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Original Article

Friction force on potato during potato-soil separation[1]

Força de fricção na batata durante a separação da batata do solo

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HIGHLIGHTS:

The friction force on the potato increases with the increase of the potato's mass and the speed of the crank.
The friction force on the potato decreases with the increase of the sieve's inclination.
The interaction of the potato's mass and the speed of the crank has the greatest effect on the friction force on the potato.

ABSTRACT: This study aimed to explore the friction force on potatoes in the process of potato-soil separation, its influencing factors and laws, and establish a testing system of potato-friction force. It was verified that the potato mass, crank speed, and sieve inclination significantly affected the potato's friction force along the sieve surface. The interaction of potato mass and crank speed had the greatest effect on the friction force on the potato along the sieve surface. In addition, under the same factors of potato mass of 200~400 g, crank speed of 200 r min^{-1}, and sieve inclination of 14.7°, the friction force of potato along the sieve surface with soil was much greater than that along the sieve surface without soil, ranging between 2.32 and 4.85.

Key words: *Solanum tuberosum*, swing separator, friction

RESUMO: O presente estudo visou investigar a força de atrito durante o processo de separação da batata do solo, bem como os fatores e padrões que influenciam essa força, além de estabelecer um sistema de teste para medir a força de atrito das batatas. Verificou-se que a massa da batata, a velocidade da manivela e a inclinação da peneira têm um impacto significativo na força de atrito ao longo da superfície da peneira. A interação entre a massa da batata e a velocidade da manivela tem o maior impacto na força de atrito ao longo da superfície da peneira. Além disso, sob os mesmos fatores - massa da batata entre 200-400 g, velocidade da manivela em 200 r min^{-1} e ângulo inclinado da peneira em 14.7°, a força de atrito das batatas ao longo da superfície com o solo é muito maior do que ao longo da superfície sem solo, variando entre 2,32 e 4,85.

Palavras-chave: *Solanum tuberosum*, peneira de separação oscilante, força de atrito

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Introduction

Potato is the fourth largest food crop in the world, mainly used as fresh vegetables. Research shows that potatoes are prone to bacterial infection and subsequent softening and decay when damaged (Li et al., 2023). The quality of potatoes determines the acceptance degree of consumers. However, the economic losses caused by the damage to potatoes during the harvest process have greatly hindered the sustainable development of the potato industry (Buitrago et al., 2004; Qu et al., 2005; Li et al., 2016; Jakubowski & Królczyk, 2020). Harvesting is the most crucial step in the entire mechanized production process of potatoes. Achieving a thorough separation of potatoes, soil, and impurities and simultaneously controlling the damage rate are extremely challenging problems in this process (Wei et al., 2019). Therefore, it is crucial to establish a theoretical foundation and reference data for advancing low-damage harvesting machinery in potato cultivation.

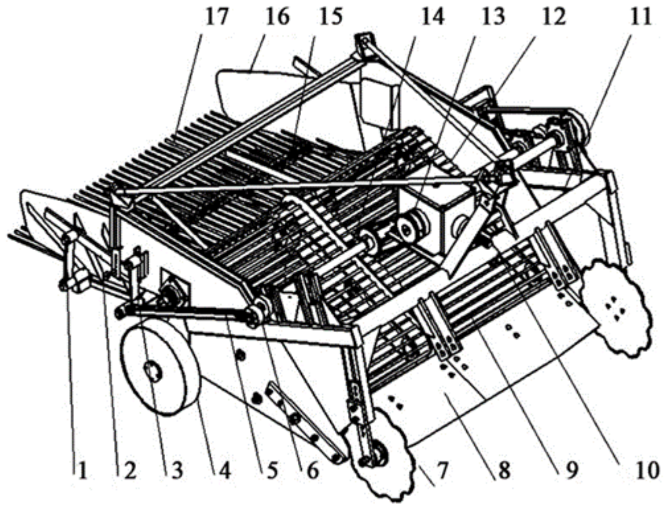
The investigation revealed that approximately 70% of potato damage is attributed to mechanical harvesting (Rymuza et al., 2014; Lv et al., 2020), with the most severe damage occurring during the separation process from the soil. Thus, research on mechanical parameters primarily focuses on understanding the mechanism behind this process. Potato damage can be categorized into surface and internal damage, with internal damage referring to severe impacts experienced during harvest (Yang et al., 2019). Since the early 20th century, extensive research has been conducted on potato internal damage in developed countries, encompassing quantification of mechanical forces exerted on tubers (Baritelle & Hyde, 2003; Bentini et al., 2006; Siberev et al., 2019; Abedi et al., 2019), analysis of how varieties and genetic factors influence the density of tuber damage caused by harvest machinery, and examination of force and acceleration curves at various heights to investigate stress-induced damage mechanisms (Li et al., 2018; Feng et al., 2019; Issa et al., 2020).

Recent studies (non-published data) discovered that, in contrast to the research on internal damage, studies concerning the surface damage resulting from friction during the separation process of potatoes from the soil are relatively scarce. Hence, this study is intended to explore the friction force on potatoes during the potato-soil separation process along with its influencing factors and patterns and to establish a completely new testing system of friction force on potatoes. This study aimed to explore the friction force on potatoes in the process of potato-soil separation and its influencing factors and laws, and establish a testing system of potato friction force.

Material and Methods

The experiment was conducted in the Inner Mongolia Agricultural University Experimental Farm in the Inner Mongolia Autonomous Region, China, which belongs to the Agricultural Mechanization farm, at 110° 46’ E, 40° 51’ N, and 1050 m above sea level. The geographical environment is suitable for potato growth, and many large potato planting areas exist.

The 4SW-170 potato excavator is shown in Figure 1. The cranks at both ends of the rotating shaft are driven by a gearbox and a chain transmission mechanism, and then the swing separation screen is driven by a connecting rod to swing back and forth; the potato-soil mixture is broken and separated by friction and elastic collision on the swing separation screen, and the broken soil falls into the field from the gap between the separation screen rods. After removing the soil, the potatoes are transported backward with the swing separating screen and laid out in strips on the ground.

