resulting in a low potato leakage rate. However, when the machine forward speed is too high or the shovel angle is too large, the potato leakage rate will increase. The main reason for this is the increase in the height of the congestion in front of the shovel. According to Wang's [32] findings, when the congestion is too high, the height of the accumulated soil increases, making it easy for the potatoes to pile up and roll back (Figure 15).



Figure 15. Potato pile up and roll back Situation.

3.2. Analysis of Discrete Element Simulation Experiment Results

3.2.1. Analysis of Potato Force and Congestion during the Picking Process

The typical force-time curve for potatoes and the typical soil accumulation curve in front of the picking shovel during the picking process are shown in Figure 16. During picking, the resultant force on the potatoes reaches its maximum instantly when they come into contact with the toggle lever, resulting in a peak force. Chen et al. [33] indicate that potato damage occurs when the stress exceeds the potatoes' yield stress. Therefore, this study focuses on the maximum peak force experienced by potatoes during the picking process.

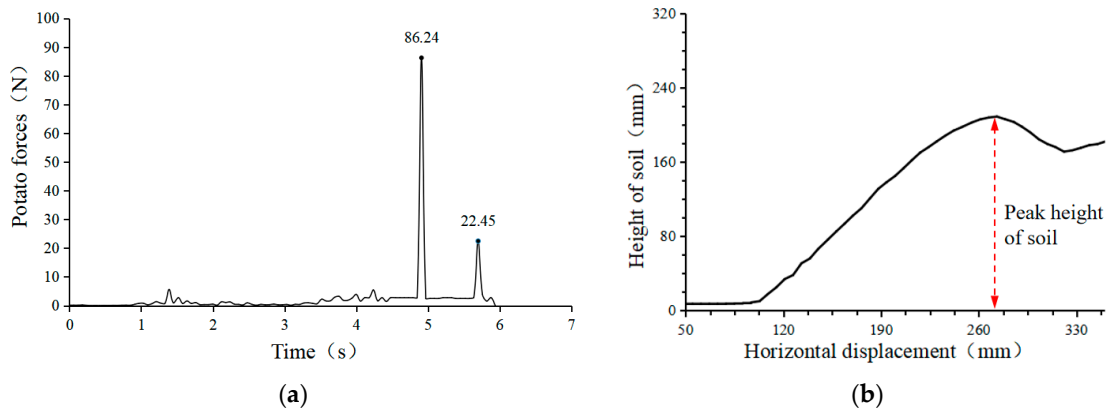


Figure 16. Forces on potatoes and congestion of the soil: (a) Typical force-time curves of potatoes; (b) Typical soil accumulation curves in front of the picking shovel.

Wang et al. [32] found that the primary cause of potato leakage during the operation of the potato picker is the excessive height of soil accumulation in front of the picking shovel. Hence, this study analyzes the peak height of soil accumulation in front of the picking shovel.

3.2.2. Influence of Factors on the Peak Force of Potatoes

The effects of different experimental factors on the peak force experienced by potatoes are shown in Figure 17. As seen in Figure 17a, the peak force on the potatoes increases linearly with the rotation speed of the potato lifting fingers. Deng [23] found a positive correlation between the degree of skin damage and the force experienced. In this experiment, as the toggle lever speed increases, the collision intensity between the potatoes and the toggle lever also increases, leading to a higher instantaneous peak force on the potatoes, which in turn increases the potato damage rate.

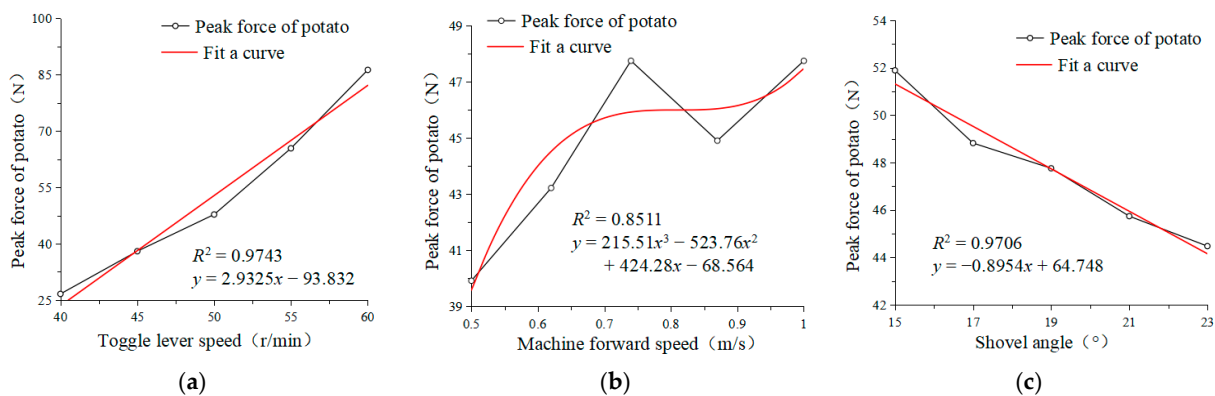


Figure 17. Influence of factors on the peak force of potatoes. (a) Influence of toggle lever speed on the peak force of potatoes; (b) influence of machine forward speed on the peak force of potatoes; (c) influence of shovel angle on the peak force of potatoes.

