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Design and Performance Test of 4UJ-180A Potato Picking and Bagging Machine

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Abstract: To address problems encountered in current potato harvesting machines, such as potato damage, poor adaptability, and low operational efficiency, a new towed potato picking and bagging machine (4UJ-180A) equipped with a soil-digging axis, flexible conveying device, and hydraulic control system was developed. The digging mechanism of the harvester can reduce soil blockage and minimize damage to potato skins. The rubber biomimetic finger can maintain stable transportation of potatoes and minimize collisions. The hydraulic control system, the buffering components, and the bagging device work together to flexibly and continuously collect potatoes, reducing skin damage during the harvesting process. Based on the structure of the whole machine, the harvesting process, and the working principle, the soil picking, lifting buffer, and potato collection process were analyzed. Theoretical calculations were used to determine the structure and operational parameters of the potato picking, lifting buffering, and bagging segments. An experiment utilizing the orthogonal method was conducted. The experiment consisted of three factors and three levels, with the test indicators being the potato skin damage rate, potato injury rate, loss rate, and impurity rate. The factors considered in the experiment were the forward speed, conveyor speed, and soil-digging shaft speed. Field experiments demonstrate that at a forward speed of 1 m/s, soil digging shaft speed of 35 rpm, and conveyor speed of 28 rpm, the rate of potato skin damage is 2.8%, the potato injury rate is 1.3%, the loss rate is 0.4%, and the impurity rate is 0.7%. These experiments verify that all indicators adhere to national industry standards, providing a valuable reference for equipment research, development, optimization, and improvement.

Keywords: potato; picking machine; pick-up unit; tonnage unitization

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1. Introduction

Potatoes rank as the world's fourth-largest food crop, claiming the largest global planting area and production volume. In developed Western nations, agricultural production primarily relies on large-scale potato harvesters [1–5]. Companies like Spudnik Equipment Company LLC in the United States, GRIMME in Germany, and AVR in Belgium specialize in manufacturing large-scale, self-propelled potato harvesters with multiple rows. However, these machines are costly and cause considerable damage to harvested potatoes. The potato industry in European and American countries is mainly focused on processing, while in China, potatoes are primarily consumed fresh. Potatoes require long-term storage, and there are specific requirements for minimizing damage to the potatoes. Consequently, the substantial potato harvesters utilized in European and American countries do not suitably match the current circumstances in our country [6].

In recent years, Zhang Z. G. et al. developed a multi-stage separation buffer potato harvesting machine to mitigate the high potato peel damage rate while harvesting in mountainous, adhesive, and compact soil conditions [7]. The machine adopts a multi-stage vibration separation, multiple buffering, and low-level side laying approach to minimize potato collision damage. Li X. Q. et al. A round potato lifting and transportation device suitable for potato lifting operation was developed to address the problems of broken skins and high potato damage rates caused by long transportation distances of existing potato harvesters [8]. Wei H. A. et al. discovered that the conveying system could easily cause scratches on potato skins due to the excessive transmission speed. The design of the potato conveying system was improved to ensure coordinated, stable functioning and a lower skin damage rate [9]. Lu J. Q. et al. addressed the mechanical damage caused to potato tubers during the lifting and transportation process of potato diggers based on kinematic and energetic analyses [10]. This research has shown some advancement in reducing potato damage, though it does not fully meet the necessary requirements for long-term potato storage. The study outlines effective technical solutions and improvement measures aimed at mitigating the high damage rates in potato picking machines.

In response to the issues mentioned above, this study proposes the creation of a traction type 4UJ-180A potato harvesting and bagging machine equipped with a toggle shaft, flexible conveyor, and hydraulic automatic control system. This machine is specifically designed to address the problems of serious skin breakage and injury to potatoes, poor impurity removal, and potato leakage in the existing potato harvester [11–13]. This study provides an in-depth analysis of the overall structure and operating principles of the machine, and then discusses the optimized design of its key components. Choosing relevant experimental parameters as factors, experiments were conducted to identify the optimal combination of operational parameters through the trial process. Subsequently, field experiments were carried out to validate the design of a model that adheres to the harvesting standards for potato-picking machines.

2. Materials and Methods

2.1. Overall Machine Structure and Operating Principles

Based on the potato drip irrigation strip ridge planting model commonly used in the northern regions of China, a 4UJ-180A potato harvesting and bagging machine was developed. It is operated by tractor traction, with dual-ridge operation and a working width of 1600 mm. Taking into account the practical requirements for low skin breakage, potato injury, loss rate, and impurity content in potato harvesting, the designed potato picking and bagging machine is depicted in Figure 1. It is mainly composed of a traction mechanism, picking device, potato–soil separation conveyor, lifting and buffering device, bagging device, frame, transmission device, etc.

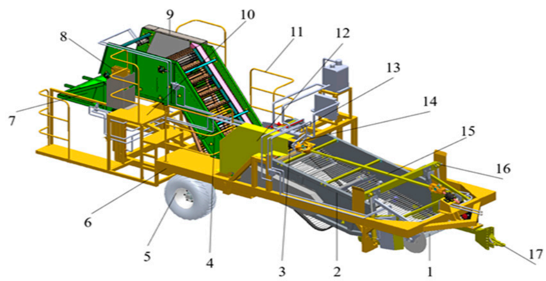

Figure 1. 4UJ-180A potato picking and bagging machine: (1) picking device; (2) potato–soil separation conveyor; (3) stem removal device; (4) lifting buffering device; (5) walking device; (6) frame; (7) bagging device; (8) hydraulic lifting assembly; (9) electromagnetic clutch; (10) operator's console; (11) guardrail; (12) transmission chain; (13) triple gear pump; (14) gearbox; (15) transmission shaft; (16) picking angle adjustment device; (17) traction device.

The potato picking and bagging machine operates in the following manner: picking potatoes, separating soil, elevating buffering, manually sorting debris, bagging, and unloading potato pieces. This machine is suitable for use on the flat terrain and minimal ground undulations present in northern regions of China. The machine builds upon the mechanized killing of potato vines and early removal of drip irrigation tapes. The potato harvesting and bagging machine utilizes a chain drive system, as depicted in Figure 2. The mechanical power is transmitted from the tractor through the driveline to the gearbox. The output shaft of the gearbox transmits power via a chain to the rear, ultimately reaching the main drive shaft for separating potatoes from the soil. Then, the main drive shaft for potato and soil separation transfers power to the main drive shaft of the dehaulming device through chain transmission. The front hydraulic cylinder controls the depth at which the picking device enters the soil, ensuring a constant depth. The hydraulic motor drives the soil turning shaft, allowing for the adjustment of the soil turning shaft speed to reduce soil blockage on different terrains. The rear-adjusting lifting buffer device is controlled by a hydraulic motor to regulate the speed, and the movement of the ton bag base is also adjusted by a hydraulic cylinder.

