DESIGN AND TEST OF POTATO CONVEYING AND GRADING DEVICE WITH VARIABLE SPACE
/
变间距式马铃薯输送分级装置设计与试验

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ABSTRACT
This paper proposed a technical idea of joint operation of conveying and grading and developed a potato conveying and grading device with variable space to realize efficient grading in the field because of the difficulties of field grading in the process of potato harvesting in the hilly mountains of northwest China. Based on field measurement of potato size distribution, the clearance between rotating plates of potato conveying and grading device was determined. The key structural parameters of the rotating plate were obtained by referring to the structure and relevant parameters of the conveying and grading device. Moreover, the conveyor chain elevation angle of the conveying and grading device was determined through the dynamics analysis of potatoes on the conveying and grading device. The inclined plane test determined the inclination angle of the potato guide plate. To reduce the damage to potatoes in the process of conveying and grading, damage analysis was carried out. Finally, Field tests were conducted with conveyor chain elevation angle, unit forward speed, and the conveyor chain line speed as test factors, and the grading accuracy and the damage rate of the potato conveying and grading device as test indexes. The test results showed that when the conveyor chain elevation angle, unit forward speed, and conveyor chain line speed were 21.0°, 0.8 m/s, and 1.3 m/s, respectively, the grading accuracy was 91.4% and the rate of potato damage was 0.88%. The operational performance of the prototype was stable, and all the test evaluation indicators could meet the agronomic requirements of the potato harvester.

摘要
针对西北丘陵山区马铃薯收获过程中田间分级困难的问题，提出了输送分级联合作业的技术思路，并研制了一种变间距式马铃薯输送分级装置，以实现田间高效分级。在实地测量马铃薯尺寸分布基础上，确定马铃薯输送分级装置的转动板间隙。参考输送分级装置结构和相关参数，得到转动板关键结构参数。通过对输送分级装置上的马铃薯进行动力学分析，确定输送分级装置输送链的提升角度。通过斜面试验确定了导薯板的倾角。为了减少马铃薯在输送分级过程中的损伤，进行了损伤分析。最后，以输送链提升角度、机组前进速度和输送链线速度为试验因素，以马铃薯输送分级装置的分级准确率和损伤率为试验指标进行田间试验。试验结果表明，当输送链提升角度、机组前进速度和输送链线速度分别为21.0°、0.8m/s和1.3m/s时，分级准确率为91.4%，损伤率为0.88%。样机运行性能稳定，各项试验评价指标均满足马铃薯收获机的农艺要求。

INTRODUCTION
Potato is the world's third most important food crop, with high nutritional value and a wide planting range *(Koga et al., 2013; Zheng et al., 2021)*. China's potato industry has grown rapidly in recent years, with its planted area and production ranking first in the world *(Kang et al., 2014; Yang et al., 2016; Zhou et al., 2015; Luo et al., 2021)*. At this stage, China's potato harvesting mainly uses a two-stage harvesting method, where the dug potatoes are laid on the ground, followed by manual picking, sorting, and conveying*(Kumar and Tripathi, 2017; Wei et al., 2019)*. In this mode, the potato conveying and grading process goes through multiple processes, which can easily cause mechanical damage and spoilage of potatoes. At the same time, the subjectivity and inconsistency of people in the grading process can easily lead to production waste *(Razmjooy et al., 2012; Wei et al., 2018; Yang et al., 2018)*. Therefore, the design of a mechanical potato conveying and grading device is of great significance in improving the quality and efficiency of grading operations.

Lv et al. (2019) developed a roller potato conveying and grading device, and *Wang Xiangyou et al*. developed a paddle roller push-type potato cleaning and sorting machine *(Wang et al., 2017)*. However, it widely suffered from the disadvantages of large size, poor field adaptability, and difficulty adapting to complex plots of land such as hilly and mountainous areas. With the development of spectral detection, spectral imaging, and other technologies, UV cameras, hyperspectral cameras, NMR and X-rays, and other potato sorting techniques came into being*(Zhou et al., 2015; Aleixos et al., 2002; Al-Mallahi et al., 2008; Blasco et al., 2009; Dacal-Nieto et al., 2009; Kong et al., 2012; Rady and Guyer, 2015)*. However, they have not been widely used due to the expense and difficulty of applying directly to field operations. Therefore, a potato conveying and grading device with a low damage rate and high grading accuracy is urgently needed to improve the economic efficiency of potato cultivation.

For this reason, this study proposed the technical idea of "rod group translational conveying, potato soil separation at the front end, rotating plate variable position grading." Designed a variable space potato conveying and grading device. By designing and experimentally verifying the key components of the conveying and grading device and studying the movement mechanism of potatoes on the grading device, efficient and low-loss grading of potatoes in the field can be achieved.