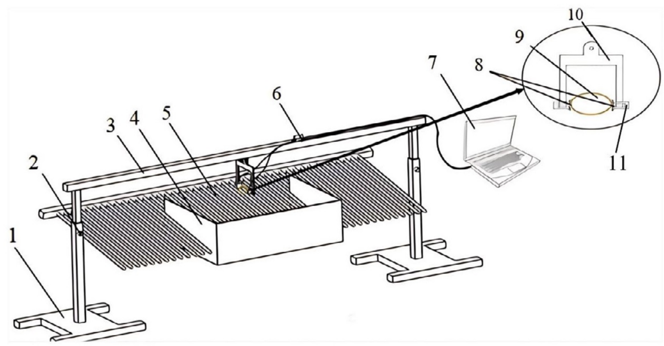


1 - Back swing rod; 2 - Screen angle adjusting mechanism; 3 - Front swing rod; 4 - Walking wheel; 5 - Connecting rod; 6 – Crank; 7 - Soil cutting disc; 8 - Excavation shovel; 9 - Lifting chain; 10 - Transmission shaft; 11 – Frame; 12 – Reducer; 13 - Sprocket transmission mechanism; 14 - Rotary shaft; 15 - Upper sieve; 16 – Baffle; 17 - Lower sieve

Figure 1. Overall structure diagram of 4SW-170 potato excavator

The friction test system of potatoes along the sieve surface is shown in Figure 2, corresponding to the components 15: upper sieve and 17: lower sieve in Figure 1.

As shown in Figure 2, the test bench bracket is divided into two parts: the base and the upper bracket. The base ensures the balance and stability of the test system, and the height of the upper bracket can be adjusted by fastening nuts. An iron plate with a hole is welded on the cross beam of the upper bracket, which is fastened and connected with the potato limiting device through a bolt assembly. By adjusting the connection angle between the potato limiting device and the iron plate with holes, the potato limiting device and the separation screen surface are kept in a relatively parallel position state. According to the actual size of potatoes in the test, the positions of push rods on the left and right sides under the limiting device can



1 - Base; 2 - Fastening nut; 3 - Upper bracket; 4 - Soil storage tank; 5 - Separating screen; 6 - Data acquisition card; 7 - Computer; 8 - Thin film pressure sensor; 9 - Potato; 10 - Limiting device; 11 - Push rod

Figure 2. Potato peel friction test system

be adjusted so that potatoes can be placed in the limiting device. The thin film sensors are installed on the end face of the potato limiting device's push rods to collect data and display the test results on the computer. In order to analyze the influence of soil on the friction force on the potato, a soil storage tank is installed under the separation screen to store the soil and ensure that the potato is always in contact with the soil during the test.

During the experiment, the separating screen swings reciprocally under the action of the driving mechanism, and the friction force acting on the potato surface makes the potato dynamically contact with the thin film pressure sensors on both sides of the limiting device. The force analysis of potatoes under two contact states is conducted, as shown in Figures 3A and B.

When the potato is in contact with sensor 1, it is subjected to its own gravity, inertia force, friction force, and support force of the separating screen on the potato, and the force of the limiting device on the potato. When the components of inertia force, friction force and gravity on the potato along the screen surface are opposite to the force of the limiting device on the potato, the value collected by sensor 1 will reach the maximum, and the force analysis at this time is shown in Figure 3A. Similarly, when sensor 2 collects the maximum value, the force state of the potato is shown in Figure 3B. The equilibrium equations along the sieve surface direction are Eqs. 1 and 2.

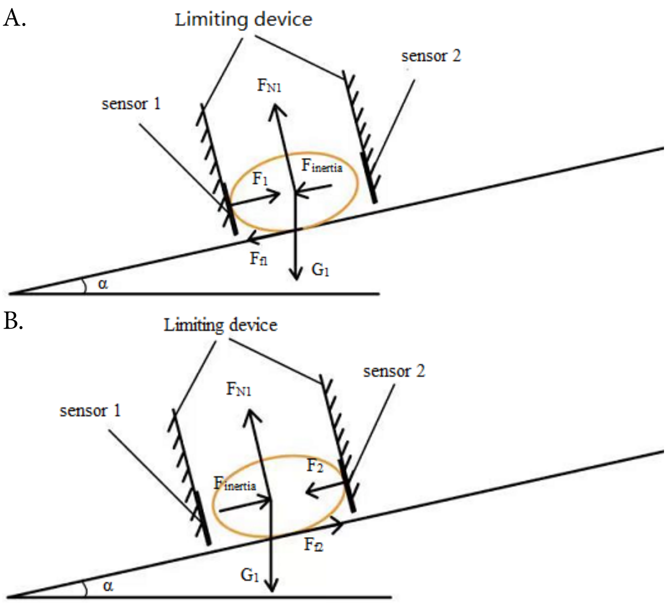
$$F_1 - F_{f1} - F_1 \sin\alpha - F_{inertia} = 0 \tag{1}$$

$$F_2 - G_1 \sin\alpha - F_{f2} - F_{inertia} = 0 \tag{2}$$

Where:

F_1 - force collected by sensor 1 at the tail end of the sieve surface F_{f1} is the friction force of the potato along the sieve surface pointing to the tail end of the sieve; and,

G_1 - potato gravity; α is the inclination angle of the screen surface;



F_{N1} - Include description; $F_{inertia}$ - Include description; F_2 - Include description; F_{f2} - Include description; G_1 - Include description; F_{f1} - Include description

Figure 3. Potato force analysis: (A) Potato is in contact with sensor 1; (B) Potato is in contact with sensor 2

$F_{inertia}$ - inertia force along the sieve surface direction;

F_2 - force collected by sensor 2 at the front end of the sieve surface; and,

F_{f2} - friction force on potato along sieve surface pointing to the front end of the sieve.

During the testing process, the potato collides with the sensors on both sides of the limiting device due to the reciprocating swing of the separating screen, so it can be considered that the potato has the same acceleration as the separating screen. The inertia force of the potato along the screen surface can be calculated according to Eq. 3.

$$F_{inertia} = ma_x \tag{3}$$

Where:

m - potato mass, kg; and,

a_x - acceleration of separating screen along the screen surface.

In previous studies (Xie et al., 2023; Liu et al., 2023), the research group obtained the acceleration of the separation screen along the screen surface at different crank speeds, as shown in Table 1.