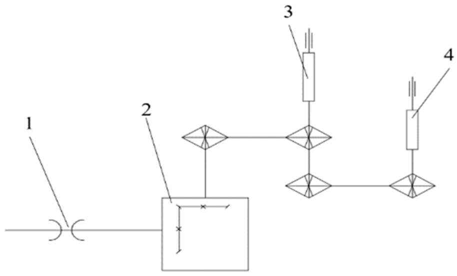

Figure 2. Schematic diagram of the drive system for the picking and bagging machine: (1) driveshaft; (2) gearbox; (3) potato–soil separation main drive shaft; (4) main drive shaft of device for removing potato stems.

2.2. Working Principle and Key Technical Parameters

During field operations, the 4UJ-180A potato picker and bagger is tractor-powered. Soil-cutting discs on either side of the picker avoid soil blockage, ensuring potatoes do not roll off. The flat shovel lifts the entire potato–soil–stem composite and conveys it to the potato–soil separation conveyor device through the soil-turning shaft. The mixture of potatoes, soil, and sprouts is separated using a rubber prong grid rod-type machine that involves shaking and conveying mechanisms. This process filters out most of the soil and fractures any remaining hard soil clumps through vibration, making them easier to remove. Then, the potato chunks and vines are conveyed further, with the chunks being directed to the bagging device, and then transported into the ton bag. When the 1000-kg bag is full, the electromagnetic clutch on the buffering device is disengaged, pausing the operation. The potatoes situated on the lifting device are stored in the buffer zone. Then, the hydraulic lever is maneuvered to lower the ton bag base to its lowest point, resulting in an automatic slide down to the ground. Once the bag replacement is completed, the electromagnetic clutch is engaged, resuming operations. The technical specifications for the 4UJ-180A potato harvesting and bagging machine are provided in Table 1.

Table 1. Main technical parameters of the working machine.

Parameter	Value
Overall dimensions length × width × height/mm	5200 × 2023 × 1550
Working width/mm	1600
Overall weight/kg	2500
Power supply/kw	66.1~88.2
Attachment Method	tractor-towed

2.3. Design of Key Components and Determination of Parameters

2.3.1. Picking Device

The picking device [14–18], as shown in Figure 3, comprises various components including a cutting soil disc, a three-part flat shovel, and a soil-pushing shaft. The flat, three-section shovel moves the potato–soil–plant mixture onto the soil-displacing axle. The soil-cutting disc helps prevent soil blockages and ensures that potatoes stay on the shovel. A flat shovel is necessary for shallow soil penetration during picking. If the shovel encounters soil blockages while entering the soil, potatoes in the soil layer may rub and squeeze against each other. To address soil blockages, a soil-displacing axle is incorporated, and the rotational speed of the axle is customized based on changes in soil moisture and texture.

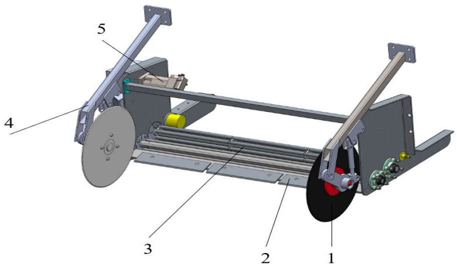

Figure 3. Schematic diagram of picking device: (1) cutting soil disc; (2) flat shovel; (3) soil-pushing shaft; (4) supporting frame; (5) hydraulic motor.

The picking device is connected to the frame through bolts, allowing for quick and straightforward replacement and maintenance. The hydraulic motor independently controls the rotation speed of the soil-pushing shaft, optimizing its effectiveness for different terrains. The hydraulic cylinder manages the picking shovel framework, ensuring a consistent penetration depth into the soil.

Based on the findings of Figure 4, it is clear that the angle "α" of the picking shovel has a considerable impact on soil blockage height, skin damage, potato injury, and potato leakage rate during operation. Taking into account the movement conditions of the potato–soil–seedling composite on the shovel surface, it is possible to develop an equation to describe these effects.

$$\begin{cases} P\cos\alpha - T - G\sin\alpha \geq 0 \\ N - G\cos\alpha - P\sin\alpha = 0 \end{cases} \tag{1}$$

$$T = N\mu \tag{2}$$

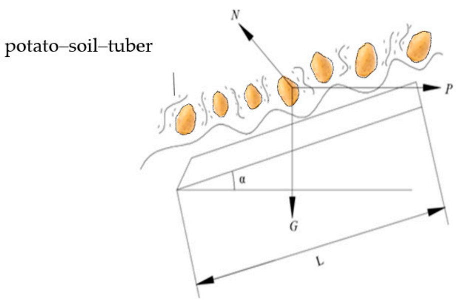

Figure 4. Schematic diagram of picking shovel operation.

In the equation, the terms are defined as follows:

P—The force required to pick up objects while moving along the picking shovel, N;

N—The reaction force of the picking shovel on the soil, N;

T—The frictional force between the shovel surface and the potato–soil–seedling composite, N;

G—The weight of the potato–soil–seedling composite on the shovel surface, N;

μ—The friction coefficient between the potato–soil–seedling composite and the picking shovel;

α—The angle of inclination of the picking shovel to the horizontal plane.

The following is calculated from Equations (1) and (2):

$$P \geq \frac{Q \tan \alpha + \mu}{1 - \mu \tan \alpha} \tag{3}$$

When the picking shovel's angle of inclination decreases, the force required for the movement of the potato–soil–seedling combination along the picking shovel also decreases in accordance with Equation (3). This results in reduced picking resistance and improved soil penetration performance. However, a decrease in the inclination angle may lead to shallower soil penetration depth and potential potato leakage. Conversely, an increase in the inclination angle of the picking shovel allows for deeper soil penetration, ensuring the collection of all potatoes, but it also encounters greater resistance. To ensure the picking shovel blade is self-cleaning, the blade angle and friction factors between the potato–seedling–soil composite and the shovel should meet the following specific criteria:

$$\begin{cases} 90^\circ - \theta > \varphi \\ \mu = \tan \varphi_{\max} \end{cases} \tag{4}$$

θ—The blade angle of the picking shovel, 45°;

φ—The friction angle between the potato–seedling–soil composite and the picking shovel, (°);

$\varphi_{\max}$—The maximum friction angle between the potato–seedling–soil composite and the picking shovel, (°), taking the critical value.