MATERIALS AND METHODS

Whole machine structure and working principle

Whole machine structure

Fig. 1 shows the whole machine structure of the variable space potato conveying and grading device. The whole machine mainly consists of a lifting device, gear shifter, diesel engine, frame, rear walking wheel, transmission device, conveying and grading device, depth limiting wheel, front walking wheel, pick-up shovel, potato toggle device, etc. A diesel engine powers the whole machine. The lifting device can change the height of the conveying and grading device relative to the ground to adapt to different terrain conditions. The pick-up shovel can pick up potatoes on the ground. The potato toggle device can move potatoes into the conveying grading device. The conveying and grading device can realize the conveying and grading of potatoes. The whole machine can complete the operation of potato collection, picking up, potato soil separation, and grading.

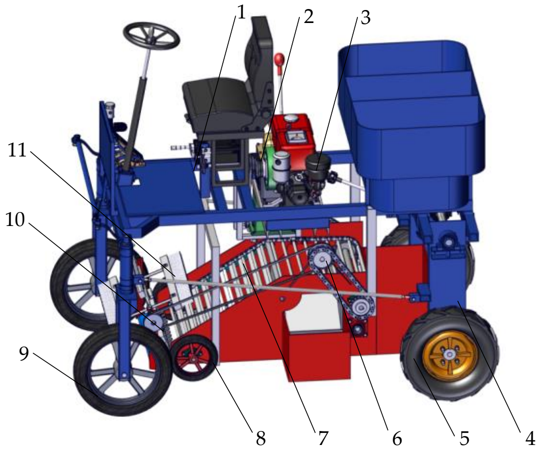


Fig. 1 - Structure diagram of the whole machine

1 – Lifting device; 2– gear shifter; 3 – diesel engine; 4 – frame; 5 – rear walking wheel; 6 – transmission device; 7 – conveying and grading device; 8 – depth limiting wheel; 9 – front walking wheel; 10 – pick-up shovel; 11 – potato toggle device

Working principle and technical parameters

The working principle of the variable space conveying and grading device is shown in Figure 2. In the field operation, while the conveying and grading device moved forward, the conveying chain drived the potatoes backward. The potatoes on the surface of the field and the soil they carry entered the conveying and grading de-vice under the joint action of the pick-up shovel and the potato toggle device and, in the process, completed the preliminary separation of potatoes and soil. Under the action of the conveying and grading device, potatoes were transported backward while the potato soil was further separated, and at its back end, the rotation of the rotating plate made the rotating plate clearance change to complete the potato grading. The device can effectively solve the damage caused by multiple mechanical operations on potatoes in the harvesting process, shorten the time of potato harvesting operations, and thus improve operational efficiency. Its main technical parameters are shown in Table 1.

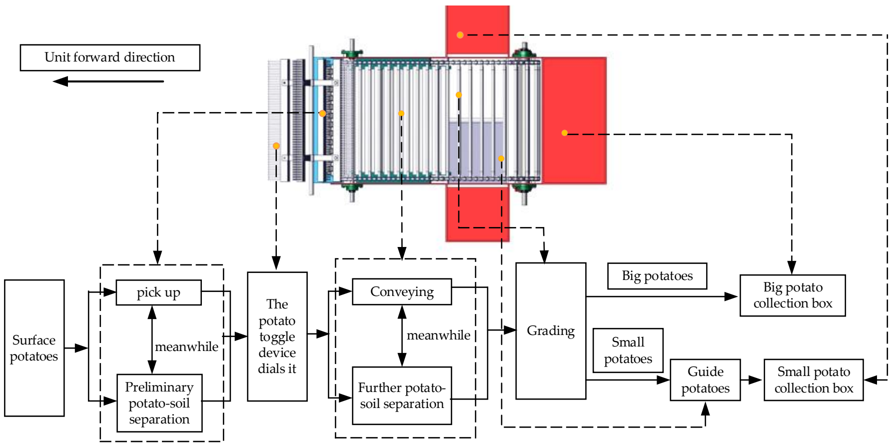


Fig. 2 - Working principle diagram of variable pitch potato conveying and grading device

Table 1

Main technical parameters of variable space potato conveying and grading device

Projects	Title 2
Diesel engine power/kW	23
Whole machine size (length× width× height)/mm× mm× mm	2000× 1300× 1600
Conveying and grading device size(length× width× height)/mm× mm× mm	1500× 800× 600
Number of harvests and rows	Single ridge and double row
Operation width/mm	1100
Travel speed/(m/s)	0.7-1.3
Net working time productivity/(hm^2/h)	0.18-0.32