According to Eqs. 1, 2, and 3, when the measured value of the thin film pressure sensor is the maximum, the friction force on the potato along the sieve surface is the maximum. Therefore, according to the above analysis, the following Eqs. 4 and 5 can be listed:

$$F_{f1max} = F_{1max} - G_{1\sin\alpha} - F_{inertia} \tag{4}$$

$$F_{f2max} = F_{2max} - G_{1\sin\alpha} - F_{inertia} \tag{5}$$

Where:

F_{f1max} - maximum friction force on potato pointing to the tail end of the screen along the screen surface direction;

F_{f2max} - maximum frictional force on potato pointing to the front end of the screen along the screen surface direction;

F_{1max} - maximum value tested by force sensor 1; and,

F_{2max} - maximum value tested by force sensor 2.

As shown in Figure 4, before the start of the experiment, after calibrating the sensor and connecting it to the computer, the upper bracket was adjusted to the position above the oscillating separation sieve so that the sensor installed on the potato contact limiting device was above the separation sieve. Then, the potato limiting device was adjusted to keep it parallel to the sieve surface. Then, the two ends of the potato were flattened and placed in the middle of the limiting device to make it just in contact with the sensors at both ends. After all the preparations were completed, the experiment began. With the back-and-forth swing of the sieve surface of the

Table 1. Crank speed corresponding to the acceleration of the separation screen along the screen surface

Crank speed (r min^{-1})	160	180	200	220	240
Acceleration a_x (m s^{-2})	12.25	18.67	29.59	40.62	50.95

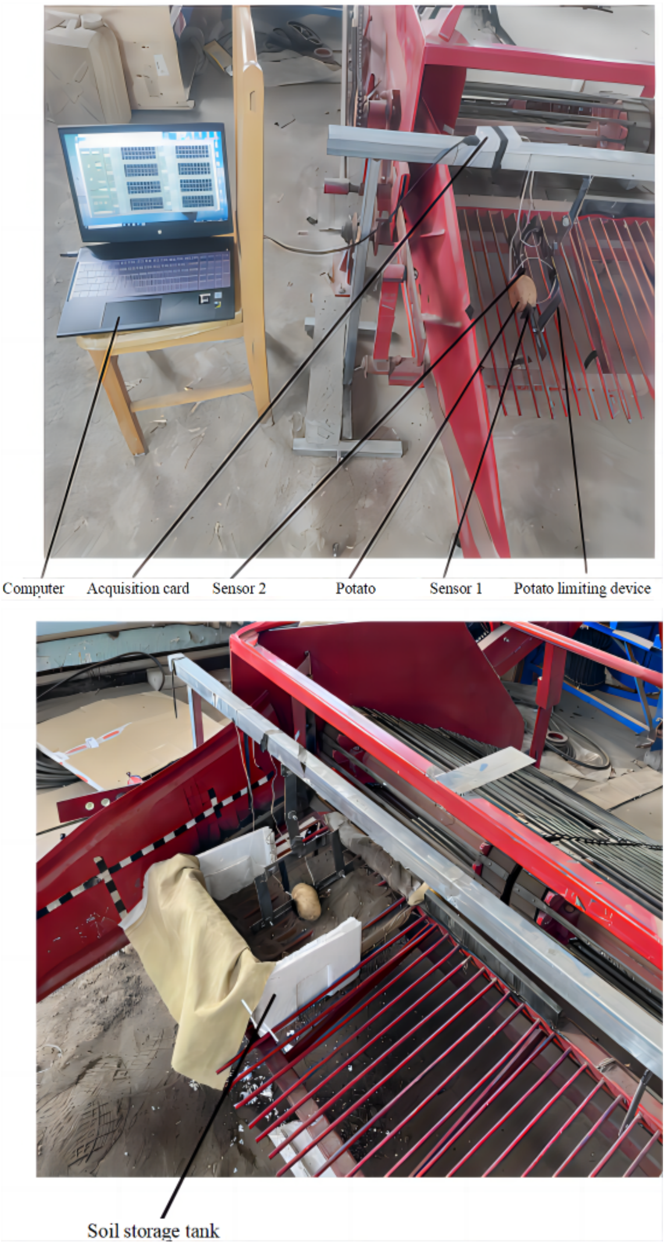


Figure 4. Potato friction test process performed in the experiment

separation sieve, the friction force received by the potato when in contact with the separation sieve could be measured through the sensor. In addition, when conducting the response surface test, a soil storage tank was added on the original basis to store the soil and ensure that the height of the soil in the soil storage tank exceeded the sieve rod to achieve the purpose of the potato contacting the soil. The thin film force sensor and acquisition card used in the test are manufactured by Suzhou Changxian Optoelectronic Technology Co, Ltd. The thin film force sensor model is A301, as shown in Figure 5, and the specific parameters are shown in Table 2. The acquisition card model is cx1004. The potatoes for the experiment were excavated from the field in the experimental farm by manual harvesting and taken to the laboratory. The potato cultivar was Kexin No.1. The tubers of Kexin No. 1 potatoes are usually oval, large, and neat. Their specific sizes may vary among individuals, and the weight is generally between 200 and 400 grams. Measured results show that the water content of the potatoes used in the experiment is within the range of 75 to 85%.

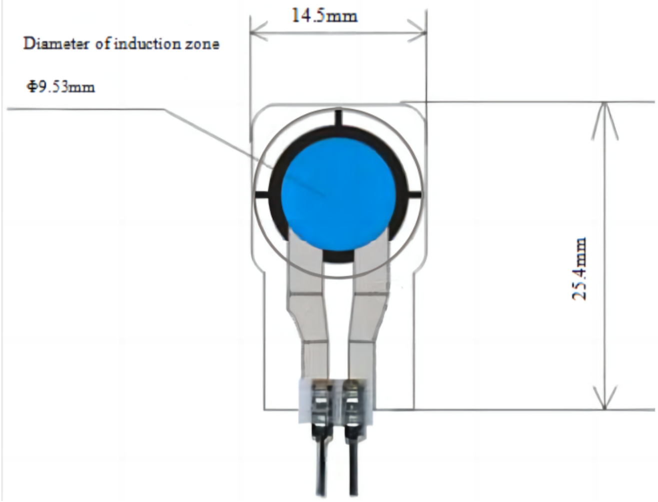


Figure 5. Model A301 Thin Film Force Sensor used in the experiment

Table 2. Parameters of A301 thin-film force sensor

Parameter	Value
Measuring range (N)	0～50
Thickness (mm)	0.2
Length (mm)	25.4
Width (mm)	14.5
Diameter of sensing range (mm)	9.53
Reaction time (ms)	<50
Operating temperature (°C)	-9 ℃ ～ 60 ℃