As the machine forward speed increases, the peak force on the potatoes shows an increasing trend (Figure 17b). Xie [31] determined that soil can provide protection and buffering for potatoes during mechanical harvesting. Chen [33] concluded that the main cause of potato damage is the collision stress between the potatoes and the machine exceeding the potatoes' yield stress. In this experiment, the variation in the potato damage rate under five different machine forward speeds was not significant. The main reason is that the peak force on the potatoes at different forward speeds remained below the critical value for skin damage. Therefore, the forward speed does not significantly affect the damage rate.

As the shovel angle increases, the peak force on the potatoes decreases linearly (Figure 17c). According to Li's research [18], under constant conditions, increasing the shovel angle increases the amount of soil fed into the picker per unit time, leading to an increase in soil thickness. Soil can provide a buffering and protective effect on the potatoes [31]. The greater the soil thickness, the better the buffering effect, which reduces the collision intensity and frequency between the potatoes and the machine, ultimately lowering the damage rate caused by the picker.

3.2.3. Influence of Factors on the Peak Height of Soil

The influence of different experimental factors on the peak height of soil is shown in the figure. As seen in Figure 18a, with the increase in the toggle lever speed, the peak height of soil in front of the shovel decreases linearly. The increased toggle lever speed enhances the disturbance effect on the soil, causing more soil to fall through the gaps in the sieving bars to the ground, thereby reducing the soil accumulation height. Combined with the results of the single-factor performance tests, the potato loss rate decreases with the increase in toggle lever speed. This is due to the reduced soil accumulation height, which allows the soil and potatoes to transition more smoothly to subsequent devices, thereby reducing the occurrence of potato leakage.

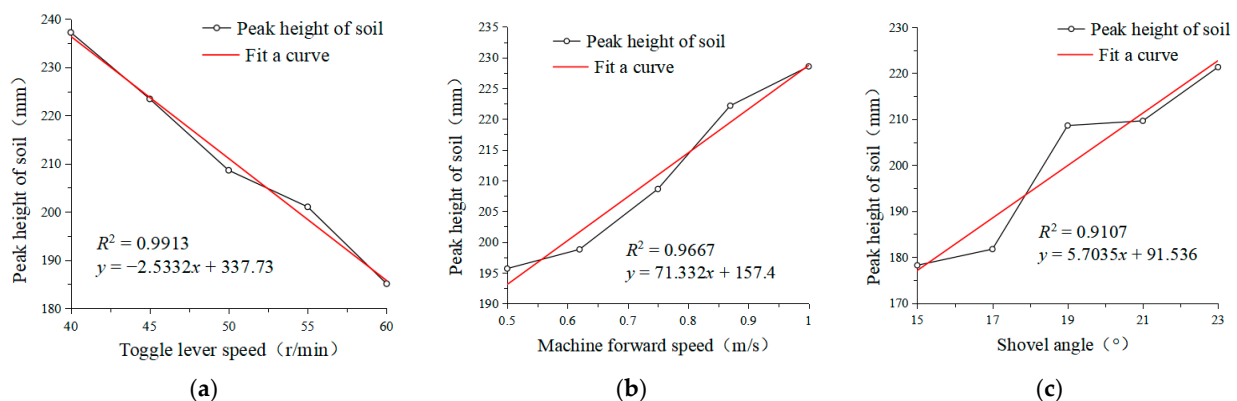


Figure 18. Influence of factors on the peak height of soil. (a) Influence of toggle lever speed on the peak height of soil; (b) influence of machine forward speed on the peak height of soil; (c) influence of shovel angle on the peak height of soil.

As the machine forward speed increases, the peak height of soil in front of the picking shovel increases linearly (Figure 18b). When the machine forward speed increases, the amount of material fed into the picking shovel per unit time also increases, leading to a higher peak soil accumulation height. Wang et al. [33] indicates that excessive soil accumulation height can cause potatoes to roll back on the picking shovel, resulting in missed potatoes. Therefore, when the machine's forward speed is too high, the potato loss rate also increases. The machine forward speed should be maintained within a reasonable range.