Design and analysis of conveying and grading device

The structure of conveying and grading device is shown in Fig. 3, which consists of the side plate, conveying chain, rotating plate, fixed guide rail, connecting rod, large potato collection box, small potato collection box, potato guide plate, etc. It adopted the technical idea of "rod group translational conveying, potato soil separation at the front end, rotating plate variable position grading ". Specifically, the connecting rod on the conveying chain was installed with the rotating plate, and the rotating plate can be rotated around the connecting rod. Combined with the fixed guide rail installed at the bottom of the front end of the conveyor chain, the rotating plate at the front end of the conveyor grading device can be supported by the fixed guide rail and be in a flat extension state, and the stage was taken as the lifting stage I. As there was no fixed guide rail at the rear end of the conveying and grading device, the rotating plate lost its supporting role and rotated in a vertical state under the action of its gravity, and the stage was taken as the lifting stage II. So the smaller potatoes fell first and entered the small potato collection boxes on both sides along the guide plate. In comparison, the larger potatoes were transported back to the large potato collection boxes at the rear, thus achieving grading.

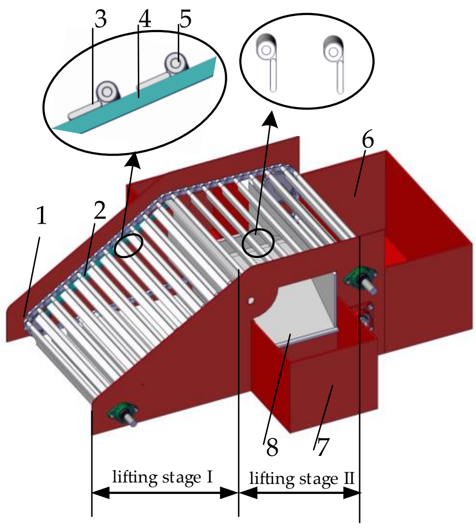


Fig. 3 - The structure of conveying and grading device

1 – side panel; 2– conveyor chain; 3 – rotating plate; 4 – fixed guide rail; 5 – connecting rod; 6 – large potato collection box;7 – small potato collection box; 8 – potato guide plate

Design of rotating plate

Determination of the rotating plate clearance

In the lifting stage I, potatoes were transported backward along the conveyor chain, and the mixed soil fell through the rotating plate clearance. In lifting stage II, when the potato thickness was less than the rotating plate clearance, the potato dropped from the rotating plate clearance, so the rotating plate gap was determined based on the potato size distribution.

Referring to the official Chinese standards for potato grades and specifications (NY/T 1066-2006, 2006) and the actual situation in Guyuan City, Ningxia, China, the potatoes were divided into two grades using 200g mass as the limit. Less than 200g of potatoes for small potatoes can be used as a seed or commercial potatoes, and greater than or equal to 200g for large potatoes can be sold directly as edible potatoes.

After the field measurement of the test object " Qingshu 9 " in Xiji County, Guyuan City, Ningxia, the potatoes were divided into spherical and ellipsoidal to clearly and accurately describe the distribution of potatoes*(Geng et al., 2019)*. According to its morphological characteristics, sphericity S_P was introduced to classify potatoes. When $S_P > 0.85$, potatoes were spherical, and when $S_P \leqslant 0.85$, potatoes were ellipsoida *(Liu et al., 2018)*. The results of potato sample measurements are shown in Table 2.

The sphericity S_P is defined as:

$$S_p = \left(\frac{\frac{\pi}{6} l_s \omega_s t_s}{\frac{\pi}{6} l_s^3}\right)^{\frac{1}{3}} = \left(\frac{\omega_s t_s}{l_s^2}\right)^{\frac{1}{3}} = \frac{(l_s \omega_s t_s)^{\frac{1}{3}}}{l_s} \tag{1}$$

where:

l_s is the length of the potato, [mm];

ω_s is the width of the potato, [mm];

t_s is the thickness of the potato, [mm].