The friction force generated when potatoes come into contact with the mechanical components of the separation screen is one of the main reasons for the damage to potato peels. In order to analyze the factors and patterns affecting the friction force on potatoes along the screen surface, a single-factor experiment was conducted under soil-free conditions with potato mass, crank speed, and screen inclination as factors. The test plan is shown in Table 3. To explore the influence of the interaction between soil and several factors on the friction force on potatoes, using potato mass (A), crank speed (B), and screen inclination (C) as factors, a response surface experiment was conducted after adding soil to the soil storage tank. The factor levels of the response surface experiment are shown in Table 4. The test indicators of both the single-factor experiment and the response surface experiment are the maximum friction

Table 3. Test for the friction force on potatoes under soil-less conditions

Test number	Potato mass (g)	Crank speed (r min^{-1})	Inclination angle of sieve surface (°)
1	200		
2	250		
3	300	200	14.7
4	350		
5	400		
6		160	
7		180	
8	300	200	14.7
9		220	
10		240	
11			0.7
12	300	200	7.7
13			14.7
14			21.7

Table 4. Factors and levels of response surface test

Level	Potato mass A (g)	Crank speed B (r min^{-1})	Inclination angle of sieve surface C (°)
1	150	160	0.7
0	350	200	14.7
-1	550	240	21.7

forces F_{f1max} and F_{f2max} of potatoes along the screen surface. Each group of experiments was repeated ten times, and the effective test time for each time was maintained at more than 10 seconds. The average value of the ten sets of test values was taken as the final result of the test indicator.

According to Box-Behnken central combination design theory (Fei et al., 2023), the response surface test was conducted. The maximum friction F_{f1max} when contacting sensor 1 and F_{f2max} when contacting sensor 2 were taken as response values. The relationship model between each test indicator and each test factor was constructed through quadratic linear regression, and variance analysis was conducted simultaneously.

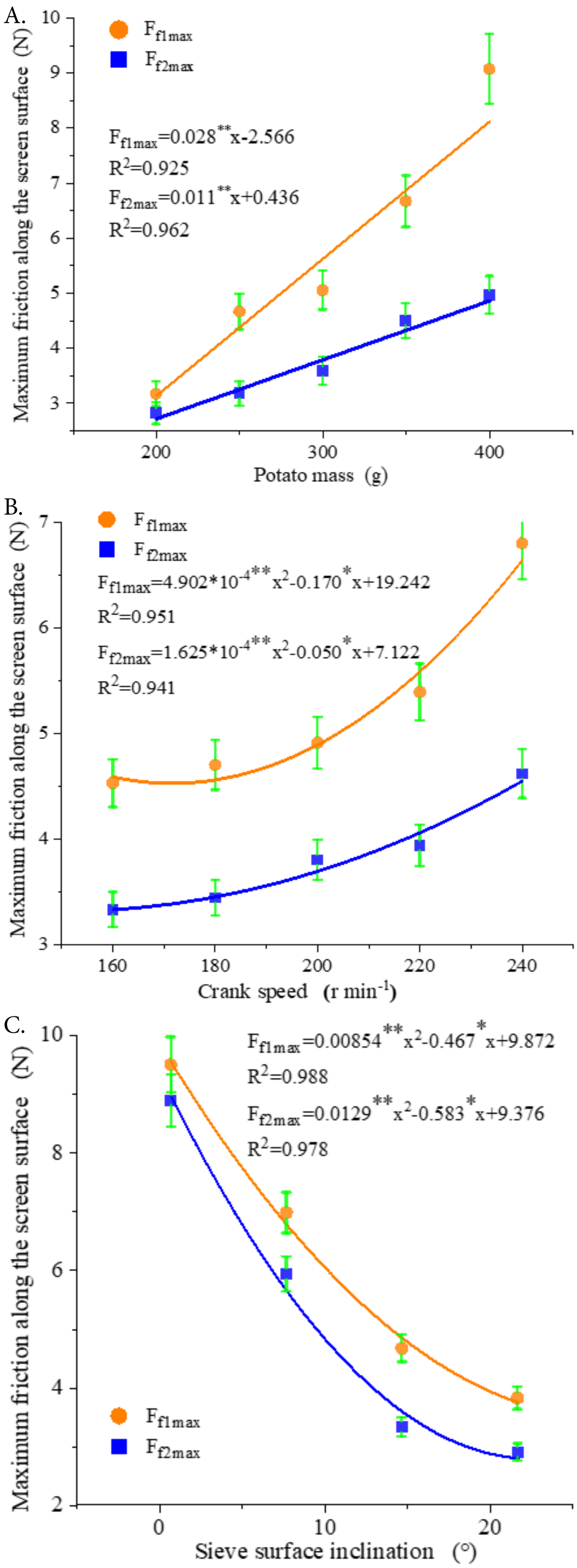
Descriptive statistics were first employed to summarize the basic characteristics of the data. Subsequently, analysis of variance and regression analysis, were utilized to assess hypotheses and identify significant differences. Using Design-expert 13 software, statistical analysis and correlation analysis were conducted on the obtained data by response surface methodology.

Results and Discussion

When the crank speed was 200 r min^{-1} with the inclination angle of the screen surface was 14.7°, the relationship between potato mass and the maximum friction along the screen surface is shown in Figure 6A. When the potato mass was 300 ± 5 g with the screen surface inclination angle was 14.7°, the relationship between the crank speed and the maximum friction force along the screen surface direction is shown in Figure 6B, and when the potato mass was 300 ± 5 g with the crank speed was 200 r min^{-1}, the relationship between the screen surface inclination angle and the maximum friction force along the screen surface direction is shown in Figure 6C.

As shown in Figure 6A, it could be seen that in the experimental range, with the increase of potato mass, the maximum friction force along the sieve surface direction of the potato also increased, which was linearly and positively correlated with the overall potato mass; at the same level, $F_{f1\ max}$ was always greater than $F_{f2\ max}$, and the difference between them is getting increase with the increase of potato mass. Within the test scope, the fluctuation range of F_{f1max} is between 3.16 and 9.07 N, and that of F_{f2max} is between 2.82 and 4.96 N.