Calculated from Equation (4), $\varphi_{\max}$ = 45°, μ = 1.

The potato picking and bagging machine's picking shovel should have an inclination angle that does not exceed 24 degrees [19]. The optimal inclination angle for the picking shovel, which is between 18 and 22 degrees and has an L value of 95 mm, was determined through the calculation and analysis of Equations (1)–(4) and based on the expected functional requirements of the picking shovel. During the field operation of a potato picking and bagging machine, relying only on the mutual interaction force between the potato–seedling–soil composite in front of the picking shovel and the composite on the picking shovel surface is inadequate to overcome the static friction force between them. Consequently, the accumulation of a large number of potatoes at the picking device leads to severe soil blockage. Additionally, the height of the soil blockage is in direct correlation with the depth that the picking shovel penetrates the soil. If the shovel penetrates shallowly, even if the soil blockage height is low, there is a substantial possibility of potato leakage. The thin soil layer protecting the potatoes leads to increased bouncing and collisions during the potato–soil separation process, resulting in severe skin damage. Furthermore, increased soil penetration depth of the picking shovel leads to higher soil blockage volume, leading to mutual compression of potatoes in the soil and resulting in severe damage. This results in increased forward resistance of the equipment, decreased work efficiency, higher energy consumption, and environmental pollution [20].

To solve the problem of soil blockage at the picking device, an extra set of soil-pushing shafts is installed at the back of the picking shovel. The rotating soil-pushing shaft pushes the potatoes backward, allowing them to move effortlessly towards the rear. The soil-pushing effect of the soil-pushing shaft is improved by distributing four and six pushing rods on the front and rear main shafts, respectively. The front soil-pushing shaft has a diameter of 78 mm, while the rear shaft has a diameter of 107 mm. Both shafts are 1356 mm in length, and the distance between them is 142 mm. Backward conveyance of the potato–seedling–soil composite occurs smoothly, which diminishes mutual compression and collisions of the potatoes in the soil, ultimately reducing the rate of skin damage.

The device that picks potatoes experiences cyclic motion due to the soil-pushing shaft, which pushes the potatoes during the feeding of the composite and soil blockage. While the soil blockage accumulates, the volume of soil blockage at time t_1 on the picking device is referred to as S_{t1}.

$$S_{t1} = S_{n-1} + \int_{(n-1)T}^{t_1} (s_\chi - s_\lambda)dt \tag{5}$$

In the equation, the terms are as follows:

S_{t1}—The volume of soil blockage on the picking device at time t_1, m^3;

S_{n-1}—After $n-1$ cycles of the soil-pushing shaft working, the remaining volume of soil blockage on the picking device, m^3;

t_1—The time at any moment during the process of soil blockage accumulation, s;

T—The time taken to complete one cycle, s;

n—The number of revolutions of the soil-pushing shaft;

s_χ—The speed of the composite material entering the picking device, m^3/s;

s_λ—The speed at which the composite material is pushed by the soil-pushing shaft, m^3/s.

In one cycle, when $t_1 = nT$, the soil blockage volume is maximized, as shown in the following:

$$S_{nt} = S_{\max} = S_{n-1} + \int_{(n-1)T}^{nT} (s_\chi - s_\lambda)dt \tag{6}$$

The schematic diagram in Figure 5 displays the force analysis of potatoes being conveyed backward by the soil-pushing shaft. When both the front and rear soil-pushing shafts' pushing rods support the potatoes during the pushing operation, a matrix analysis is conducted clockwise as the positive direction.

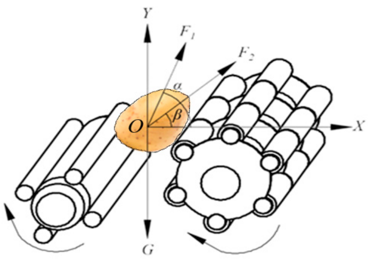

Figure 5. The force analysis diagram during the operation of the soil-pushing shaft. Note: G represents the weight of the potato in Newtons (N).

$$M_{xy} = F_1(l_{1x}\sin\beta + l_{1y}\cos\beta) + F_2(l_{2x}\sin\alpha + l_{2y}\cos\alpha) \tag{7}$$

In the equation, the terms are as follows:

M_{xy}—Represents the torque experienced by the potato on the θ surface, Nm;

F_1, F_2—Represent the forces exerted by the pushing rods of the front and rear soil-pushing shafts on the potato, respectively, N;

l_{1x}, l_{2x}—Represent the projections on the x-axis of the distances from the contact points of the front and rear soil-pushing shafts with the potato to the center of mass of the potato, m;

l_{1y}, l_{2y}—Represent the projections on the y-axis of the distance from the contact point of the front and rear soil-pushing shafts with the potato to the center of mass of the potato, m;

α, β—Represent the angles between F_1, F_2 and the horizontal plane, respectively, (°).

The analysis demonstrates that the force from the soil-pushing shaft creates torque on the potato. As the soil-pushing shaft moves the potatoes and soil forward, collisions and compression between potatoes are averted after soil blockage, preventing skin damage. Furthermore, the rotation of the soil-pushing shaft lessens the adhesive force between soil and potatoes, reducing collisions and friction, and soil blockage. This leads to fewer occurrences of soil sticking to the potatoes.

2.3.2. Upward Buffering Device

After the potatoes are separated from the soil and the vines, the potatoes may still contain hard clods and stones that cannot be separated. To minimize damage from bouncing and collisions during transportation, and to ensure continuous operation in coordination with the hydraulic control sliding-rail bagging device, a new solution was proposed. This solution involves a cast rubber biomimetic lifting and buffering device [21]. This device is flexible and equipped with a biomimetic lifting chain that can grip the potatoes, ensuring stable conveyance and minimal skin damage. When a ton bag filled with potatoes needs to be unloaded, the electromagnetic clutch disengages, allowing the lifting chain to transfer the potatoes onto the material storage platform. After replacing the bag, the electromagnetic clutch re-engages for uninterrupted operation, enhancing operational efficiency [22]. The device primarily comprises a lifting drive shaft, a material storage platform drive shaft, an electromagnetic clutch, a cast rubber biomimetic lifting chain, support and guide wheels, a frame, and other integral components, as illustrated in Figure 6 [21].