Table 2

Results of potato sample measurements

Type	Thickness range (mm)	Average mass (g)	Average thickness (mm)	Thickness size distribution (mm)	Proportion (%)
Small spherical potato	20~30	16.4	26.9	25.1~28.6	0.5
	30~40	40.5	36.1	31.9~39.8	4.9
	40~50	68.3	44.5	40.0~49.1	1.9
	50~60	116.95	54.55	52.1~59.6	2.2
Small ellipsoidal potato	20~30	30.5	26.9	23.0~29.9	3.3
	30~40	70.0	36.2	30.2~40.0	11.5
	40~50	126.9	44.5	40.1~50.0	32.1
	50~60	160.1	53.2	50.1~59.9	7.6
Big ellipsoidal potato	40~50	221.2	47.9	42.3~49.8	2.3
	50~60	263.7	55.0	50.2~59.9	28.6
	60~70	360.0	62.8	60.6~67.1	5.1

The small potatoes of " Qingshu 9 " had two shapes: spherical and ellipsoidal, of which small spherical potatoes accounted for 9.5%, and the thickness was mainly concentrated in 31.9~39.8mm, with an average thickness of 36.1mm in this range. Small ellipsoidal potatoes accounted for 54.5%, with the thickness mainly concentrated in the range of 40.1~50.0mm, and the average range thickness is 44.5mm. Large ellipsoidal potatoes accounted for 36%, with thickness mainly concentrated in the range of 50.2~59.9mm, and the average range thickness is 55.0mm. To ensure that the potatoes cannot fall from the rotating plate clearance in lifting stage I, the rotating plate clearance was 31mm in lifting stage I. To ensure that as many small potatoes as possible fell into the small potato collection box through the clearance of the rotating plate and large potatoes entered the large potato collection box at the back side in the lifting stage II, to achieve two-stage grading in the lifting stage II successfully. According to Table 2, the value range of the clearance of the rotating plate in the lifting stage II was 44.5~55.0mm, and the clearance of the rotating plate in the lifting stage II was 52.0mm.

Determination of structural parameters of the rotating plate

From Fig. 4(a), it can be seen that the rotating plate is in flat extension under the action of the fixed guide rail in the lifting stage i. The clearance C_I of the rotating plate in this stage is:

$$C_1 = d - R - l \tag{2}$$

where:

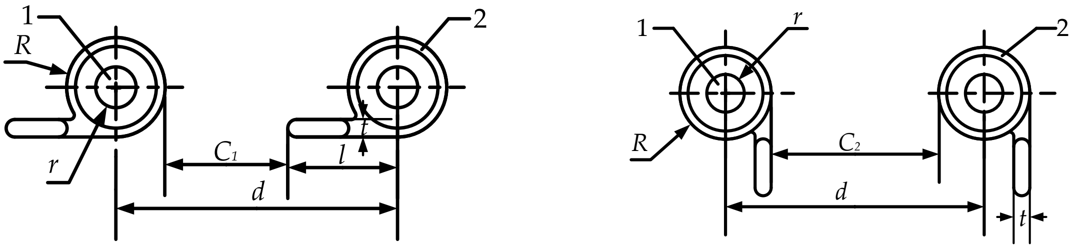
d is the center distance of the connecting rod, [mm];

R is the outer diameter of the rotating plate, [mm];

l is the extended length of the rotating plate, [mm].

From Fig. 4(b), it can be seen that there is no fixed guide rail in the lifting stage II and the rotating plate is in the vertical stage. The clearance of the rotating plate C_2 in this stage is:

$$C_2 = d - 2R \tag{3}$$



(a) rotating plate at lifting stage I (b) rotating plate at lifting stage II

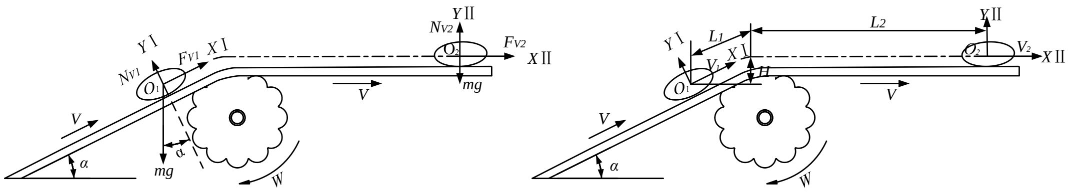
Fig. 4 - Structural Diagram of Rotating Plate

1 – connecting Rods; 2– rotating plate

The outer diameter R, the extended length l, the rotating plate's thickness t, and the connecting rod's center distance d need to satisfy equations (2) and (3). Referring to the structure and relevant parameters of the potato harvester conveying and grading device, the outer diameter of the rotating plate R was 15mm, the inner diameter r was 8mm, the extended length l was 36mm, and the thickness t was 3mm.