As shown in Figure 6B, in the test range, with the increase of crank speed, the maximum friction force on potatoes along the screen surface gradually increased, showing a quadratic positive correlation with crank speed. It could be seen from the fitting curve that with the increase of crank speed, the maximum friction force F_{f1max} increased faster than the maximum friction force $F_{f2\ max}$. Under the same condition, $F_{f1\ max}$ was always larger than $F_{f2\ max}$, and the difference between them became larger with increased crank speed. Within the test scope, the fluctuation range of F_{f1max} is between 4.52 and 6.79 N, and that of F_{f2max} is between 3.33 and 4.61 N.



*; ** - Significant at p ≤ 0.05 and p ≤ 0.01 respectively by t-test; The vertical bar represents the standard deviation of the mean of the seven values; F_{f1max} - Maximum friction force on potato pointing to the tail end of the screen along the screen surface direction; F_{f2max} - Maximum frictional force on potato pointing to the front end of the screen along the screen surface direction

Figure 6. Trend chart of maximum friction along the screen surface: (A) Relationship between potato mass and the maximum friction; (B) Relationship between crank speed and the maximum friction; and (C) Relationship between screen surface inclination angle and the maximum friction

As shown in Figure 6C, in the experimental range, with the increase of screen surface inclination angle, the maximum friction force on potatoes along the screen surface direction gradually decreased, negatively correlated with the overall screen surface inclination angle. The maximum friction force $F_{f1\ max}$ pointing to the tail end of the screen along the screen surface direction was always greater than the maximum friction force $F_{f2\ max}$ pointing to the front end of the screen along the screen surface direction. Within the test scope, the fluctuation range of F_{f1max} is between 3.82 and 9.49 N, and that of F_{f2max} is between 2.90 and 8.88 N.

The response surface results are shown in Table 5. It can be seen from the table that the addition of soil has a significant influence on the friction force on potatoes.

The results of analysis of variance are shown in Tables 6 and 7. Among them, A represents potato mass (g), B represents crank rotational speed (r min^{-1}), and C represents screen inclination angle (°). The lack-of-fit test, signal-to-noise ratio, and correlation coefficient (R^2) in the variance analysis determine whether the constructed relationship model can be used to predict the relevant test indicators and the fitting degree between the predicted data and the test data.

According to the analysis of variance in Table 6, we could see that the relationship models of maximum friction F_{f1max} and F_{f2max} along the screen surface were extremely significant ($p < 0.01$). The misfit items of the relational models were not significant ($p < 0.05$), and the signal-to-noise ratio was greater than 18, which indicated that the relational models established were reasonable and better and could be used to predict the related test performance indexes. Both the correlation coefficient R^2 and the adjusted R^2 were greater than 0.9, which indicated that the predicted data of the established relational model had a high degree of fitting with the experimental data (Wu et al., 2017; Song et al., 2020; Baoer et al., 2022).

According to the test results in Table 5, regression analysis was conducted on the test data, and the response surface regression models of the maximum frictional forces F_{f1max} and F_{f2max} along the screen surface direction with potato mass (g) A, crank rotational speed (r min^{-1}) B, and Inclination angle of sieve surface (°) C were established. The regression equations are shown as Eqs. 6 and 7.

$$\begin{aligned} F_{f1max} &= 55.81588 - 0.064969 \times A - 0.378609 \times B + \\ &+ 0.839874 \times C + 0.000296 \times A \times B - 0.000846 \times A \times C - \\ &- 0.002729 \times B \times C + 0.000073 \times A \times A + \\ &+ 0.000872 \times B \times B - 0.014920 \times C \times C \end{aligned} \tag{6}$$

Table 5. Results of response surface experiments on the friction force exerted on potatoes under soil conditions

Test number	Potato mass (g)	Crank speed (r min^{-1})	Inclination angle of sieve surface (°)	Maximum friction $F_{f1\ max}$ (N)	Coefficient of variation F_{f1max} (%)	Maximum friction $F_{f2\ max}$ (N)	Coefficient of variation F_{f2max} (%)
1	150	160	0.7	15.81	8.24	14.21	7.83
2	550	160	14.7	26.55	16.48	20.80	18.21
3	150	240	14.7	14.60	6.91	13.70	7.28
4	50	240	0.7	41.32	23.45	25.64	25.67
5	150	200	0.7	16.54	11.27	14.64	9.97
6	550	200	0.7	32.01	20.16	23.07	20.16
7	150	200	21.7	13.40	8.20	12.13	8.34
8	550	200	21.7	23.12	15.62	17.36	12.72
9	350	160	0.7	21.61	14.57	17.85	14.55
10	350	240	0.7	26.01	17.23	19.09	19.13
11	350	160	21.7	14.59	7.96	13.12	10.91
12	350	240	21.7	16.79	9.74	15.08	11.14
13	350	200	14.7	19.92	10.33	16.61	10.28
14	350	200	14.7	18.44	10.49	16.61	10.53
15	350	200	14.7	17.46	10.25	16.60	11.02
16	350	200	14.7	17.91	9.98	15.99	10.38
17	350	200	14.7	19.49	10.64	15.99	10.74

Table 6. Analysis of variance of the maximum friction force F_{f1max} along the sieve rod direction

Source of variance	Sum of squares	Degree of freedom	Mean squares	F-value	P value	Significance
			Maximum friction F_{f1max} along the sieve rod direction			
Model	816.88	9	90.76	44.22	< 0.01	**
A	343.11	1	343.11	167.17	< 0.01	**
B	20.22	1	20.22	9.85	0.016	*
C	99.85	1	99.85	48.65	< 0.01	**
AB	13.67	1	13.67	6.66	0.036	*
AC	15.66	1	15.66	7.63	0.028	*
BC	6.51	1	6.51	3.17	0.118	ns
A^2	29.63	1	29.63	14.44	< 0.01	**
B^2	6.81	1	6.81	3.32	0.111	ns
C^2	5.06	1	5.06	2.47	0.160	ns
Residual	14.37	7	2.05			
Total	831.25	16				
					$R^2 = 0.98$, adjusted $R^2 = 0.96$	
	CV (%)				6.85	

** - Significant at 0.01 probability by the F test; *: Significant at 0.05 probability by the F test; ns - Not significant; DF - Degrees of freedom; MS - Mean squares; CV - Coefficient of variation; F_{f1max} - Maximum friction force on potato pointing to the tail end of the screen along the screen surface direction; A - Potato Mass; B - Crank speed; C - Inclination angle of sieve surface