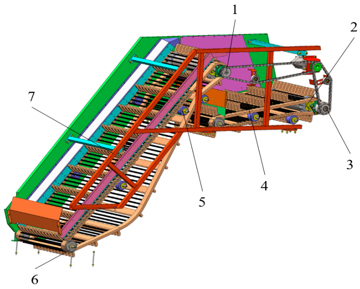

Figure 6. The schematic diagram of the lifting buffering device: (1) lifting drive shaft; (2) material storage platform drive shaft; (3) electromagnetic clutch; (4) cast rubber biomimetic lifting chain; (5) supporting wheels; (6) guide wheels; (7) frame.

The primary operational factors influencing the lifting buffering device include the speed of the cast rubber biomimetic conveyor belt, the belt's angle of inclination, the length of the blocking finger, and the depth of the buffering apparatus. Given that the device's main purpose is to transport potatoes, it is reasonable to assume that the parameters used for conveying other materials are approximately applicable to potatoes as well. The speed of the cast rubber biomimetic conveyor belt should be adjusted accordingly to ensure optimal transportation.

$$v_{r2} = \frac{n_s \pi (D_1 + 2D_2)}{60} \tag{8}$$

Among them, the soil blockage is as follows:

$$S = ab$$

In the equation:

n_s—The speed of the output shaft of the hydraulic motor in the lifting buffering device, r/min;

D_1—The pitch circle diameter of the rubber flange on the cast rubber biomimetic conveyor belt, m;

D_2—The thickness of the cast rubber biomimetic conveyor belt, m.

2.3.3. Hydraulic Control Sliding-Rail Bagging Device

During operation of the potato picking and bagging machine, the ton bag base is raised to its highest position. After the potatoes have undergone multiple separations from soil clods, stones, seedlings, and weeds during the picking process, potatoes are deposited into the ton bag at the end of the buffering component. To streamline the labor-intensive process of manually unloading potatoes, a sliding-rail bagging device with hydraulic controls is utilized. Figure 7 illustrates this hydraulic control sliding-rail bagging device, which is situated at the termination point of the potato picking and bagging machine. The device consists of the ton bag base, ton bag base support, a Y-shaped track, hydraulic rod, pulley chain assembly, rolling wheel, and other components [23,24].

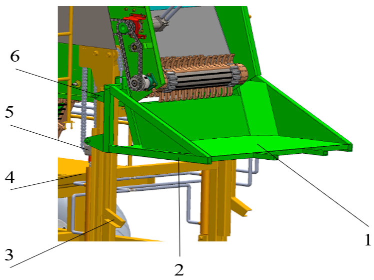

Figure 7. Schematic diagram of the hydraulic control sliding-rail bagging device: (1) ton bag base; (2) ton bag base bracket; (3) Y-shaped rail; (4) hydraulic rod; (5) pulley chain assembly; (6) rolling wheel.

Potato harvesting is a crucial aspect of potato picking and harvesting machines. This process significantly influences the skin quality of the potatoes. During the ejection process at the end of the lifting buffer device, the potatoes are subjected to the combined forces of gravity and centrifugal force [25,26]. To examine the motion trajectory of potato chunks during their descent and the force characteristics upon landing in the collection device, we conducted an experiment using a single potato chunk as the subject, as illustrated in Figure 8.

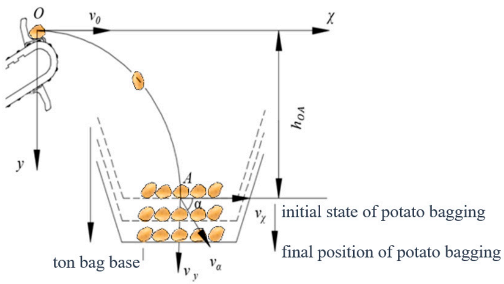

Figure 8. The kinematic analysis of potatoes during the harvesting process.

The potato pieces are ejected from the end of the lifting buffer device at a specific initial velocity, denoted as v_0, and descend into the ton bag. Throughout their trajectory, potatoes are influenced only by gravitational force, with air resistance considered negligible. This motion is depicted in segment *OA* in Figure 8. A Cartesian coordinate system was established for analysis, taking the center point *O* of the potato pieces at the end of the lifting buffer device as the origin. In this system, the end of the lifting buffer device aligns with the positive *x*-axis, and the vertical downward direction corresponds to the positive *y*-axis. The potato chunks were treated as point masses for the purpose of this analysis. When a potato fragment is ejected from the end of the lifting buffer apparatus with a horizontal velocity of v_0 and descends onto the ton bag base, it is subject to gravitational acceleration of 9.8 m/s^2. Under these conditions, the kinematic equation describing the motion of the potato fragment can be formulated as follows:

$$\begin{cases} v_x = v_o \\ v_y = \sqrt{2gh_{OA}} \end{cases} \quad (9)$$

In the equation, the terms are as follows:

v_x—The horizontal component of the potato chunk's velocity at the moment of initial contact with the ton bag base, m/s;

v_y—The vertical component of the potato chunk's velocity at the moment of initial contact with the ton bag base, m/s;

h_{OAt}—The vertical height of the potato chunk at a specific moment when it is ejected from the lifting buffer device to the ton bag base, m.

The primary sources of damage during potato harvesting are the collisions between potato chunks and the ton bag base, as well as compression among the potato chunks themselves. The instantaneous velocity v_0 of a potato chunk during ejection is equal to the linear velocity v_{r2} of the rubberized biomimetic conveyor belt. The velocity of a potato chunk at the moment it collides with the ton bag base is a critical factor to consider.

$$\begin{cases} v_\alpha = \frac{v_x}{\cos\alpha} \\ \alpha = \arctan\frac{\sqrt{2gh_{OA}}}{v_{r2}} \end{cases} \quad (10)$$

The potato chunk satisfies the law of conservation of energy in segment OA, and the process of its motion analysis is as follows:

$$\begin{cases} E_{ka} - E_o = \frac{1}{2}(mv_a{}^2 - mv_o{}^2) \\ E_{ka} - E_{ko} = mgh_{OA} \end{cases} \quad (11)$$

In the equation, the terms are as follows:

E_{ko}—The kinetic energy of the potato chunk during ejection from the lifting buffer device, J;

E_{ka}—The kinetic energy of the potato chunk as it falls onto the ton bag base, J;

m—The mass of the potato chunk, g;

v_a—The velocity of the potato chunk at the moment of collision with the ton bag base, m/s.

