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Improved design and experiment of separating sieve for potato digger[1]

Aprimoramento do projeto e do teste da tela de separação da escavadeira de batata

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HIGHLIGHTS:
It is highly desirable to improve the performance of the existing separation sieve through redesign.
The new sieve has solved the contradictory problem between the potato detection rate and the potato skin breakage rate.
Reducing the potato skin breakage rate during potato harvesting can increase farmers' income.

ABSTRACT: The original two-order separating sieve has a good potato-soil separating ability, but it causes significant damage to potatoes while ensuring a high potato detection rate, which in turn affects the working effectiveness of the potato digger. Thus, it is necessary to improve the design of the original swing separation sieve with a two-order sieve surface to one with a three-order sieve surface to solve the contradiction between the potato detection and potato damage. On this basis, the movement characteristics of potatoes and the separation performance of the new sieve were experimentally investigated. The experiment was conducted in a test field in Wuchuan County using a completely randomized design in a single-factor scheme with three factors and five levels, with five crank speeds (140, 150, 180, 210 and 225 rpm), five machine forward speeds (1.41, 1.51, 1.70, 1.89 and 2.21 km h^{-1}) and five boom-connecting rod length combinations (250-350-1,030, 250-370-1,040, 270-370-1,050, 290-370-1,060 and 310-370-1,070 mm). Each experiment was repeated three times at each level, and the average value was taken as the final result. The experimental results demonstrate that the new three-order separation sieve can ensure a high potato detection rate while maintaining a low potato skin breakage rate.

Key words: potato harvest, kinematic characteristics, separating sieve performance

RESUMO: A peneira de separação de duas ordens original tem uma boa capacidade de separação batata-solo, mas causa danos significativos às batatas ao mesmo tempo em que garante uma alta taxa de evidência de batatas, o que, por sua vez, afeta a eficácia do trabalho da escavadeira de batatas. Assim, o estudo teve como objetivo aprimorar a peneira de separação de balanço original com uma superfície de peneira de duas ordens para uma nova peneira de separação com uma superfície de peneira de três ordens para resolver a contradição entre a taxa obvia de batatas e os danos às batatas na operação da peneira original. Com base nisso, as características de movimentação das batatas e o desempenho de separação da nova peneira foram investigados experimentalmente no campo. O experimento foi conduzido em um campo de teste no Condado de Wuchuan, utilizando um delineamento completamente aleatório em um esquema de fator único com três fatores e cinco níveis, com cinco velocidades de manivela (140, 150, 180, 210 e 225 rpm), cinco velocidades de avanço da máquina (1,41, 1,51, 1,70, 1,89 e 2,21 km h^{-1}) e cinco combinações de comprimento da haste de ligação do braço (250-350-1.030, 250-370-1.040, 270-370-1.050, 290-370-1.060 e 310-370-1.070 mm). Cada experimento foi repetido três vezes em cada nível, e o valor médio foi considerado como o resultado final. Os resultados experimentais demonstram que a nova peneira de separação de três ordens pode garantir uma alta taxa de detecção de batatas enquanto mantém uma baixa taxa de danos à casca das batatas.

Palavras-chave: colheita de batata, características cinemáticas, desempenho da peneira separadora

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Introduction

Potato harvesting is the most labour-intensive aspect of potato production. Mechanized harvesting offers high efficiency and low production costs (Zhao, 2020; Dou et al., 2019; Yang et al., 2021). Researchers have developed various types of potato diggers with different structures (Wu et al., 2011; Shi et al., 2012; Lv et al., 2015; Yang et al., 2016; Wei et al., 2018; Liu et al., 2020'; Li et al., 2022a). These machines have been applied and popularized to varying degrees in different potato production areas of China. However, the problem of low efficiency in potato-soil separation and high potato damage still persists (Zhang et al., 2009; Yang et al., 2023; Opara et al., 2013).

The swing separation sieve is the core working component in the rod chain-swing sieve combined potato digger (Fu et al., 2013). The original two-order separating sieve has a good potato-soil separating ability, but while ensuring a high potato detection rate, it causes significant damage to potatoes, which in turn affects the working effectiveness of the potato digger (Zhao et al., 2023).

The aim of this study was to present the design and field test results of a new three-order separation sieve. This new apparatus resolves the contradiction between the potato detection rate and potato damage in the operation of the original sieve design.