Table 7. Analysis of variance of the maximum friction force (F_{f2max}) along the sieve rod direction

Source of variance	Sum of squares	Degree of freedom	Mean squares	F value	P value	Significance
			Maximum friction F_{f2max} along the sieve rod direction			
Model	197.88	9	21.99	61.21	< 0.01	**
A	99.98	1	99.98	278.34	< 0.01	**
B	2.82	1	2.82	7.86	0.026	*
C	35.92	1	35.92	100.01	< 0.01	**
AB	0.7275	1	0.73	2.03	0.197	ns
AC	3.55	1	3.55	9.88	0.016	*
BC	0.0231	1	0.02	0.0643	0.807	ns
A^2	3.31	1	3.31	9.21	0.019	*
B^2	0.7456	1	0.75	2.08	0.192	ns
C^2	3.66	1	3.66	10.18	0.015	ns
Residual	2.51	7	0.36			
Total	200.40	16				
				$R^2 = 0.98$, adjusted $R^2 = 0.97$		
	CV(%)			5.53		

** - Significant at 0.01 probability by the F test; * - Significant at 0.05 probability by the F test; ns - Not significant; DF - Degrees of freedom; MS - Mean squares; CV - Coefficient of variation; F_{f2max} - Maximum frictional force on potato pointing to the front end of the screen along the screen surface direction; A - Potato mass; B - Crank speed; C - Inclination angle of sieve surface

$$\begin{aligned} F_{f2max} &= 25.26297 - 0.006878 \times A - 0.121357 \times B + \\ &+ 0.255743 \times C + 0.000068 \times A \times B - 0.000403 \times A \times C - \\ &- 0.000162 \times B \times C + 0.000024 \times A \times A + \\ &+ 0.000289 \times B \times B - 0.012679 \times C \times C \end{aligned} \quad (7)$$

Through the obtained response surface, the influence of the interaction between potato mass (A), crank speed (B), and Inclination angle of sieve surface (C) on the frictional force of potatoes was analyzed, as shown in Figures 7 and 8. Figures 7 and 8 correspond to Eq. 6 and 7, respectively. Moreover, when studying the interaction of A and B, the value of C is the intermediate level of 11.2°; when studying the interaction of A and C, the value of B is the intermediate level of 200 r min^{-1}; when studying the interaction of B and C, the value of A is the intermediate level of 350 g.

According to Figure 7, under the influence of interactive test factors, with the increase of potato mass, the friction force F_{f1max} along the screen surface increased slowly, which was inconsistent with the conclusion that potato mass was positively correlated with the F_{f1max} along the screen surface in single factor analysis; At the same time, with the increase of crank speed, the F_{f1max} along the sieve surface decreased first and then increased, which was inconsistent with the conclusion that there was a quadratic positive correlation between crank speed and F_{f1max} along the sieve surface in single factor analysis. Moreover, it could be seen that the F_{f1max} along the screen surface gradually decreased with the increase of the screen surface inclination, which was consistent with the conclusion that the screen surface inclination was negatively correlated with the potato friction F_{f1max} along the screen surface by single factor analysis. However, the degree of influence was low. The above conclusions showed that the response surface results were inconsistent with the single factor results due to soil factors, and the interaction of experimental factors influenced the F_{f1max} along the sieve surface of potatoes, consistent with the variance analysis results in Table 6.

Figure 7A was a response surface diagram of potato mass and crank speed on the influence of potato on the maximum friction force F_{f1max} along the sieve surface. When the inclination angle of the sieve surface was 11.2°, with the increase of potato mass, the friction force of the potato increased with the increase of crank speed. However, when the potato mass was 150 to 200 g, the friction force on the potato decreased with increased crank speed. This was because when the potato mass was low, the contact area of the potato and the component of gravity in X axis was very small, so the friction force changed little at this time, but the increase of crank speed made the inertia force increase, which made the friction force on potato decrease slowly with the increase of crank speed when the mass was low. When the potato mass was large, the influence of crank speed on the friction force on the potato was significantly increased. This can be explained because when a potato with a large mass moves under the action of a high-speed crank, its inertia will also increase. A larger inertia will make it more difficult for the potato to change direction in its movement on the screen surface, thereby increasing the frictional resistance between it and the screen surface. At the same time, the curved surface of potato mass was steeper than the curved surface of crank speed, which indicated that the influence of potato mass on the F_{f1max} along the sieve surface was greater than that of crank speed under the interaction. In this case, when the crank speed was 240 r min^{-1} with the potato mass was 550 g, the maximum friction force along the sieve surface reached 35.59 N.

Figure 7B shows the response surface diagram of the influence of potato mass and sieve surface inclination angle on the potato's maximum friction F_{f1max} along the sieve surface. When the crank speed was 200 r min^{-1} with the potato mass was less than 250 g, the F_{f1max} increased slowly. The response surface was concave, indicating that the interaction between the two factors strongly influenced the F_{f1max} along the sieve surface. When the potato mass was greater than 250 g, the F_{f1max} increased rapidly, and the response surface was convex, which indicated that the influence of potato mass on the F_{f1max} along the sieve surface was stronger than that of interaction, and the curved surface of potato mass was steeper than that of the inclination angle of sieve surface, which indicated that under the interaction, the influence of potato mass on the F_{f1max} along the sieve surface was greater than that of the inclination angle of sieve surface. In this case, when the inclination angle