According to Equation (8), the kinetic energy of the potato chunk upon collision with the ton bag base is obtained as follows:

$$E_{ka} = mgh_{OA} + \frac{1}{2}mv_{r2}{}^2 \quad (12)$$

After the initial layer of potato chunks falls onto the base of the ton bag, the bag absorbs the impact energy. Each subsequent layer of potatoes added to the bag also absorbs its own impact energy. As the total weight of the potato mass inside the bag gradually increases, the hydraulic cylinder rod that controls the bag's movement begins to retract. The fall height of the potato chunks (h_{OA}) is meticulously regulated to prevent potentially damaging impacts on the ton bag base. The forward speed of the equipment, the linear speed of the lifting buffer device, and the vertical height from which the potato chunks fall are interdependent variables. Taking into account the necessary adjustments for the chosen track, the positioning of the hydraulic cylinder, and the tilt angle of the ton bag base, the height of the ton bag base was set at 300 mm.

2.3.4. Experimental Design

In a preliminary experiment aimed at reducing potato damage and enhancing operational efficiency in the 4UJ-180A potato picking and bagging machine, the selected factors for optimization were as follows: (A) forward speed, (B) soil separation conveyor speed, and (C) ridger shaft speed. Experimental analysis determined that the optimal range for forward speed is 1–2 m/s, while the conveyor speed should be between 20–28 rpm, and the ridger shaft speed should range from 35–45 rpm. The forward speed of the machine causes the potato pieces to miss being picked up; as well, debris cleanup is not clean, and the broken skin rate, injury rate, loss rate and the rate of impurity increase; with a slower forward speed, the operational efficiency is low, and the operating cost is high. When the speed of the paddle shaft is faster, the potato pieces are strongly pushed and collide, and a backward force leads to potato skin damage caused by the skin breakage rate, and the rate of injury to the potato pieces increases. When the paddle shaft speed is slower, the congestion is serious and the potato pieces are over-squeezed, resulting in skin breakage caused by the skin breakage rate and the rate of loss. The machine is subjected to greater resistance, and the operational efficiency is low. When the speed of the potato and soil separating conveying device is faster, the high frequency vibration of cast rubber barbed wire conveyor chain leads to potatoes without soil protection, and damage results in skin breakage and increased rate of injury. When the speed is slower, the separation of potato and soil is incomplete, and the conveying device and lifting caching device become clogged, resulting in increased skin breakage, loss rate, and increased rate of impurity. The key performance indicators for the harvesting process include the rates of potato skin damage, bruising, loss, and the presence of impurities. An L9(3ˆ4) orthogonal array was used for a three-factor, three-level orthogonal experiment. The goal was to examine the primary and secondary relationships between the experimental factors and performance indicators to identify the most effective combination. The orthogonal test factor levels are shown in Table 2.The tractor's gear and throttle control the forward speed of the potato picking and bagging machine during experimentation, while the speed of the conveyor for potato–soil separation and the ridging shaft was adjusted using hydraulic speed control valves [27,28].

Table 2. Levels of factors for orthogonal experimental design of harvesting performance.

Levels	A/(m/s)	B/(rpm)	C/(rpm)
1	1	20	35
2	1.5	24	40
3	2	28	45

2.3.5. Experimental Conditions and Performance Indicators

In August 2023, a preliminary trial was conducted at a potato planting center in Hohhot, Inner Mongolia Autonomous Region, China. The site utilized a drip irrigation strip ridge planting model for dryland cultivation, with the soil moisture content ranging from 12% to 14%. Each experimental plot was maintained with a length of 200 m and a width of at least 50 m. At the ridge planting site, the ridge width was 900 mm, the furrow width was 350 mm, and the ridge height was 250 mm. The potato variety used was 'Wotu'. After the surface sprouts were cleared using a vine killing machine, the potatoes were excavated and spread out on the ground by a digger, then left to dry for a period of 2 to 3 h Performance tests for the 4UJ-180A potato picking and bagging machine were conducted in accordance with the national industry standards GB/T5667-2008 [29] and NY/T2464-2013 [30]. These standards govern the testing methods for agricultural machinery production and the quality of potato harvester operation (Figure 8). In adherence to these standards, the machine's design and functions were objectively tested. The prototype of the machine was paired with a John Deere 5-904 tractor, which has a power output of 59.58 kW. The evaluation criteria for the machine's performance included the skin damage rate, bruise rate, loss rate, and impurity rate during operation.

$$L_1 = \frac{Q_1 + Q_2}{Q} \times 100\% \quad (13)$$

$$L_2 = \frac{Q_3}{Q} \times 100\% \quad (14)$$

$$L_3 = \frac{Q_5}{Q} \times 100\% \quad (15)$$

$$L_4 = \frac{Q_6}{Q_4 + Q_6} \times 100\% \quad (16)$$

In the equations, the terms are as follows:
L_1—The loss rate, %;
Q_1—The weight of potatoes missed during harvesting, kg;
Q_2—The weight of potatoes missed during digging, kg;
Q—The total weight of potatoes, kg;
L_2—The bruise rate, %;
Q_3—The weight of bruised potatoes, kg;
L_3—The missed potato rate, %;
Q_5—The weight of potatoes with damaged skin, kg;
Q_4—The harvested potato mass, kg;
L_4—The impurity rate, %;
Q_6—The weight of impurities, kg.

A benchmark double-ridge body width of 30 m was designated for the experimental site. Experimental intervals at the site were selected randomly. Three repeated picking experiments were conducted, and the average results from these trials were considered. Additionally, the working performance of the picking device, lifting buffer device, and hydraulic control sliding-rail-type bagging device was observed [31].

3. Results

To determine the best parameter combination, a three-factor, three-level orthogonal experiment was performed on the chosen factor levels. Results of the experiment are presented in Table 3.

Table 3. Results of the orthogonal experimental design for harvesting performance.

Test Number	Factors				Evaluation Indicators			
	Empty Column	A	B	C	Skin Damage Rate W (%)	Bruise Rate X (%)	Loss Rate Y (%)	Impurity Rate Z (%)
1	1	1	1	1	4.9	1.7	0.5	0.8
2	1	2	2	2	9.2	3.5	1.1	0.7
3	1	3	3	3	10.4	4.4	1.3	1.4
4	2	1	2	3	7.7	2.3	1	0.9
5	2	2	3	1	7.3	1.3	0.7	1
6	2	3	1	2	9.2	6.4	1	1.2
7	3	1	3	2	3.4	2.2	0.9	0.9
8	3	2	1	3	9.8	4.2	1.5	0.7
9	3	3	2	1	8.7	3.4	1.4	0.8

3.1. Orthogonal Analysis

Range analysis and variance analysis are two methods used to analyze results in orthogonal experiments. Range analysis is straightforward and easy to understand. In contrast, variance analysis delves into identifying which variables significantly impact the outcome by examining the variance of the observed variables. The results of both the range and variance analyses are presented in Tables 4 and 5.