As the shovel angle increases, the peak height of soil also increases linearly (Figure 18c). With other conditions being constant, a larger tilt angle of the picking shovel results in more soil being fed into the picker per unit time, leading to an increased soil accumulation

height at the front end of the shovel [19]. For the picker to ensure a low potato damage rate while maintaining a low potato leakage rate, the soil accumulation height should be optimized. Both excessive and insufficient soil accumulation height can adversely affect the picking efficiency and performance of the potato picker [33]. Therefore, a reasonable match of the picking shovel's tilt angle is essential to enhance the working efficiency and picking performance of the potato picker.

3.3. Analysis of Response Surface Experiments Results

3.3.1. Analysis of Variance

The results of the response surface experiments are shown in Table 7.

Table 7. Table of response surface experiments protocol and results.

Experiment Number	Toggle Lever Speed: A	Machine Forward Speed: B	Shovel Angle: C	Y ₁ : Potato Leakage Rate (%)	Y ₂ : Potato Damage Rate (%)
1	1(55)	1(1)	0(19)	6.1	9.8
2	0(50)	-1(0.75)	1(21)	9.3	3.5
3	-1(45)	-1	0	8.9	5.9
4	0	1	-1(17)	5.1	5.7
5	0	0(0.87)	0	2.4	2.8
6	0	1	1	8.1	5.2
7	-1	1	0	6.7	8.4
8	0	0	0	1.9	2.8
9	1	0	1	7.1	8.4
10	0	0	0	2.7	2.3
11	1	-1	0	7.2	9.5
12	0	0	0	1.9	2.3
13	-1	0	1	8.2	7.7
14	0	-1	-1	9.9	5.4
15	0	0	0	2.3	2.5
16	1	0	-1	6.6	11.1
17	-1	0	-1	7.1	8.2

The quadratic response surface regression models for the potato leakage rate (Y_1) and the potato damage rate (Y_2) were established using Design-Expert 13 data analysis software, with toggle lever speed (A), machine forward speed (B), and shovel angle (C) as independent variables.

$$Y_1 = 6.38 - 0.08A - 3.78B - 0.3C + 0.004AB - 0.0002AC + 0.04BC + 0.0008A^2 + 1.87B^2 + 0.007C^2 \quad (19)$$

$$Y_2 = 5.82 - 0.18A - 0.71B - 0.12C - 0.009AB - 0.0006AC + 0.01BC + 0.002A^2 + 0.63B^2 + 0.004C^2 \quad (20)$$

The results of the analysis of variance for the regression equation are shown in Table 8.

The p -values for potato leakage rate (Y_1) and potato damage rate (Y_2) were both <0.0001 , indicating that the models are highly significant. The lack of fit p -values were 0.1599 and 0.2376 (both greater than 0.05), suggesting high fitting adequacy within the experimental parameter range with no significant lack of fit.

In the potato leakage rate model, the factors B , BC , A^2 , B^2 , and C^2 had highly significant effects, while A and C had significant effects. The interactions AB and AC had no significant effects on the potato leakage rate.

In the potato damage rate model, factors A , B , C , AB , AC , A^2 , B^2 , and C^2 had highly significant effects, while BC had no significant effect on the potato damage rate. After removing the non-significant regression terms ($p > 0.05$) from the regression equations, the optimized regression equations were obtained as follows:

$$Y_1 = 6.38 - 0.08A - 3.78B - 0.30C + 0.004AB + 0.0008A^2 + 1.87B^2 + 0.007C^2 \quad (21)$$

$$Y_2 = 5.82 - 0.18A - 0.71B - 0.12C - 0.009AB - 0.0006AC + 0.002A^2 + 0.63B^2 + 0.004C^2 \quad (22)$$

Table 8. The results of the analysis of variance.

Source	Y ₁				Y ₂			
	Sum of Squares	Degrees of Freedom	F	p	Sum of Squares	Degrees of Freedom	F	p
Model	0.0119	9	60.67	<0.0001 **	0.0139	9	164.24	<0.0001 **
A	0.0002	1	8.73	0.0213 *	0.0009	1	98.50	<0.0001 **
B	0.0011	1	49.64	0.0002 **	0.0003	1	30.68	0.0009 **
C	0.0002	1	9.18	0.0191 *	0.0004	1	41.77	0.0003 **
AB	0.0000	1	1.39	0.2771	0.0001	1	12.89	0.0089 **
AC	0.000009	1	0.4133	0.5408	0.0001	1	12.89	0.0089 **
BC	0.0003	1	14.88	0.0062 **	0.0000	1	5.22	0.0562
A ²	0.0018	1	82.64	<0.0001 **	0.0100	1	1068.34	<0.0001 **
B ²	0.0036	1	164.56	<0.0001 **	0.0004	1	43.08	0.0003 **
C ²	0.0036	1	167.39	<0.0001 **	0.0009	1	91.74	<0.0001 **
Residual	0.0002	7			0.0001	7		
Lack of Fit	0.0001	3	2.97	0.1599	0.0000	3	2.14	0.2376
Pure Error	0.0000	4			0.0000	4		
Cor Total	0.0120	16			0.0139	16		

** Indicates highly significant ($p < 0.01$); * indicates significant ($p < 0.05$).

From Equations (21) and (22), it can be observed that the interaction between machine forward speed and shovel angle has an extremely significant impact on the potato leakage rate. Moreover, the interaction between toggle lever speed and machine forward speed, as well as the interaction between toggle lever speed and shovel angle, has an extremely significant impact on the potato damage rate.

