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Research Status and Progress of Potato-Soil Separation Device in Potato Harvester

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Abstract: As the fourth largest food crop globally, potatoes play a vital strategic role in ensuring food security. China ranks among the world leaders in both potato cultivation area and total production. The mechanization level during the harvesting stage is a critical factor driving industrial upgrading, creating an urgent demand for high-efficiency, low-damage combined harvesting equipment. As the core component of potato combine harvesters, the design and operational performance of potato-soil separation devices directly affect the overall machine efficiency, soil removal effectiveness, and product quality. This paper reviews the research progress on potato-soil separation devices in domestic and international potato harvesters, analyzes the structural designs and research status of mainstream global devices, and explores the application advances of key technologies such as Discrete Element Method analysis, high-speed imaging, and monitoring techniques in these systems. Future development directions are also discussed to provide references and technical insights for the development of high-efficiency, low-loss potato-soil separation devices.

Keywords: Potato machinery, Potato-soil separation device, Discrete Element Method, High efficiency.

1. Introduction

Potatoes, with their wide adaptability, high-yield potential, and rich nutritional value, have become the world's fourth largest staple food crop after rice, wheat, and corn, occupying an indispensable strategic position in global food security and agricultural economy [1]. As the largest potato producer globally, China has witnessed continuous expansion of its industrial scale since implementing the “potato staple crop strategy” in 2015, with its total output remaining the highest in the world [2]. However, there is still a significant gap between China's mechanization level in potato harvesting and that of developed countries in Europe and America, with the mechanization rate remaining below 32%. Manual and semi-mechanical harvesting modes are still prevalent [3], which not only severely restricts the economic benefits of large-scale cultivation but also limits industrial development due to high labor costs and intensity. Addressing the technical shortcomings in mechanized potato harvesting has therefore become a critical challenge requiring urgent resolution.

In the process of mechanized potato harvesting, the potato-soil separation device serves as the core functional unit, whose performance directly influences the overall operational efficiency of the harvester and the final harvesting quality. The primary task of this device is to effectively separate the mixture excavated from the soil together with potato tubers in complex field environments, ultimately yielding clean tubers with low impurity content and minimal damage. This requires the separation device to possess both high-efficiency soil and impurity removal capabilities and excellent vibration-damping, buffering, and flexible contact characteristics to protect tubers from damage to the greatest extent possible.

Current mainstream potato-soil separation devices mainly adopt chain-type, screen-type, roller-type structures, as well as their combined configurations or optimized forms [4]. By systematically reviewing the research progress of domestic and foreign potato-soil separation devices, deeply analyzing their structural features and the integrated application of innovative technologies in equipment development, especially the supporting role of cutting-edge methods such as discrete element simulation and monitoring in optimizing the performance of the devices, it is of guiding significance for the development of efficient and low-loss potato harvesting equipment that is adapted to China's agricultural conditions.

2. The Current Research Status of Potato-Soil Separation Devices

Based on the working principles and structural forms, the potato-soil separation devices currently used in potato harvesters in both domestic and foreign markets can mainly be classified into chain-type, screening-type, and roller- type.

2.1. Chain-type Separation Device

The chain-type device is also known as the bar conveyor belt. Its structure consists of a chain conveyor belt with several horizontal bars, and the gap between the bars is equivalent to the sieve holes. During the transportation process, the soil mixture leaks out through the gaps between the bars under the action of its own gravity and frictional vibration, while the potato blocks are held and continue to be transported forward. Its structure is simple and the cost is relatively low. The research focus lies in optimizing the shape and spacing of the bars, the running speed of the chain, and adding auxiliary vibration, etc.

For the planting areas with heavy clay soil in northern China's spring cropping regions, Lv et al. [5] designed a new type of lifting chain with a multi-segment curved and straight structure combination, as shown in Figure 1. Based on the dynamic model, the influence laws of the morphological changes of the rods on the motion trajectory and collision energy of the potato-soil mixture were revealed, and an optimization model including key operation parameters such as the running speed of the chain body, the working face inclination angle, and the material throwing height was established.