Material and Methods

This design will meet the requirements of gradually decreasing the potato-soil separation ability while maintaining the material transportation capacity. The original second-order separation sieve design was improved to a third-order separation sieve in order to reduce the impact of the sieve on potatoes during the separation process, thereby minimizing damage to potatoes during harvest.

To develop a new mechanical structure, it is crucial to determine whether the machine has a definite motion (Xia, 2022; Li et al., 2022b; Luo et al., 2023), which is satisfied when the number of driving parts of the mechanism is equal to its number of degrees of freedom. The fundamental formula (Xia, 2022) for calculating the degrees of freedom for planar mechanisms is:

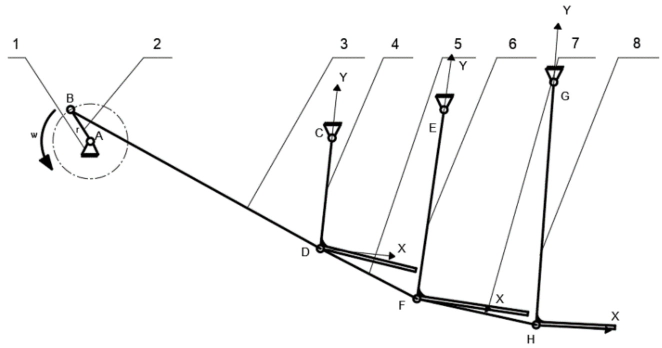
$$F = 3n - 2P_L - P_H$$

where:

F - degrees of freedom of plane mechanism;
n - number of active components;
P_L - plane low number of pairs; and,
P_H - plane high profile.

In this paper, the improved separation sieve mechanism can be simplified as a plane motion mechanism (Figure 1).

Based on the above analysis, the separation sieve mechanism consists of eight components, including one frame ground and seven active components that are connected by rotating pairs. Composite hinges are formed at points D and F, resulting in low pairs and high pairs, respectively, which introduce constraints.



1 - Frame ground; 2 - Crank; 3 - Connecting rod of first order sieve surface; 4 – First-order sieve surface and boom; 5 - Connecting rod of second-order sieve surface; 6 – Second-order sieve surface and boom; 7 - Connecting rod of third- order sieve surface; 8 – Third-order sieve surface and boom; A - Axis of crank; B - Connection point of crank and drive shaft; C, E, G - Articulated position of sieve frame and boom; D, F, H - Articulated position of the boom and the sieve; X - Orientation of the sieve surface; Y - Direction of vertical sieve surface

Figure 1. Improved motion mechanism diagram of separation sieve

Thus, the degrees of freedom of the transmission mechanism is calculated as F = 1.

When using the crank as the original moving part, the mechanism satisfies the condition of definite movement and has a unique movement trajectory. This allows for the design of a new mechanical structure with a three-order sieve surface that meets the design requirements.

The main potato-soil separation process occurs on the first sieve surface, while only a small amount of soil, potatoes, and hard soil blocks that are difficult to break are delivered to the second and third sieve surfaces. Thus, the length of the first-order sieve is designed to be 400 mm, while the lengths of the second- and third-order sieves are 300 mm. The sieve rod spacing and sieve surface width remain the same as the original separation sieve parameters, at 45 mm and 1,700 mm, respectively.

The connecting rod and suspender of the separation sieve include the connecting rod, sieve surface connecting rod, and suspender of each order sieve surface. The length of the sieve connecting rod mainly depends on the length of the sieve surface. To prevent potato clamping, potato leakage, and other separation sieve work phenomena, the length of the connecting rod between the first- and second-order sieve surfaces is designed to be 370 mm, and that of the second- and third-order sieve surfaces is designed to be 270 mm.

To clarify the influence of the boom-connecting rod length combination on the parameters of the potato motion characteristics during potato-soil separation, the length of the connecting rod and each sieve surface is designed to be adjustable. The length adjustment range is 1,000-1,100 mm, while that on the first sieve surface is 250-90 mm, and 350-370 mm on the second sieve surface (Table 1).