3.3.2. Factor Interaction Analyses

The effects of the interaction between different factors on the performance indicators of the picker are shown in Figure 19. It can be seen that increasing the machine forward speed and decreasing the shovel angle can reduce the potato leakage rate. However, with a further increase in the machine forward speed and a continued decrease in shovel angle, the potato leakage rate starts to increase again (Figure 19a). Lowering the machine forward speed and the rotation speed of the potato lifting fingers can reduce the potato damage rate (Figure 19b). However, if the toggle lever speed is too low, the potato damage rate increases. Increasing the toggle lever speed and decreasing the shovel angle can reduce the potato damage rate, but with a further decrease in the shovel angle, the potato damage rate starts to increase again (Figure 19c).

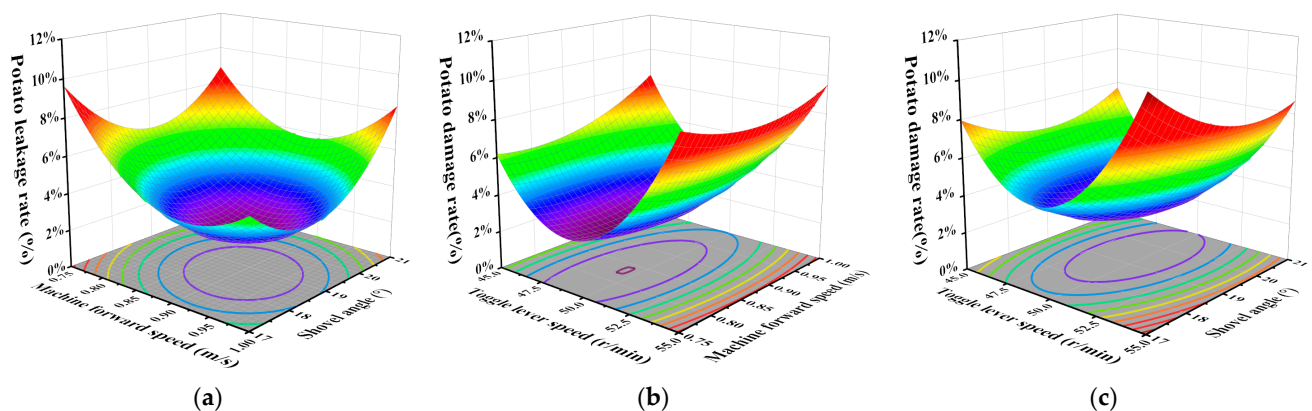


Figure 19. Influence of factors on indicators. (a) Influence of machine forward speed and shovel angle on potato leakage rate; (b) influence of toggle lever speed and machine forward speed on potato damage rate; (c) influence of toggle lever speed and shovel angle on potato damage rate; the colors in the figure represent the values, ranging from high to low as follows: red, yellow, green, blue, and purple.

Utilizing the optimization solver in Design-Expert 13 software, the regression equations with insignificant regression terms were solved. Constraints were set as follows:

$$\begin{cases} \min Y_1(A, B, C) \\ \min Y_2(A, B, C) \\ 45 \leq A \leq 55 \\ 0.75 \leq B \leq 1 \\ 17 \leq C \leq 21 \\ 0 \leq Y_1 \leq 5\% \\ 0 \leq Y_2 \leq 6\% \end{cases} \quad (23)$$

The theoretical optimal solution is obtained as follows: toggle lever speed of 50 r/min, machine forward speed of 0.9 m/s, and shovel angle of 19°. With these parameters, the potato leakage rate is estimated to be 2.23%, the potato damage rate is 2.61%, and the expected value of the optimization results is 0.967.

3.4. The Field Experiment Results

The field experimental results indicate that under the optimal parameters, the potato picker achieved a potato leakage rate of 2.32% and a potato damage rate of 2.72%.

4. Conclusions

1. In response to the issues of excessive soil accumulation and potato damage caused during potato picking, a toggle lever-type potato picker was designed, achieving effective potato manipulation and conveying.
2. The theoretical optimal working parameter combination for the picker is a toggle lever speed of 50 r/min, a machine forward speed of 0.9 m/s, and a shovel angle of 19°.
3. Under optimal operating parameters, the performance indicators of the picker meet the requirements of the mechanized potato picking technical specifications (the potato leakage rate is $2.32\% \leq 5\%$, the potato damage rate is $2.72\% \leq 6\%$).

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