Table 4. Range analysis of each factor in the orthogonal experimental design for harvesting performance.

Experimental Indicator	Analysis Item	Error	A	B	C
Skin Damage Rate/%	K1	24.5	16	23.9	20.9
	K2	24.2	26.3	25.6	21.8
	K3	21.9	28.3	21.1	27.9
	Range	0.87	4.1	1.5	2.3
	Importance order		A > C > B		
	Optimal choice		$A_1C_1B_3$		
Bruise Rate/%	K1	9.6	6.2	12.3	6.4
	K2	10	9	9.2	12.1
	K3	9.8	14.2	7.9	10.9
	Range	0.1	2.7	1.5	1.9
	Importance order		A > C > B		
	Optimal choice		$A_1C_1B_3$		
Loss Rate/%	K1	2.9	2.4	3	2.6
	K2	2.7	3.3	3.5	3
	K3	3.8	3.7	2.9	3.8
	Range	0.37	0.43	0.2	0.4
	Importance order		A > C > B		
	Optimal choice		$A_1C_1B_3$		
Impurity Rate/%	K1	2.9	2.6	2.7	2.6
	K2	3.1	2.4	2.4	2.8
	K3	2.4	3.4	3.3	3
	Range	0.2	0.33	0.3	0.1
	Importance order		A > B > C		
	Optimal choice		$A_2B_2C_1$		

Table 5. Analysis results and variance analysis of harvesting performance orthogonal experiment.

Experimental Indicator	Sources of Variance	Sum of Squares of Deviations	Degrees of Freedom	Mean Squared Sum of Deviations	F-Value	*p*-Value
Skin Damage Rate/%	Error	1.35	2	0.68		
	A	29.04	2	14.52	21.53	0.0444 *
	B	3.44	2	1.72	2.55	0.2815
	C	9.67	2	4.84	7.17	0.1224
	Total T_K	43.5	8	21.76		
Bruise Rate/%	Error	0.03	2	0.02		
	A	10.99	2	5.50	412.00	0.0024 **
	B	3.41	2	1.71	127.75	0.0078 **
	C	6.02	2	3.01	225.75	0.0044 **
	Total T_K	20.45	8	10.24		
Loss Rate/%	Error	0.23	2	0.12		
	A	0.30	2	0.15	1.29	0.4364
	B	0.07	2	0.04	0.30	0.7687
	C	0.25	2	0.13	1.09	0.4791
	Total T_K	0.85	8	0.44		
Impurity Rate/%	Error	0.09	2	0.05		
	A	0.19	2	0.01	2.15	0.3171
	B	0.14	2	0.07	1.62	0.3824
	C	0.03	2	0.02	0.31	0.7647
	Total T_K	0.45	8	0.15		

Note: ** indicates extremely significant ($p < 0.01$); * indicates significant ($0.01 \le p < 0.05$).

Variance Analysis

Based on Table 4, one can retrieve the variance analysis, F-values, and significance of the experimental indicators. The outcomes are presented within Table 5.

Through the range and variance analysis, it can be observed that the forward speed, conveyor speed, and ridging shaft speed of the picking machine each have different effects on the skin damage rate, bruise rate, loss rate, and impurity rate. According to the variance analysis results presented in Table 5, it is clear that factors A (forward speed), B (conveyor speed), and C (ridging shaft speed) do not significantly impact the loss rate and impurity rate of the potatoes.

However, the skin damage rate is significantly affected by the forward speed of the machine. A higher speed results in greater impact and compression forces during the potato picking process, leading to increased skin damage. Conversely, a lower speed can lead to serious soil blockage, causing mutual compression among the potatoes and resulting in skin damage. According to the experimental findings, the factors influencing the bruise rate in descending order of impact are as follows: forward speed (A), ridging shaft speed (C), and conveyor speed (B). All of these factors are highly significant. A faster forward speed increases the likelihood of mechanical collisions, mutual compression, and scraping of the potato during the harvesting process, leading to internal tissue damage. An increase in the ridging shaft speed intensifies soil stirring, causing the potatoes to collide and become damaged. Conversely, a slower ridging shaft speed results in severe soil blockages, leading to potato damage from compression between the potatoes and soil clods. A higher initial velocity, caused by a faster conveyor speed when propelling the potatoes into the ton bag, also leads to damage upon impact. At a slower conveyor speed, potatoes tend to accumulate between the soil separation system and the lifting device. This accumulation can result in mutual compression and collisions when the lifting device engages the potatoes, potentially causing damage. Moreover, the potential for potatoes to fall off the rubberized tine grid increases at a slower conveyor speed, further contributing to the risk of damage [11,32,33].

By utilizing range and variance analysis and considering the primary and secondary relationships between various experimental factors and their effects on performance indicators, criteria were established for selecting the optimal combinations to reduce skin damage, bruising, loss, and impurities in the machine. After a thorough evaluation, the final optimal combination was determined to be $A_1C_1B_3$, corresponding to a forward speed of 1 m/s, a ridging shaft speed of 35 rpm, and a conveyor speed of 28 rpm.

3.2. Field Test

Based on the results of the range analysis and orthogonal experimental analysis, the optimal working combination parameters are $A_1C_1B_3$, with a forward speed of 1 m/s, ridging shaft speed of 35 rpm, and conveyor speed of 28 rpm. To validate the accuracy of these parameters, nine performance tests were conducted on the 4UJ-180A potato picking and bagging machine using the optimal working parameters. These tests were carried out under the same conditions as described in Sections 2.3.3 and 3.1. The results showed a skin damage rate of 2.8%, a bruise rate of 1.3%, a loss rate of 0.4%, and an impurity rate of 0.7%. Under these optimal working parameters, the experiment demonstrated a marked improvement in the quality of potato harvesting during the mechanized picking process. Thus, the optimal parameter combination can be deemed reliable. The picker field operation optimization test is shown in Figure 9.

Figure 9. Field experiment of the machine.