Table 1. Separation sieve structure parameters

Parameter	Dimensions (mm)
Crank radius	35
Length of the connecting rod (adjustable)	1,030, 1,040, 1,050, 1,060, 1,070
Length of first sieve suspender length (adjustable)	250, 270, 290
Length of second-order boom (adjustable)	350, 370
Length of third-order boom	570
Length of separation sieve	1,000
Width of separation sieve	1,700

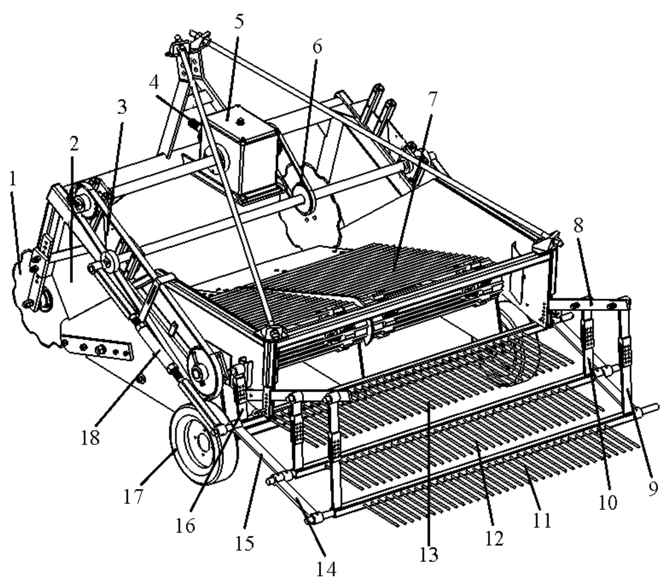
The improved separation sieve was installed on the potato digger, resulting in a new type of 4SW-170 potato digger (Figure 2), which consists of a frame, gearbox, excavation shovel, lifting chain, and the new separation sieve. The separation sieve includes a chain drive mechanism, crank, connecting rod, three-order sieve surface, and sieve frame.

During operation, the soil cutting disc cuts off potato seedlings and weeds on both sides of the potato digger, while the potato-soil mixture, which is mixed with a small amount of roots and weeds, is dug up and transported to the lifting chain. As the potato-soil mixture is lifted backwards, approximately 20 to 30% of the soil falls to the ground through the rod gap, while the remaining mixture is transported to the separation sieve, which is composed of a three-order sieve surface. Each order of the separation sieve moves reciprocally under the drive of the crank link mechanism, during which the potato-soil mixture is separated on the sieve surfaces of each order. The soil falls to the ground through the sieve rod gap, and the potatoes are transported to the end of the sieve and laid on the ground in strips.

The field experiment was conducted in early October 2021 at the potato planting base in Wuchuan County, Hohhot City, Inner Mongolia, China. The soil type of the test field is inceptisol, with a row spacing of 800 mm and plant spacing of 350 mm for potato cultivation, and the depth of tuber formation was about 50-200 mm. The potato variety chosen was Jizhangshu 12, which is widely cultivated in the central and western regions of Inner Mongolia.

The testing machine used was a potato digger equipped with the new type of swing separation sieve (Figure 2), powered by a DF900 wheel tractor. The instruments and equipment used in the experiments included a high-speed camera, photoelectric tachometer, tape and stopwatch.

The experiment conducted in the test field in Wuchuan County used a completely randomized design in a single-factor scheme with three factors and five levels, with five crank speeds (140, 150, 180, 210 and 225 rpm), five machine forward speeds (1.41, 1.51, 1.70, 1.89 and 2.21 km h^{-1}) and five boom-connecting rod length combinations (250-350-1,030, 250-370-1,040, 270-370-1,050, 290-370-1,060 and 310-370-1,070 mm). Each experiment was repeated three times at each level, and the average value was taken as the final result. The data group at the level under the boom-connecting rod length combinations is denoted as “The length of first-order sieve boom-The length of second-order sieve boom-The length of connecting rod (mm)”. The adjustment of the crank speed could be achieved by changing the number of sprocket teeth in the sprocket drive mechanism, and the machine’s forward working speed could be adjusted using the tractor gear. The boom-connecting rod length combinations could be directly adjusted on the separation sieve.