Determination of elevation angle of conveyor chain

The elevation angle of the conveyor chain was an important factor that affected the movement time and state of potatoes and greatly influenced the grading efficiency and accuracy. To determine the conveyor chain elevation angle, the dynamics analysis of potatoes was carried out. The potatoes were subjected to the supporting force of the conveyor chain N_{V1}, N_{V2}, the friction force of the conveyor chain F_{V1}, F_{V2}, and the potatoes' gravity mg. O_1 and O_2 were the cores of potatoes in the lifting stage I and lifting stage II, respectively. In lifting stage I, the conveying direction along the conveyor chain was the XI axis, and the vertical conveyor chain direction was the YI axis. In lifting stage II, the conveying direction along the conveyor chain was the XII axis. The vertical conveyor chain direction was the YII axis. The coordinate system shown in Figure 5 is established.



(a) Potato stress analysis (b) Potato movement analysis

Fig. 5 - The dynamics analysis of potatoes

From Fig. 5(a), it can be seen that the potatoes were subjected to frictional force F_{V1} in the lifting stage I is:

$$F_{V1} = \mu mgsoc\alpha \tag{4}$$

where:

m is the mass of potatoes, [kg];

μ is the coefficient of friction of potatoes in the lifting stage I;

α is the angle between the conveyor chain and the horizontal plane in the lifting stage I, [°].

Assuming that the potato enters conveying and grading device through the pick-up shovel at a speed of V_0, the speed V_1 of the potato at the O_1 position is:

$$V_1 = V_0 + (\mu cos\alpha - sin\alpha)gt_1 \tag{5}$$

where:

t_1 is the time from the potato entering the lifting stage I to moving to point O_1, [s].

It can be seen from Fig. 5 (b) that the friction force F_{V2} of potatoes in the lifting stage II is:

$$F_{V2} = \mu mg \tag{6}$$

Potatoes moved from O_1 to O_2 on the conveyor chain, ignoring the bouncing of potatoes in this process. According to the theorem of conservation of energy, we can get the following:

$$\frac{1}{2}mV_2^2 = \frac{1}{2}mV_1^2 + F_{V1}L_1 + F_{V2}L_2 - mgH \tag{7}$$

where:

V_2 is the speed of the potato at O_2, [m/s];

L_1 is the distance of the potato from O_1 to the end of the lifting stage I, [m];

L_2 is the length of potato movement from the endpoint of the lifting stage I to O_2, [m];

H is the height of the potato from O_1 to O_2, [m].

In Fig. 5(b), the length L_1 is related to the height H as:

$$H = L_1 sin\alpha \tag{8}$$

Combining the above equations yields:

$$V_2 = \sqrt{[V_0 + (\mu cos\alpha - sin\alpha)gt_1]^2 + 2\mu g(cos\alpha L_1 + L_2) - 2gsin\alpha L_1} \tag{9}$$

To sum up, potatoes moved backward, relying on the friction between them and the conveyor chain. It can be seen from Formula (9) that the speed of the potato in the lifting stage II, namely the grading stage, was related to the inclination angle α of the conveyor chain in lifting stage I. Considering the extension relationship between the conveying and grading device and the pick-up shovel and the relevant agronomic requirements of potato harvesting machinery, the value range of the conveyor chain elevation angle in this paper was 13°-23°.

Design of potato guide plate

The role of the potato guide plate was to ensure that potatoes falling from the clearance between the rotating plates of the conveying and grading device could enter the small potato collection boxes on the left and right sides through the potato guide plate. To ensure that potatoes did not accumulate on the potato guide, the sliding friction angle of the potato-steel plate needed to be measured. This measurement test was carried out with a homemade inclinometer composed of a bench, a pulley, a gearbox, an inclined surface, and a steel wire. Since the friction received by the material was related to its material, shape, and quality of the object *(Cui et al., 2013)*, to ensure the reliability of the test data, potatoes with the maximum, intermediate, and minimum S_p and mass values were selected as test objects in the actual potato measurement data in Section 2.1. The test results are shown in Table 3.

Table 3

Potato-plate sliding friction angle test results

No	Length (mm)	Width (mm)	Thickness (mm)	Mass (g)	S_p	Shape	Potato-plate sliding friction angle (°)
1	24.67	32.43	32.93	41.4	1.21	spheroidal	26.2
2	72.92	50.49	39.86	81.7	0.72	ellipsoidal	26.8
3	128.11	56.49	45.73	168.1	0.54	ellipsoidal	27.5
4	155.39	80.1	61.8	482.1	0.59	ellipsoidal	27.3
5	84.69	61.3	49.14	126.4	0.75	ellipsoidal	26.6
6	28.38	28.19	25.13	12.3	0.96	spheroidal	26.2
			average value				26.8

Through many measurements, the sliding friction angle between the potato and steel plate was 26°~28°, the average value was 26.8°, and the maximum value was 27.5°. When the tilt angle of the guide plate was too large, the momentum of the potatoes sliding down was too large, which would increase the collision phenomenon of the potatoes and the potato collection box, thus causing damage to the potatoes. So the tilt angle of the guide plate was 28°.