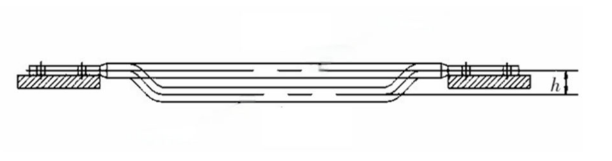

Figure 1. The chain with a multi-segment curved and straight structure combination

Yan [6] proposed a design of installing a cover plate rotating device above the lifting chain. The cover plate rotating device is shown in Figure 2. Under the differential action of the upper layer cover plate rotating device and the lower layer lifting chain, the potato-soil mixture separates. A dynamic model based on the interaction mechanism of potatoes and soil was established to analyze the collision process of the potato blocks. Through single-factor and response surface experiments, the optimal combination of device parameters was revealed to achieve low-loss and efficient potato-soil separation effect.

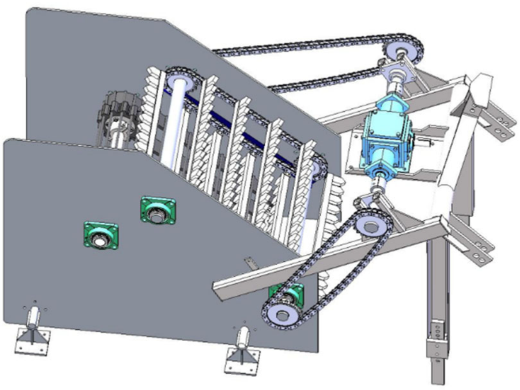

Figure 2. Three-dimensional model of the cover plate rotating device

The side-mounted potato harvesting equipment developed by German GRIMME Company innovatively adopts a stepless speed control drive technology [7], as shown in Figure 3. Its two-stage material conveying system is equipped with independent control modules, which can implement continuous adjustable operation of the lifting chain running speed and vibration parameters, and has a reverse operation mode to cope with the risk of conveyor chain blockage. The amplitude control mechanism is driven by an electro-hydraulic actuator to achieve continuous and non-stop amplitude control. The bottom of the conveying chain is innovatively configured with an integrated self-cleaning device and a soil-breaking mechanism, which effectively solves the main advantages of the chain-type separation for sticky soil: simple structure and relatively small damage to the tubers, but the disadvantages are that the separation effect is limited and prone to blockage when the soil is heavy or the humidity is high.

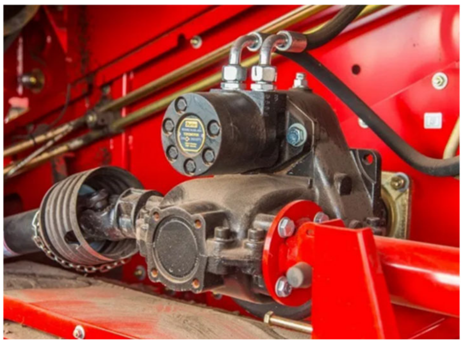

Figure 3. Stepless speed control drive technology

2.2. Screening-type Separation Device

The screening device usually separates the potato blocks from the soil by vibrating or shaking the sieve screen. It utilizes the vibration of the sieve surface to weaken the adhesion between the soil and the potato blocks, disrupt the internal friction and cohesion of the soil, and allow the soil to pass through the sieve holes and fall down, thereby achieving the separation of potato and soil. The key technical parameters include vibration frequency, amplitude, and the inclination angle of the sieve surface.