1 - Soil cutting disc; 2 - Frame; 3 - Crank; 4 - Dynamic input shaft; 5 - Gearbox; 6 - Chain drive mechanism; 7 - Lifting chain; 8 - Sieve frame; 9 - Boom of third-order sieve surface; 10 - Boom of second-order sieve surface ; 11 - Third-order sieve surface; 12 - Second-order sieve surface; 13 - First-order sieve surface; 14 - Second- and third-order sieve surface connecting rod; 15 - First-order sieve surface connecting rod; 16 - First-order sieve surface suspension rod; 17 - Walking wheel; 18 - Connecting rod

Figure 2. Essential parts of the 4SW-170 potato digger

The numbers of jumps and the movement time of the potatoes on the separation sieve were selected as high-speed photographic test indicators. The potato detection rate and the rate of potato skin breakage were chosen as the separation sieve performance test indicators. The formulas for the potato detection rate and the rate of potato skin breakage are:

$$Y_1 = \frac{q_1}{Q} \times 100\%$$

$$Y_2 = \frac{q_2}{Q} \times 100\%$$

where:

Y_1 - potato detection rate, %;

Y_2 - potato skin breakage rate, %;

q_1 - mass of potato exposed to the ground after the completion of machine operation, kg;

q_2 - mass of potato with epidermal damage in exposed potato, buried potato after the completion of machine operation, kg; and,

Q - total mass of potato harvested after completion of the machine work, kg.

Before conducting the experiment, the high-speed camera was fixed on the digger frame with a support, and the camera angle was adjusted to capture the entire separation sieve area in which the potatoes were moving. The high-speed camera used in this study was the Phantom Miro2 high-speed digital camera manufactured by Vision Research, USA. This camera boasts a maximum resolution of 1280 × 800 pixels and a peak frame rate of up to 200 frames per second (fps). The longest attainable exposure time is 1 s, and it possesses an ample storage capacity of up to 128 GB. In this test, the camera resolution was set to 640 × 480 pixels and the frame rate was 200 fps.

At the beginning of the test, the tractor started to move forward. Once the machine was running stably, the high-speed camera began recording the movement of potatoes on the separation sieve. The high-speed image data of the 30-meter stable test area were collected according to the methods outlined in the NY/T 648-2015 Technical Specification for Quality Evaluation of Potato Harvesters. The mass of potatoes that were exposed to the ground, received epidermal injuries, and were harvested after machine operation were recorded. Each test group was repeated three times, and the average value of the three repeated test results was used as the final result.

Following the experiment, the high-speed camera images were analysed using TEMA dynamic image processing software, which allowed retrieval of the number of jumps and the movement time of potatoes on the separation sieve during the potato-soil separation process under the different separation sieve parameters. The mean value of the results obtained from the three replicates was considered as the final result. SPSS 19.0 software was utilized for the analysis, employing Kendall's Tau-b method to calculate the correlation coefficients and determine the significance levels for the single-factor testing of the high-speed photographic test. In addition, linear equations were fitted to the performance test results (the potato detection rate) under the various crank speeds and machine forward speeds. The camera testing outcomes are presented in a tabular format, while the performance test results are graphically represented using Origin software. Further analysis and interpretation of the experimental data are based on these graphical representations.

Results and Discussion

At the crank speed of 140 rpm, the number of jumps of the potatoes was 3 and their movement time was 1.06 s. This decreased to 0.763 s when the crank speed was increased to 225 rpm and the numbers of jumps was reduced to 2 (Table 2).

When the boom-connecting rod length combination is 270-370-1,050 mm and the machine forward speed is 1.51 km h^{-1}, the number of jumps and movement time of potatoes on the separation sieve decrease as the crank speed increases.

This phenomenon is due to the fact that at low crank speeds, the swing frequency of the separation sieve is lower, resulting in a smaller acceleration perpendicular to the sieve surface (Liu et al., 2013). As a result, the jump height of the potato on the sieve surface is lower, leading to more jumps and a longer movement time of potatoes on the sieve surface. With the increase of crank speed, the swing frequency of the separation sieve also increases, resulting in an increase in acceleration perpendicular to the separation sieve surface, and an increase in the hopping distance of the potato on the separation sieve. This leads to a decrease in the number of jumps of potatoes on the sieve surface and a shorter movement time.

Xie et al. (2019) believed that as the crank speed increases, the movement state of the potato changes from a slight jump to a violent jump, and the positive speed of the potato relative to the separation sieve increases, which increases the positive displacement of the potato relative to the separation sieve. This ultimately results in a decrease in the number of jumps and movement time of the potatoes.