Analysis of potato damage

To reduce the mechanical damage of potatoes in mechanized harvesting, the damage analysis of potatoes was carried out *(Bao et al., 2021; Bentini et al., 2006; Opara and Pathare, 2014)*. The potato was regarded as a particle, ignoring the influence of air resistance and potato rolling in the potato's process of potato movement. The potato from the end of the lifting stage I moved to lifting stage II for an oblique throwing motion. This transition phase trajectory is shown in Figure 6.

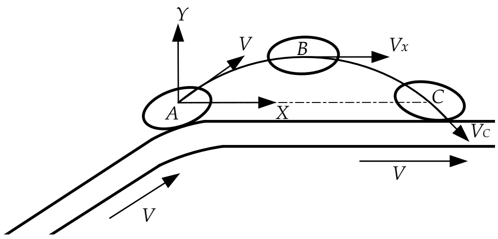


Fig. 6 - Trajectory of potato movement in the transition phase

Taken the center of mass of the potato at the end of lifting stage I as the origin A of the coordinate system, the horizontal to the right was the positive direction of the X axis, and the vertical to the up was the positive direction of the Y axis, established a rectangular coordinate system.

The collision speed V_C between the potato and the rotating plate when the potato is obliquely thrown down to position *C* is:

$$V_C = V \tag{10}$$

where: V is the conveyor chain line speed, [m/s].

When the potato collided with the rotating plate, the collision speed between the potato and the rotating plate was the main factor that caused damage to the potato *(Lv et al., 2020)*. From equation (10), the conveyor chain speed V can be reduced to lower the collision speed V_C. Since the linear speed, V of the conveyor chain, was less than the forward speed of the unit (the value range is 0.7-1.4 m/s), it was not conducive to the smooth transmission of potatoes on the conveying and grading device *(Lv et al., 2015)*. So the conveyor chain linear speed V should not be too small, and the value range of the linear speed V was 0.7~2.1 m/s.

RESULTS

Field experiment

Experimental conditions

The field experiment was conducted in November 2021 in Yangling District, Xianyang City, Shaanxi Province (34°28′N, 108°07′E). The potatoes were spread out in the field with a length of 10 m and a width of 1 m to simulate the state of the field after excavation work, and the field test is shown in Figure 7.

Fig. 7 - Field experiment

Test parameters and evaluation indexes

According to the results of the transport mechanics analysis of potatoes in the process of conveying and grading, the elevation angle of the conveyor chain, the forward speed of the unit, and the line speed of the conveyor chain were determined as the three primary parameters of the test study. According to the provisions of NY/T 1130-2006 Potato Harvesting Machinery, the essential evaluation indexes in the potato conveying and grading process: grading accuracy Y_1 and potato damage rate Y_2 were taken as the test indexes.

$$Y_1 = \frac{n_1}{N} \times 100\% \tag{11}$$

$$Y_2 = \frac{n_2}{N} \times 100\% \tag{12}$$

where:

N is the total mass of potatoes entering the conveying and grading unit, [kg];

n_1 is the total mass of potatoes correctly graded, [kg];

n_2 is the total mass of potatoes damaged after conveying and grading, [kg].

Experimental protocol and analysis of results

Experimental protocol and results

A quadratic orthogonal rotating combination test method was used to verify the grading performance of the conveying classifier and the potato damage. The forward speed of the unit was 0.7~1.3 m/s, the elevation angle of the conveyor chain was 13°~23°, and the speed of the conveyor chain was 0.7~2.1 m/s were used as the test factors, and the grading accuracy and potato damage rate were used as the test indexes. The test results analyzed the significance of the three test factors, and the parameters were optimized according to the actual needs to obtain the optimal combination of each factor. The coded levels of the test factors are shown in Table 4, and the test scheme and results are shown in Table 5.