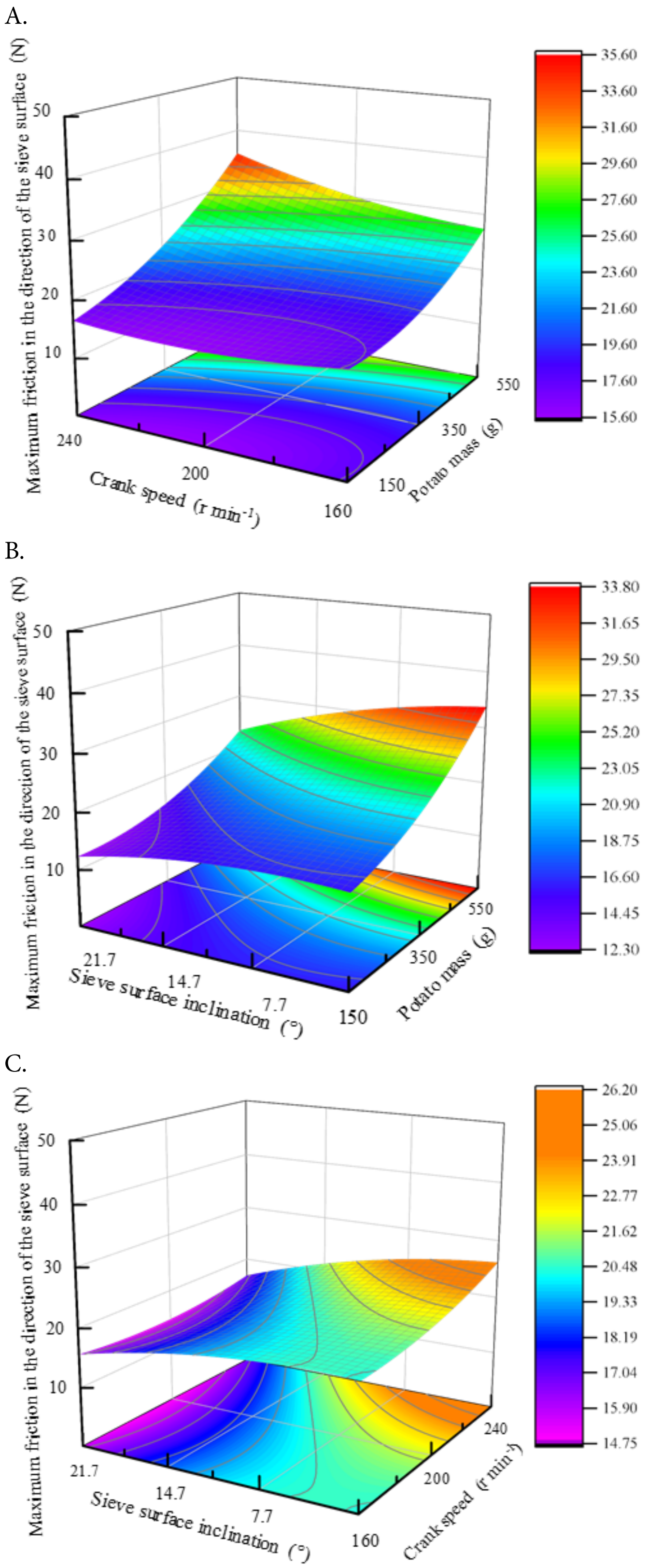


Figure 7. Response surface of potato subjected to friction force F_{f1max} along sieve surface and experimental factors. (A) Interaction effect between potato mass and crank speed, (B) Interaction effect between potato mass and inclination angle of the sieve surface, and (C) Interaction effect between crank speed and inclination angle of the sieve surface

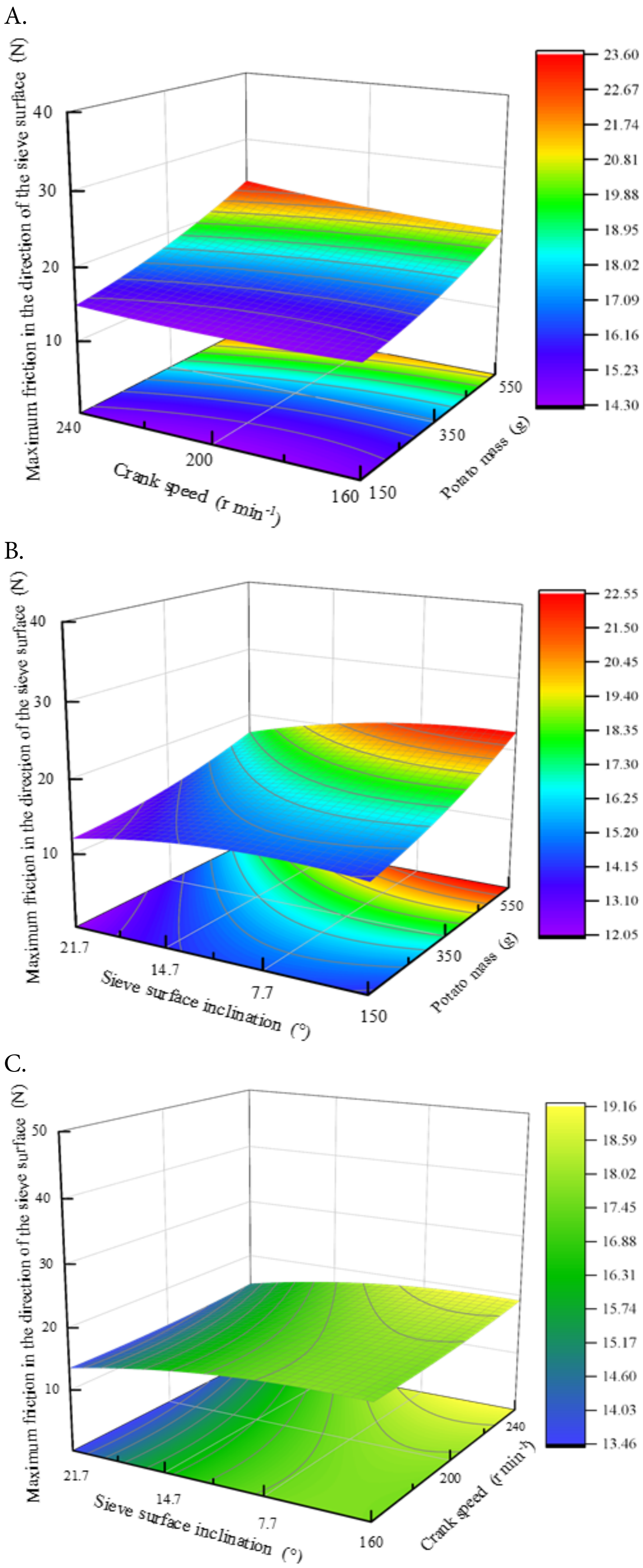


Figure 8. Response surface of potato subjected to friction force F_{f2max} along sieve surface and experimental factors. (A) Interaction effect between potato mass and crank speed, (B) Interaction effect between potato mass and inclination angle of the sieve surface, and (C) Interaction effect between crank speed and inclination angle of the sieve surface

of the sieve surface was 0.7, and the potato mass was 550 g, the maximum friction force of the potato along the sieve surface reached 33.75 N.