Xie et al. [8] conducted research on the correlation mechanism between the movement characteristics of potato blocks and the separation performance during the operation of the oscillating separation screen. By constructing a dynamic model of the coupled motion of potatoes and the screen surface, they derived the mathematical expression of the absolute speed of the potato blocks, providing a quantitative basis for the adaptive adjustment of parameters such as the amplitude and frequency of the separation screen in the soil, and promoting the optimization of potato low-loss separation technology towards an environmentally responsive direction. Chen et al. [9] addressed the problems of high soil block adhesion rate and insufficient soil fragmentation in traditional potato harvesters, proposing a scheme of installing vibrating wheels below the separation screen to enhance the separation effect of the potato-soil mixture, providing a low-power and highly reliable technical path for the simplification and improvement of small and medium-sized potato harvesting equipment. The GRIMME EVO series models in Germany adopt a hedgehog screen separation unit [10], as shown in Figure 4. A rotating finger-like rod mechanism is installed above the hedgehog screen to remove soil blocks and the surface soil of potatoes. The application of multi-level screening and flexible screen nets is a research direction for reducing damage.

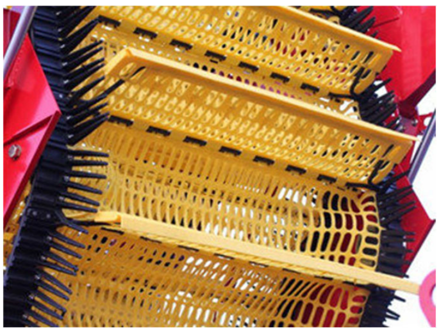

Figure 4. German GRIMME EVO Hedgehog Screen

2.3. Roller-type Separation Device

The roller-type separation device achieves efficient screening and sorting of soil through the coordinated rotation of multiple axes. Its structural design typically employs parallel arranged roller shaft groups or finger-shaped soil-discharging wheels. The surface of the roller shafts can be equipped with differentiated textures such as ridges and grids to enhance the soil crushing ability. During the operation, the rotating roller shafts break and separate soil aggregates through centrifugal force and friction.

Yang et al. [11] designed a potato soil separation device based on multi-level roller friction. The drum roller device is shown in Figure 5. A kinematic model of the potato block movement in the device was established, achieving efficient and low-loss potato harvesting. Lv [12] optimized the overall structure of the cleaning device based on the 4UL-170D bagging-type potato harvesting machine. The cleaning roller device is shown in Figure 6.

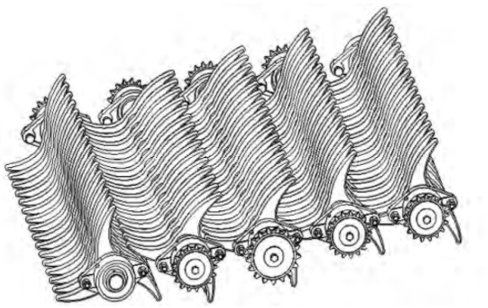

Figure 5. Drum roller device

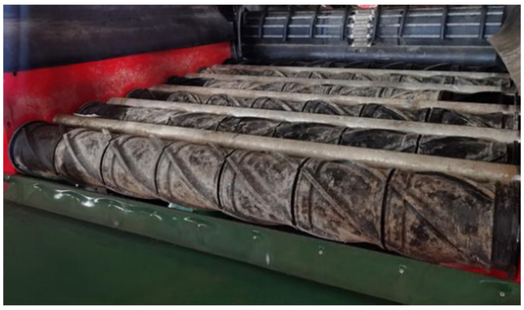

Figure 6. Cleaning roller device

Bayboboev et al. [13] designed a potato soil separation device combining elastic fingers and rubber rollers, as shown in Figure 7. Potato tubers falling from the bar-type conveyor chain rolled onto the horizontal conveyor belt, while soil, stems, and leaves and other impurities were lifted by the elastic fingers to the upper rubber rollers for removal. Through theoretical modeling and numerical simulation, the key parameter optimization issues of the device were studied, providing a theoretical basis for improving the separation efficiency of the potato harvesting machine and reducing damage. Kostenko et al. [14] proposed installing a spring-type mixer above the traditional potato conveyor chain to enhance potato soil separation and reduce damage to potatoes. The device is shown in Figure 8. Tests showed that the potato soil separation performance was improved on both light and heavy soils. At the same time, the damage rate of potatoes was reduced through elastic materials and gap adjustment. The design takes into account the simplicity and adaptability of the structure, providing a technical solution for reducing harvesting labor intensity and energy consumption.