Table 4

Code values and levels of factors

Code value x_j	test factors: conveyor chain elevation angle x_1 (°)	unit forward speed x_2 (m/s)	conveyor chain speed x_3 (m/s)
-1.682	13	0.7	0.7
-1	15	0.8	1.0
0	18	1	1.4
1	21	1.2	1.8
1.682	23	1.3	2.1

Table 5

Experimental protocol and results

No	test factors: x_1 (°)	x_2 (m/s)	x_3 (m/s)	Y_1 (%)	Y_2 (%)
1	15	0.8	1	85.6	2.3
2	21	0.8	1	90.4	0.9
3	15	1.2	1	84.3	3.4
4	21	1.2	1	87.1	1.9
5	15	0.8	1.8	87.3	3.9
6	21	0.8	1.8	91.3	2.6
7	15	1.2	1.8	86.5	4.3
8	21	1.2	1.8	94.2	3.7
9	13	1.0	1.4	83.4	4.3
10	23	1.0	1.4	92.2	2.0
11	18	0.7	1.4	91.1	1.9
12	18	1.3	1.4	88.0	3.5
13	18	1.0	0.7	85.9	1.4
14	18	1.0	2.1	89.5	4.0
15	18	1.0	1.4	91.4	2.3
16	18	1.0	1.4	91.8	2.2
17	18	1.0	1.4	92.7	2.4
18	18	1.0	1.4	89.9	2.3
19	18	1.0	1.4	91.0	2.1
20	18	1.0	1.4	90.2	2.5
21	18	1.0	1.4	91.3	2.5
22	18	1.0	1.4	90.6	2.2
23	18	1.0	1.4	92.1	2.2

Experimental results and analysis

Design-Expert 13.0 software was used to fit multiple regression to the test results in Table 5 to obtain the regression equation of grading accuracy Y_1 and potato damage rate Y_2. And test the significant influence of each test factor on the working performance of the coveying and grading device.

(1) grading accuracy Y_1

By analyzing and fitting the test results, Table 6 provides the ANOVA of grading accuracy. According to the ANOVA results, the model F=19.52, indicating that the model was significant; P<0.0001, showing that the model term was significant. For the test index grading accuracy, the main order of influence of each test factor and the interaction between factors was x_1, x_3, x_3^2; x_1^2, x_2x_3, x_2^2, x_2, x_1x_3, x_1x_2; where x_1, x_3, x_3^2; x_1^2 had a highly significant influence(P<0.01); x_2x_3, x_2^2 had a significant influence (0.01<P<0.05); x_2 had a slightly significant influence(0.05<P<0.1); x_1x_3, x_1x_2 had no significant influence(P>0.1). After removing the insignificant factors x_1x_3 and x_1x_2, the regression equation of each test factor and the interaction between factors on the grading accuracy Y_1 was obtained as follows:

$$Y_1 = 17.97960 + 5.53791x_1 + 10.40392x_2 + 14.02373x_3 + 10.46875x_2x_3 - 0.130711x_1^2 - 13.94211x_2^2 - 7.57349x_3^2 \quad (13)$$

Table 6

ANOVA of grading accuracy

Source	Sum of squares	Degree of freedom	Mean square	F	P
Model	170.84/168.38	9/7	18.98/24.05	19.52/23.88	<0.0001***/<0.0001***
x_1	85.14/85.14	1/1	85.14/85.14	87.54/84.54	<0.0001***/<0.0001***
x_2	4.36/4.36	1/1	4.36/4.36	4.48/4.33	0.0542*/0.0551*
x_3	23.60/23.60	1/1	23.60/23.60	24.27/23.44	0.0003***/0.0002***
x_1x_2	0.3612	1	0.3612	0.3714	0.5527
x_1x_3	2.10	1	2.10	2.16	0.1654
x_2x_3	5.61/5.61	1/1	5.61/5.61	5.77/5.57	0.0320**/0.0322**
x_1^2	21.99/21.99	1/1	21.99/21.83	22.61/21.83	0.0004***/0.0003***
x_2^2	4.94/4.94	1/1	4.94/4.94	5.08/4.91	0.0421**/0.0426**
x_3^2	23.33/23.33	1/1	23.33/23.33	23.99/23.17	0.0003***/0.0002***
residual	12.64/15.11	13/15	0.9726/1.01		
Lack of fit	6.09/8.55	5/7	1.22/1.22	1.49/1.49	0.2941/0.2929
Error	6.56/6.56	8/8	0.8194/0.8194		
Total	183.49/183.49	22/22	18.98/24.05	19.52/23.88	<0.0001***/<0.0001***

Note: / Posterior values represent ANOVA results for Y_2 after excluding non-significant test indicators;
**** extremely significant (P<0.01), ** significant (0.01<P<0.05), * slightly significant (0.05<P<0.1).*