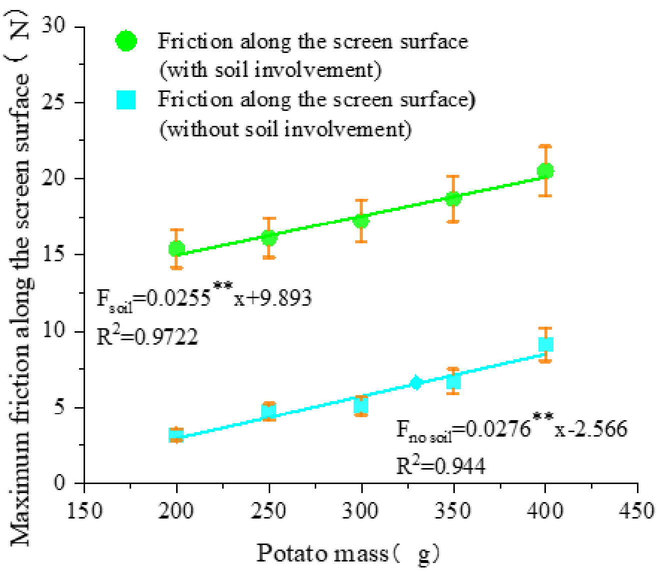
Figure 7C shows the response surface diagram of the influence of crank speed and screen surface inclination angle on the maximum friction force F_{f1max} on the potato along the screen surface. When the middle level of potato mass was 350 g, and the crank speed was kept constant, the maximum friction force on the potato along the screen surface decreased with the increase of the screen surface inclination angle. It could be observed that the interaction between crank speed and screen inclination angle had little influence on the maximum friction force of the potato along the screen surface; the slope was slow, and the friction force changed little. It also verified that the interaction of B and C in the variance model is not significant and proved the model's accuracy. In this case, when the screen inclination angle was 0.7° with the crank speed was 240 r min^{-1}, the maximum friction force on the potato reached 26.15 N.

According to Figure 8, under the influence of interactive test factors, the interaction of several factors had a similar influence on the friction force F_{f1max} along the screen surface. The response surface diagram was similar, inconsistent with the conclusion that the potato mass was positively correlated with the friction force F_{f2max} along the screen surface in single factor analysis. It was inconsistent with the conclusion that there was a quadratic positive correlation between crank speed and the F_{f2max} of potato along the screen surface in single factor analysis. The results of single factor analysis were not consistent with the quadratic negative relationship between the inclination angle of the sieve surface and the F_{f2max} of the potato along the sieve surface. It showed that the interaction of experimental factors influenced the F_{f2max} of the potato along the sieve surface, which was consistent with the results of the analysis of variance in Table 6. It also verified the case of $F_{f1max} > F_{f2max}$ in the single-factor analysis.

Figures 8A and B show the response surface of potato mass and crank speed on the maximum friction force F_{f2max} along the sieve surface and the response surface diagram of potato mass and inclination angle of sieve on the F_{f2max} along the sieve surface, respectively. The response surface was concave, and the response surface diagram was similar to Figures 7A and B, indicating that the interaction affects the F_{f2max} along the sieve surface. The response surface diagram of Figure 8C also verified that the B-C interaction in the variance model was not significant, which proved the model's accuracy again. At the same time, it could be found that F_{f2max} was uniformly less than F_{f1max}, indicating that the friction force along the sieve surface of the potato at sensor 1 was greater than that at sensor 2, which verified that F_{f1max} was larger than F_{f2max}.

The above analysis shows that after adding soil, the friction force on potatoes differs from the conclusion drawn from the single-factor analysis, which prominently shows the importance of considering multi-factor interaction in the experimental design. Among them, the interaction of AB and AC has the greatest influence on the friction force on potatoes. Aiming to verify whether the response surface model is reliable, the test randomly selected the level factors: the potato mass of 350g, the crank speed of 160 r min^{-1}, and the sieve surface inclination angle of 0.7°. The regression equation predicts that F_{f1max} and F_{f2max} are 21.801 and 17.692 N, respectively. Through five repeated verification tests, the average values of F_{f1max} and F_{f2max} were 20.166 and 18.231 N, respectively, and the errors between the experimental data and the predicted data were 7.450 and 3.046%, respectively. Thus, it can be seen that this model can be used to estimate the friction force on potatoes during the actual harvest process, and the interaction influence and laws obtained from the response surface have certain reference values for the subsequent research on reducing potato epidermal damage.

In order to analyze the influence of soil on potato friction, when crank speed was 200 (r min^{-1}) and screen surface inclination was 14.7°, the variation of potato friction with potato mass under single factor test and response surface test was compared, and in the actual potato harvest, the weight of potato was different, and F_{f1max} was higher than F_{f2max} in single factor and response surface test, F_{f1max} was chosen as the contrast ratio. Based on Equations. 6 and 7, the friction force was obtained to be 15.362, 16.091, 17.185, 18.644, and 20.466 N when the potato mass was 200, 250, 300, 350, and 400 g at 200 r min^{-1} and screen angle 14.7°, respectively. The comparison data is shown in Figure 9. It could be seen that within the test range, F_{f1max} with soil participation was significantly greater than F_{f1max} without soil participation, and the multiple range of the increase was between 2.32 and 4.85. The reason for this result was that with the participation of soil, the contact area of the potato increased, so the friction force increased.



** - Significant at p≤0.05 by t-test; The vertical bar represents the standard deviation of the mean of the seven values

Figure 9. Comparison of the friction of Maximum friction alongside the screen surface in function of potato mass, with or without soil

Conclusions

1. As the mass of potatoes increases, the rotational speed of the crank increases, and the inclination angle of the screen surface decreases, the friction force on potatoes along the direction of the screen surface increases.

2. The interaction between potato mass and crank speed has the greatest influence on friction.

3. The friction force of potatoes along the screen surface is greater when there is soil than when there is no soil.

4. Through a self-built potato friction testing system, a quadratic regression equation between potato mass, crank speed, inclination angle of the sieve surface, and the friction force on potatoes along the screen surface is obtained, which can be used to predict relevant values.

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