When the boom-connecting rod length combination is 270-370-1,050 mm and the crank speed is 150 rpm, the number of jumps and movement time of potatoes on the separation sieve show a decreasing trend as the machine forward speed increases. When the machine forward speed is 1.41 km h^{-1} and the number of jumps of potatoes is 3.67, the movement time is 1.363 s. When the machine forward speed increases to 2.21 km h^{-1} and the number of jumps of potatoes decreases to 1, the movement time is reduced to 0.807 s (Table 2). This contributes to a reduction in collisions between the potatoes and the separating sieve, thus lowering the incidence of potato skin breakage.

Xie et al. (2019) concluded in the field experiment that, as the machine forward speed increases, the amount of potato-soil mixture falling from the lifting chain to the separation sieve increases. This hinders the potato movement relative to the separation sieve, which gradually increases the alternating change range of forward and reverse displacement of the potato relative to the separation sieve, and gradually increases the maximum difference of the potato's forward and reverse displacement in one cycle. Ultimately, this results in a decreased number of jumps and a shortened movement time of the potato on the separation sieve.

The correlation between the number of jumps and movement time of potatoes on the separation sieve and the different experimental factors was significant (Table 2), indicating that the separation sieve parameters directly affect

Table 2. Number of jumps and movement time of potatoes on the new three-order separation sieve under different separation sieve parameters

Initial conditions	Factors	Levels	Number of jumps	KTB1	Movement time (s)	KTB2
Machine forward speed (km h^{-1}): 1.51 Boom-connecting rod length combination (mm): 270-370-1050	Crank speed (rpm)	140	3	Tau: -0.949 Sig: *	1.06	Tau: -1.000 Sig: **
		150	3		1	
		180	2.67		0.93	
		210	2.33		0.8	
		225	2		0.76	
Crank speed (rpm):150 Boom-connecting rod length combination (mm): 270-370-1050	Machine forward speed (km h^{-1})	1.41	3.67	Tau: -0.949 Sig: *	1.36	Tau: -1.000 Sig: **
		1.51	3		1.13	
		1.70	2		0.95	
		1.89	2		0.86	
		2.21	1		0.81	
Crank speed (rpm):150 Machine forward speed (km h^{-1}): 1.51	Boom-connecting rod length combinations (mm)	250-350-1,030	2.67	/	0.89	/
		250-370-1,040	3		0.98	
		270-370-1,050	3.33		1	
		290-370-1,060	3.33		1.08	
		290-370-1,070	4		1.53	

KTB1 - Result of Kendall's Tau-b test for the number of jumps; KTB2 - Result of Kendall's Tau-b test for movement time; Tau - Kendall's correlation coefficient; Sig - Significance; * - Significant at p ≤ 0.05; ** - Significant at p ≤ 0.01

the motion characteristics of potatoes, thereby influencing the performance of the separation sieve.

When the machine forward speed is 1.51 km h^{-1} and the crank speed is 150 rpm, the number of jumps and movement time of the potatoes vary with different boom-connecting rod length combinations. When the boom-connecting rod length combination is 250-350-1,030 mm and the number of jumps of potatoes is 2.67 s, the movement time of potatoes is 0.885 s. When the boom-connecting rod length combination is 290-370-1,070 mm and the number of jumps of potatoes is reduced to 4 s, the movement time is reduced to 1.533 s (Table 2).