4. Discussion

Currently, in China, the main method for harvesting potatoes uses potato excavators for digging and manual picking to reduce the damage rate of potatoes. However, this method has low work efficiency and high costs. Chinese scholars have conducted research on key components of potato harvesters to improve their harvesting efficiency and ensure better coordination and stability of each component. Despite these efforts, the damage rate of potatoes remains high, and the requirements for long-term potato storage have not been met.

This study described the development of the 4UJ-180A potato picking and bagging machine, with key operating components like the picking device, lifting buffer device, and hydraulic control sliding rail-type bagging device being optimized for design and theoretical analysis. The primary objective was to reduce the skin damage rate, bruise rate, loss rate, and impurity rate during harvesting. The machine's ridging shaft, which uses a push rod to drive both potatoes and soil forward, effectively addresses the issue of skin damage caused by collisions and compression after soil blockage. Wang X. et al. developed a picking apparatus capable of dual-layer reversing chain clamping and conveying, employing baffles that move in opposite directions to push the potatoes backwards, though this may cause skin damage due to direct contact and mutual compression [15]. The harvester features a hydraulically controlled sliding rail-type bagging device, which maintains an optimal vertical drop height for the potatoes, thereby enabling flexible harvesting and minimizing collisions. Wei Z. C. et al. further enhanced this potato harvester with an efficient packaging and unloading system that includes a buffering process to decrease the kinetic energy of the potatoes before bagging, though some damage may still occur from two collision areas [34]. This mechanization not only increases harvesting efficiency and reduces labor costs, but also promotes the independent research and development of agricultural machinery in China, aligning with the evolving needs of agricultural production. Field trials showed that, at a forward speed of 1 m/s, a ridging shaft speed of 35 rpm, and a conveyor speed of 28 rpm, the potato picking machine achieved a skin damage rate of 2.8%, a bruise rate of 1.3%, a loss rate of 0.4%, and an impurity rate of 0.7%, demonstrating that the 4UJ-180A meets national industry standards.

5. Conclusions

(1) The 4UJ-180A potato picking and bagging machine is a traction-type machine equipped with a ridging shaft, a flexible conveying system, and a hydraulic control system. The ridging shaft is designed to efficiently reduce soil blockage, thus minimizing skin damage on potatoes. Additionally, the machine features a rubberized biomimetic deflector that ensures stable potato conveying, thereby reducing collision-related damage. The hydraulic control system, in conjunction with buffer components and the bagging

device, work collaboratively to facilitate a consistent and adaptable potato harvesting and bag unloading process, further decreasing skin damage during harvest.

(2) Field experiments with the 4UJ-180A potato picking and bagging machine show that the skin damage rate, bruise rate, loss rate, and impurity rate are 2.8%, 1.3%, 0.4%, and 0.7% respectively. These performance tests indicate that the machine complies with national industry standards, achieving skin damage rates of less than or equal to 3%, bruise rates of less than or equal to 2%, loss rates of less than or equal to 4%, and impurity rates of less than or equal to 4%. These results satisfy the design criteria for the machine.

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References

1. Wang, H.C.; Zhao, W.Y.; Sun, W.; Zhang, H.; Liu, X.L.; Li, H. Research progress on the technology and equipment for potato mechanized harvesting. *Trans. Chin. Soc. Agric. Eng.* **2023**, *39*, 1–22.
2. Fan, J.; Li, Y.; Luo, W.; Yang, K.; Yu, Z.; Wang, S.; Hu, Z.; Wang, B.; Gu, F.; Wu, F. An Experimental Study of Stem Transported-Posture Adjustment Mechanism in Potato Harvesting. *Agronomy* **2023**, *13*, 234. [CrossRef]
3. Zh Shkaruba, N.; Leonov, O.A.; Bogolubova, D.A. Ranking of Quality Indicators Influencing the Choice of Potato Harvester. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *981*, 042038. [CrossRef]
4. Hrushetsky, S.M.; Yaropud, V.M.; Duganets, V.I.; Pryshliak, V.M.; Kurylo, V.L. Research of constructive and regulatory parameters of the assembly working parts for potato harvesting machines. *INMATEH Agric. Eng.* **2019**, *59*, 101–110. [CrossRef]
5. Ruzhylo, Z.; Bulgakov, V.; Adamchuk, V.; Bondarchuk, A.; Ihnatiev, Y.; Krutyakova, V.; Olt, J. Experimental research into impact of kinematic and design parameters of a spiral potato separator on quality of plant residues and soil separation. *J. Agric. Sci.* **2020**, *31*, 202–207.
6. Wei, Z.; Li, H.; Sun, C.; Su, G.; Liu, W.; Li, X. Experiments and Analysis of a Conveying Device for Soil Separation and Clod-Crushing for a Potato Harvester. *Appl. Eng. Agric.* **2019**, *35*, 987–996. [CrossRef]
7. Zhang, Z.G.; Wang, H.Y.; Li, Y.B.; Yang, X.; Ibrahim, I.; Zhang, Z.D. Design and Experiment of Multi stage Separation Buffer Potato Harvester. *Trans. Chin. Soc. Agric. Mach.* **2021**, *52*, 96–109.
8. Li, X.Q.; Wang, X.H.; Liu, Y.; Wang, F.M.; Meng, P.X.; Wang, J.M. Design and Experiment of Circular Reducing and Collecting Potato Lifting Device for Potato Combine Harvester. *Trans. Chin. Soc. Agric. Mach.* **2023**, *54*, 1–12.
9. Wei, H.A.; Zhang, J.L.; Yang, X.P.; Huang, X.P.; Dai, L.X.; Sun, G.H.; Liu, X. Improvement Design and Experiment of 4UFD-1400 Potato Combine Harvester. *Trans. Chin. Soc. Agric. Mach.* **2014**, *30*, 12–17.
10. Lu, J.Q.; Yang, X.H.; Lu, Y.N.; Li, Z.H.; Li, J.C.; Du, C.L. Analysis and experimentation on tuber damage mechanism during the lifting and separating process of potato harvester. *Trans. Chin. Soc. Agric. Mach.* **2020**, *51*, 103–113.
11. Wei, Z.C.; Han, M.; Su, G.L.; Zhang, H.; Li, X.Q.; Jin, C.Q. Design and Experiment of 4UL-2 Potato Ton Bag Combine Harvester. *Trans. Chin. Soc. Agric. Mach.* **2023**, *54*, 1–12.
12. Wang, W.; Yang, R.; Pan, Z.; Qing, Y.; Zhang, J.; Chen, D.; Guo, X.; Lyu, S. Design and Experimental Study of Single Plant Harvester for Potato Breeding Experiments. *Agriculture* **2023**, *14*, 71. [CrossRef]
13. Mamatov, F.; Mirzaev, B.; Rustamova, N.; Razzokov, T.; Hamroev, O. Kinematic Mode of Operation of Potato Harvester Auger. *E3S Web Conf.* **2023**, *365*, 04029. [CrossRef]
14. Wang, X.Y.; Lu, D.Y.; Ren, J.Y.; Zhang, M.; Meng, P.X.; Li, X.Q. Development of a bagging-type potato combined harvester with cleaning and sorting device. *Trans. Chin. Soc. Agric. Eng.* **2022**, *38* (Suppl. 1), 8–17.