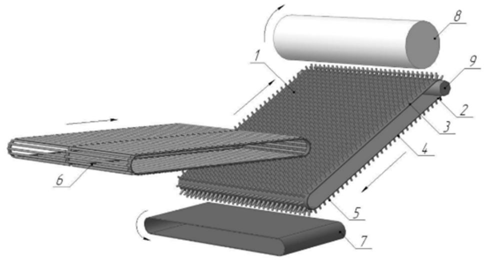

Figure 7. Separation device combining elastic fingers and rubber rollers

Figure 8. Separation device combining spring-type mixer and conveyor chain

3. The Application of Advanced Technology in the Potato-Soil Separation Device

3.1. Numerical Simulation Technology

The discrete element method (DEM) has been widely applied in the simulation and analysis of the potato soil separation stage during the potato harvesting process [15]. Researchers use DEM to study the basic principles and performance of the separation process [16]. Meng et al. [17] used 3D scanning and DEM simulation methods to analyze the variation laws of the movement speed of potatoes under different shaking frequencies and screen surface inclination angles, providing theoretical references for revealing the mechanism of potato soil separation and optimizing the structure of the screen body. Li et al. [18] used the DEM-MBD coupling method to consider factors such as the line speed of the separation screen, the forward speed, and the inclination angle, and conducted simulation and experimental research on the collision characteristics and separation performance of the potato soil separation device, and determined the optimal working parameter combination. Wang [19] used the discrete element software to establish discrete element models of potatoes, soil, and separation screens, and analyzed the influence laws of the group effect of potato populations and the interaction between potato and soil discrete particles on the acceleration of potatoes. Chen et al. [20] designed a rotating vibration-type potato soil separation device, used DEM-MBD coupling simulation to reveal its working process, optimized the vibration point position, chain speed, amplitude, and frequency, and proved the accuracy of the model through field experiments.

3.2. High-Speed Imaging and Image Processing Technology

The high-speed camera system can capture the transient motion details of potatoes during the potato soil separation process. Combined with image processing technology, it can precisely track the movement trajectory of the tubers, quantify kinematic parameters such as speed, and analyze the effects of different working conditions. It also provides verification data for numerical models. Meng [21] used a high-speed camera and TEMA dynamic image tracking technology to capture the two-dimensional motion trajectories and speed changes of regular-shaped potatoes on the swinging separation screen, and analyzed the influence laws of the screen swing parameters on the motion behavior of potatoes, as shown in Figure 9. Wang [22] et al. used high-speed cameras and dynamic tracking technology, combined with the SPSS statistical analysis method, to study the influence laws of the mass, height, collision angle and material properties of potatoes during the falling process on the impact speed and damage degree.

Figure 9. The installation positions of camera and potato harvester

3.3. Intelligent Monitoring Technology

The potato harvesting equipment faces technical challenges such as dynamic loads and frequent impacts in the complex and variable field operation environment. By constructing a multi-sensor fusion-based multi-dimensional operation status monitoring system for working components and combining real-time data collection, intelligent monitoring and early warning of potential faults in key mechanisms can be achieved. Zhang [23] collected the strain signals of the comb teeth, the vibration signals of the rod bar sieve bearings, and the speed signals under various working conditions, and used the GA-SVM model to identify the soil blockage in the potato soil separation device. Hosainpour et al. [24] developed an acoustic-based identification system for potato tubers and soil blocks, using the impact of potatoes and soil blocks on the steel plate to collect acoustic signals, extracting the time-domain and frequency-domain features of the signals, and inputting the features into the neural network for pattern recognition.