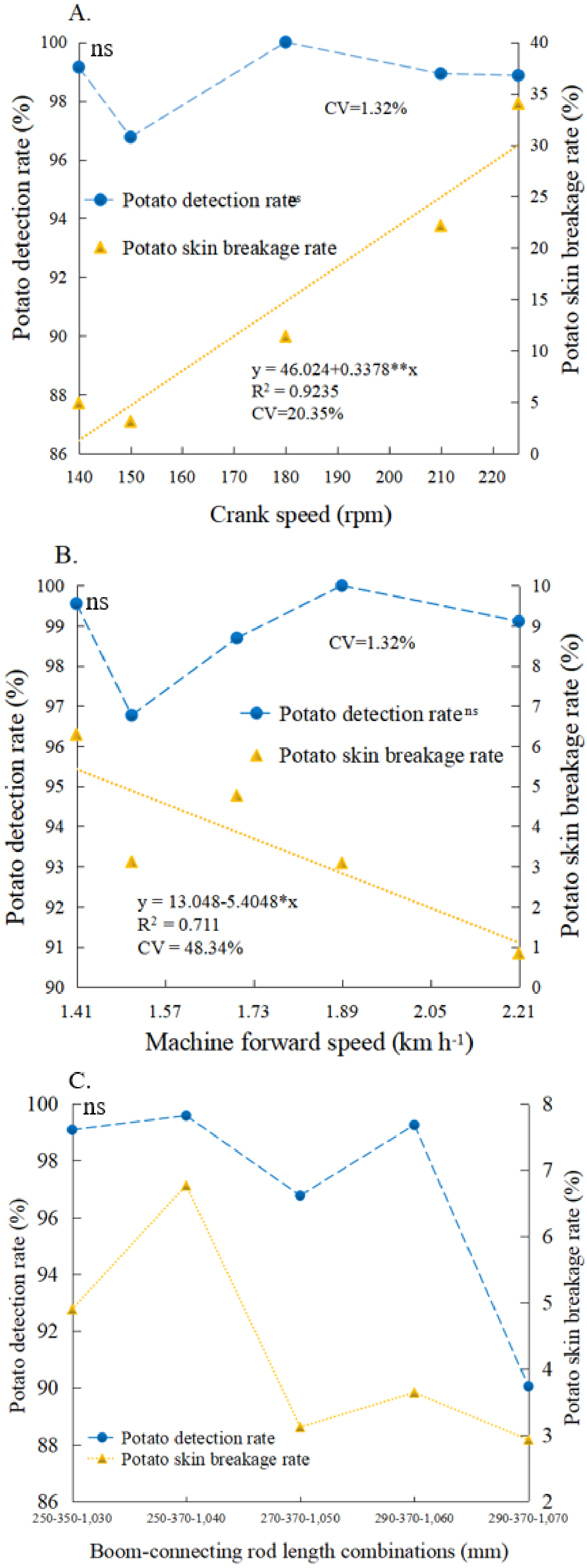
In situations where the boom-connecting rod length combinations are both long, it becomes difficult for the potato to move towards the end of the sieve, resulting in a significant increase in the number of jumps and movement time of potatoes. This implies that the boom-connecting rod length combination directly impacts the separation efficiency of the swing separation sieve. A higher number of potato jumps on the separation sieve increases the contact time between the potato and the separation sieve, thus improving the separation of the potato-soil mixture. However, this also leads to more severe potato damage.

The potato detection rate varied with the crank speed, stabilizing at approximately 97% for the five different rotation speeds, and reaching 100% at a rotation speed of 180 rpm (Figure 3A). Analysis of the high-speed camera footage revealed that effective separation occurred on the first separation sieve at a crank speed of 180 rpm, resulting in a higher potato detection rate due to the material on the separation sieve consisting mainly of potato and unbroken soil. However, as the crank speed continued to rise, the movement time of potatoes on the sieve surface shortened, causing incomplete broken soil to fall to the ground and a decrease in the potato detection rate.

The potato skin breakage rate showed a gradual increase with an increase in crank speed. The rate was less than 5% when the crank speed was 140 and 150 rpm, but exceeded 10% at 180 rpm and reached 34.04% at 225 rpm (Figure 3A). At lower crank speeds, the distance of the potato after take-off on the separation sieve was short, resulting in a larger number of jumps and a longer movement time of potatoes, leading to a lower rate of potato skin breakage and a higher potato detection rate. As the crank speed increased, the swing frequency of the separation sieve increased, causing a decrease in the jumping frequency of the potato on the separation sieve and a reduction in the movement time, resulting in a higher rate of potato skin breakage.

Meng et al. (2020) pointed out in their study of potato movement characteristics that the swing intensity of the swing separation sieve increases with an increase in swing frequency, resulting in more severe potato movement on the sieve surface and aggravating the collision intensity between the potato and the rod. This leads to a decrease in the number of jumps and movement time of the potatoes on the separation sieve, resulting in serious potato damage after separation and a higher skin breakage rate.

The experimental results indicate that the new type of separation sieve has a better sieving effect than the original one,



CV - Coefficient of variation; R^2 - Coefficient of determination; * - Significant at $p \leq 0.05$; ** - Significant at $p \leq 0.01$; ns - Not significant

Figure 3. Effect of crank speed (A), machine forward speed (B) and boom-connecting rod length combination (C) on the rate of potato detection and potato skin breakage using the new three-order separation sieve

resulting in a higher potato detection rate at different crank speeds. However, excessive crank speed could result in serious potato skin damage, necessitating a reduction in crank speed for optimal potato-soil separation performance.