15. Wang, X.; Yang, D.Q.; Liu, M.M.; Li, Y.; Chen, X.Y.; Cheng, Z.W. Parameter optimization and experimentation on the picking device of a self-propelled potato picker. *Trans. Chin. Soc. Agric. Mach.* **2023**, *54* (Suppl. 2), 20–29.
16. Wang, L.; Liu, F.; Wang, Q.; Zhou, J.; Fan, X.; Li, J.; Zhao, X.; Xie, S. Design of a Spring-Finger Potato Picker and an Experimental Study of Its Picking Performance. *Agriculture* **2023**, *13*, 945. [CrossRef]
17. Wei, H.A.; Wang, D.; Lian, W.X.; Shao, S.L.; Yang, X.P.; Huang, X.P. Development of the 4UFD-1400 potato combined harvester. *Trans. Chin. Soc. Agric. Eng.* **2013**, *29*, 11–17.
18. Wang, F.H.; Xiong, H.H.; Lai, Q.H.; Liu, Z.Y.; Chen, K.F.; Lu, C.Y. Research on intelligent design system and evaluation method for potato harvester digging device. *Trans. Chin. Soc. Agric. Mach.* **2021**, *52*, 86–97.
19. Wei, Z.C.; Li, H.W.; Sun, C.Z.; Li, X.Q.; Su, G.L.; Liu, W.Z. Design and experimentation of a potato combined harvester based on multi-stage separation process. *Trans. Chin. Soc. Agric. Mach.* **2019**, *50*, 129–140+112.
20. Dai, F.; Zhao, W.Y.; Sun, W.; Wu, Z.W.; Song, X.F.; Li, Y. Design and experimentation of a combined operation machine for potato harvesting and pneumatic-assisted residual film recovery. *Trans. Chin. Soc. Agric. Mach.* **2017**, *48*, 64–72.
21. Lu, X.H.; Wang, X.; Zhang, W.J.; Shi, M.M.; Wei, H.A. Parameter analysis and experimentation of the separation and conveying device of the 4U-1400 potato combined harvester. *J. China Agric. Univ.* **2015**, *20*, 269–276.
22. Wei, Z.C.; Li, H.W.; Sun, C.Z.; Li, X.Q.; Liu, W.Z.; Su, G.L.; Wang, F.M. Improvement of a two-stage separation potato harvester with vibration and wave. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 42–52.
23. Hou, J.L.; Zhang, E.P.; Zhang, K.B.; Li, Y.H. Optimization design and experimentation of the transplanting device for chili based on DEM-MFBD. *Trans. Chin. Soc. Agric. Mach.* **2023**, *54*, 1–14.
24. Lu, J.Q.; Wang, P.R.; Liu, Z.F.; Li, Z.H.; Zou, F.Y.; Yang, D.Q. Design and experimentation of the potato and haulm separation device for potato harvester. *Trans. Chin. Soc. Agric. Mach.* **2019**, *50*, 100–109.
25. Yang, R.B.; Yang, H.G.; Shang, S.Q.; Xu, P.X.; Cui, G.P.; Liu, L.H. Design and experimentation of a roller pushing-type potato harvester. *Trans. Chin. Soc. Agric. Mach.* **2016**, *47*, 119–126.
26. Xin, L.; Liang, J. Design of Conveyor Separation Device for Potato Harvester and Analysis of Its Vibration Characteristics. *J. Comput. Methods Sci. Eng.* **2022**, *22*, 1385–1392. [CrossRef]
27. Wei, Z.C.; Wang, Y.W.; Li, X.Q.; Wang, J.M.; Su, G.L.; Meng, P.X.; Han, M.; Jin, C.Q.; Li, Z.H. Design and experiments of the potato combine harvester with elastic rubbing technology. *Trans. Chin. Soc. Agric. Eng.* **2023**, *39*, 60–69.
28. Wang, F.A.; Cao, Q.Z.; Li, Y.B.; Pang, Y.L.; Xie, K.T.; Zhang, Z.G. Design and passability testing of a self-propelled potato combined harvester in hilly and mountainous areas. *Trans. Chin. Soc. Agric. Mach.* **2023**, *54* (Suppl. 2), 10–19.
29. *GB/T 5667-2008*; Productive Testing Methods for Agricultural Machinery. China Machinery Industry Federation: Beijing, China, 2008.
30. *NY/T2464-2013*; Operating Quality for Potato Harvesters. Ministry of Agriculture of the PRC: Beijing, China, 2013.
31. Lu, J.Q.; Sun, H.; Dui, H.; Peng, M.M.; Yu, J.Y. Improved design and experimentation of the separation and conveying device of a potato harvester in sticky and heavy soils. *Trans. Chin. Soc. Agric. Mach.* **2017**, *48*, 146–155.
32. Chang, H.; Shi, W.; Li, W.; Wang, C.; Zhou, L.; Liu, J.; Yang, Y.; Ramesh, K.A. Experimental Optimization of Jet Self-Priming Centrifugal Pump Based on Orthogonal Design and Grey-Correlational Method. *J. Therm. Sci.* **2020**, *29*, 241–250. [CrossRef]
33. Tang, S.Q.; Yang, D.Y.; Bai, Q.Q. Orthogonal Testing Optimum Design in Radial Electrodynamic Magnetic Bearings. *Appl. Mech. Mater.* **2013**, *397–400*, 779–782. [CrossRef]
34. Wei, Z.C.; Han, M.; Su, G.L.; Zhang, H.; Li, X.Q.; Jin, C.Q. Design and experimentation of the bagging and unbagging potato combined harvester. *Trans. Chin. Soc. Agric. Mach.* **2023**, *54*, 92–104.