4. Problems and Prospects of the Potato Soil Separation Device

4.1. Problems of the Potato-Soil Separation Device

In recent years, although the research and development of potato soil separation equipment in our country have achieved some phased progress, the overall technical path still mainly relies on the adaptive improvement of mature foreign models. There is relatively little innovation in structural design and separation principles. Currently, the mainstream separation devices such as chain type, screening type, and roller shaft type each have their advantages and disadvantages, and it is difficult to perfectly balance high separation rate and low damage rate. The chain type and screening type are relatively gentle but prone to blockage, and have poor adaptability to sticky and heavy soil; the roller shaft type has high efficiency but high damage risk. The core problem lies in the insufficient accumulation of basic research on the interaction mechanism of different regional soils and crops, and there is no systematic design theory based on local agricultural production conditions yet.

From the perspective of equipment adaptability, the environmental adjustment capabilities of key functional components are significantly lagging behind the complex agricultural needs. The main potato-producing areas in China cover diverse geographical units such as black soil in the northeast, loess in the northwest, and hills in the southwest. There are significant differences in soil moisture content, particle distribution, and viscosity coefficients. However, the core motion parameter adjustment mechanism of the existing devices still remains at the level of manual experience setting, lacking dynamic adaptive control strategies based on real-time perception of soil physical properties. This results in significant fluctuations in performance of the same model in different operation scenarios, making it difficult to meet the requirements of precision harvesting.

In terms of the integration of intelligent technologies, current domestic research is mainly limited to the optimization of pure mechanical structures, and there is a gap compared with advanced foreign technologies. Countries like Europe and the United States have already embedded intelligent technologies such as machine vision recognition, pressure sensor arrays, and adaptive algorithms into separation devices to achieve real-time identification of impurities and tubers and automatic calibration of separation parameters. However, related research in China is still at the stage of collecting sensor signals and accumulating basic data, and has not yet established an intelligent control system that integrates state monitoring, fault diagnosis, and parameter self-adaptation. This has restricted the development of equipment.

4.2. Prospects of the Potato-Soil Separation Device

In response to the core issues such as insufficient structural innovation, weak environmental adaptability, and low intelligence level existing in the current potato soil separation device, future research should focus on the following directions for breakthroughs:

(1) Based on the interaction mechanism between the characteristics of Chinese potato varieties and the diverse soil environments, we conduct fundamental theoretical research on the contact mechanics and kinematics of soil-stem-block components. By combining discrete element simulation and high-speed photography techniques, we analyze the critical mechanical thresholds for stem damage under different separation forms, and construct a design model based on the dual-objective optimization of separation efficiency and damage control. We explore new separation principles such as biomimetic desiccation reduction, coupling of vibration screening and air flow sorting, and flexible material contact, and develop efficient and low-loss separation structures, forming a systematic design theory system that is adapted to local agricultural needs.

(2) In view of the regional differences in potato cultivation

in our country, a modular design architecture of "core functional module + replaceable accessories" should be established. For example, for heavy clay soil, a non-blocking vibrating screen component should be configured; for sandy soil, a roller shaft structure with a low friction coefficient should be adopted. Through rapid replacement, one piece of equipment can be adapted to multiple agricultural scenarios. At the same time, the performance evaluation standards of the potato soil separation device should be improved, and a standardized testing platform including indicators such as separation efficiency, damage rate, energy consumption, and blockage frequency should be established. This will provide a scientific and quantitative verification system for the research and development of new equipment.

(3) Promote the intelligent transformation of the separation device. Equip with IoT modules to achieve equipment status monitoring, and combine with fault diagnosis algorithms to proactively warn of abnormal conditions such as screen blockage and component wear. Pay attention to the green design trend, explore low-carbon materials, low-noise vibration structures, and soil fragment recycling technologies to reduce operational energy consumption and environmental disturbance. At the interdisciplinary intersection level, integrate hydraulic, materials science and control engineering to develop flexible separation components with coupling rigidity and flexibility, reduce mechanical damage caused by rigid contact, and achieve collaborative optimization of efficient separation and quality protection.

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