The potato detection rate decreased to a minimum when the machine forward speed was 1.51 km h^{-1}, then increased with an increase in forward speed until reaching 100% at 1.89 km h^{-1}, and decreased slightly thereafter (Figure 3B). At the machine forward speed of 1.89 km h^{-1}, the number of jumps and movement time of potatoes on the sieve surface were moderate, resulting in an effective separation of the potato-soil mixture on the first sieve surface and the highest potato detection rate. As the machine forward speed increased further, the number of jumps of potatoes on the sieve surface was too small, and the movement time was too short (Table 2), resulting in inadequate separation of the potato-soil mixture before it fell to the ground and a decrease in the potato detection rate.

The rate of potato skin breakage exhibited a decreasing trend overall with increasing machine forward speed and reached its lowest value of 0.84% when the speed was 2.21 km h^{-1} (Figure 3B). The primary reason for this is that the amount of potato-soil mixture transported to the separation sieve per unit time increases with the acceleration of the machine forward speed, and more potato-soil mixture can play a protective role for the potatoes, thereby reducing direct contact between the potatoes and the separation sieve surface. Additionally, with the increase of the machine forward speed, the number of jumps of potatoes on the sieve decreased, the movement time shortened (Table 2), and the contact between potatoes and rods decreased, which in turn reduced the skin damage to the potatoes.

Xie et al. (2018) concluded in their potato movement characteristics test that the absolute movement speed and the maximum height of the thrown sieve surface of the potato gradually decreased with the increase of the machine forward speed, thereby reducing the impact strength of the potatoes during potato-soil separation. Based on these findings, it can be concluded that the improved swing sieve can appropriately increase the machine forward speed and effectively reduce skin breakage damage to potatoes while ensuring a higher potato detection rate.

The test results of the potato detection rate under different experimental factors such as crankshaft speed and machine forward speed showed no significant correlation, and the potato detection rate did not change significantly with the variation of separation sieve parameters. Conversely, the potato skin breakage rate varied significantly with the changing experimental factors, with a high correlation coefficient obtained from the fitted equation (Figures 3A and B). In the performance test results of the traditional two-order separation sieve, there exists a certain correlation between the potato detection rate and potato skin breakage rate (Xie et al., 2019). It is impossible to ensure a low rate of damaged potatoes while maintaining a high rate of undamaged potatoes. It was observed that the potato detection rate and potato skin breakage rate of the new three-order design exhibited a non-contradictory relationship, aligning with the objective of this research.

When the length of the first and second sieve boom was between 250-290 mm and 350-370 mm, respectively, and the length of the connecting rod was between 1,030-1,060 mm, the potato detection rate was greater than 96%, indicating a better potato-soil separation effect. However, when the length of the first and second sieve boom and connecting rod was 290, 370, and 1070 mm, respectively, the potato detection rate decreased to 90.05% (Figure 3C).

Overall, the potato detection rate was good for each boom-connecting rod length combination, but a significant decrease in the potato detection rate was observed when the length of the connecting rod increased to 1,070 mm. This was due to the excessive gap between the separation sieve's front end and the lifting chain under this length of connecting rod, causing some potato-soil mixture to fall directly to the ground when dropping from the lifting chain to the separation sieve.

Under different boom-connecting rod length combinations, the rate of potato skin breakage was less than 7%, while a combination of 270~290 mm and 370 mm for the length of the first and second sieve boom, respectively, resulted in a rate of potato skin breakage less than 4%. Comparison of motion images of potatoes on the original separation sieve (Su et al., 2016) revealed that potato movement on the new separation sieve was relatively smooth, and the potato-soil separation strength decreased gradually with decreasing debris, such as soil. This effectively reduced the skin breakage damage during potato-soil separation.

Based on the above analysis, the improved separation sieve design can minimize damage to potatoes while ensuring a high rate of potato detection. This can increase farmers' profits and allow for increased machine speed during operation, thereby improving the working efficiency of potato diggers.

Conclusions

1. An improved three-order separation sieve has been designed based on the original separation sieve with a two-order sieve.
2. The new three-order separation sieve can ensure a high potato detection rate while maintaining a low potato skin breakage rate.
3. The number of jumps and the movement time of potatoes on the separation sieve directly affect the performance of the sieve.

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