(2) potato damage rate Y_2

By analyzing and fitting the test results, Table 7 provides the ANOVA of the potato damage rate. According to the ANOVA results, the model F=21.57, indicating that the model was significant; P<0.0001, showing that the model term was significant. For the test index potato damage rate, the main order of influence of each test factor and the interaction between factors was x_2, x_3, x_3^2; x_1^2, x_1, x_1x_3, x_2^2, x_2x_3, x_1x_2; where x_2, x_3, x_3^2; x_1^2 had a highly significant influence(P<0.01); x_1, x_1x_3 had a significant influence (0.01<P<0.05); x_2^2 had a slightly significant influence; x_2x_3, x_1x_2 had no significant influence. After removing the insignificant factors x_2x_3 and x_1x_2, the regression equation of each test factor and the interaction between factors on the potato damage rate Y_2 was obtained as follows:

$$Y_2 = 19.73157\text{-}1.55255x_1 - 4.68117x_2 - 2.42073x_3 + 0.104167x_1x_3 + 0.033198x_1^2 + 3.49218x_2^2 + 0.873045x_3^2 \quad (14)$$

Table 7

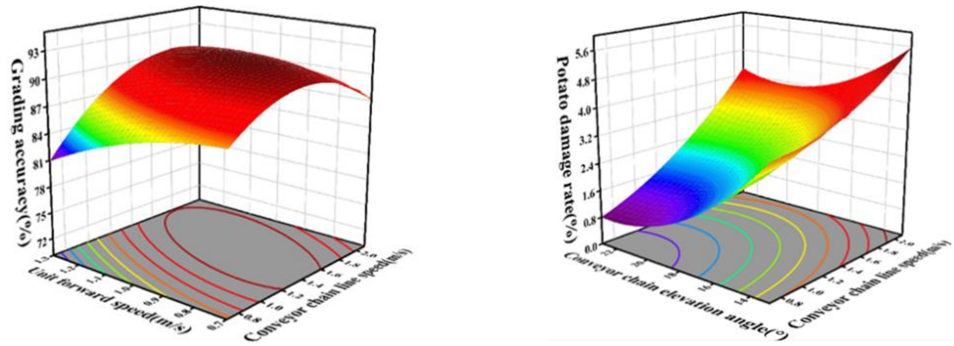
ANOVA of potato damage

Source	Sum of squares	Degree of freedom	Mean square	F	P
Model	18.51/18.42	9/7	2.06/2.63	99.97/110.43	< 0.0001***/< 0.0001***
x_1	5.50/5.50	1/1	5.50/5.50	267.45/230.89	< 0.0001***/< 0.0001***
x_2	2.90/2.90	1/1	2.90/2.90	140.87/121.61	< 0.0001***/< 0.0001***
x_3	7.88/7.88	1/1	7.88/7.88	382.97/330.62	< 0.0001***/< 0.0001***
x_1x_2	0.0450	1	0.0450	2.19	0.1630
x_1x_3	0.1250/0.1250	1/1	0.1250/0.1250	6.08/5.25	0.0284**/0.0369**
x_2x_3	0.0450	1	0.0450	2.19	0.1630
x_1^2	1.42/1.42	1/1	1.42/1.42	68.96/59.53	< 0.0001***/< 0.0001***
x_2^2	0.3100/0.3100	1/1	0.3100/0.3100	15.07/13.01	0.001964***/0.0026***
x_3^2	0.3100/0.3100	1/1	0.3100/0.3100	15.07/13.01	0.0019***/0.0026***
residual	0.2674/0.3574	13/15	0.0206/0.0238		
Lack of fit	0.1074/0.1974	5/7	0.0215/0.0282	1.64/1.41	0.4408/0.3187
Error	0.1600/0.1600	8/8	0.0200/0.0200		
Total	18.78/18.78	22/22			

Note: / Posterior values represent ANOVA results for Y_1 after excluding non-significant test indicators;
**** extremely significant (P<0.01), ** significant (0.01<P<0.05), * slightly significant (0.05<P<0.1).*

Response surface analysis

Design-Expert 13.0 software was used to analyze the experimental results. The response surface with significant interaction of the conveyor chain elevation angle x_1, unit forward speed x_2, and conveyor chain line speed x_3 on the test index grading accuracy Y_1 and potato damage rate Y_2 was obtained, as shown in Figure 8.



(a) x_1=18° (b) x_2=1m/s

Fig. 8 - Response surfaces of grading accuracy and the potato damage rate

When the conveyor chain elevation angle x_1=18°, the response surface between the unit forward speed and the conveyor chain line speed is shown in Figure 8(a). When the conveyor chain line speed was certain, the grading accuracy Y_1 increased gradually as the forward speed of the unit decreased. The reason was that as the unit forward speed increased, the number of potatoes entering the conveying and grading device per unit of time exceeded the maximum grading capacity of the conveying and grading unit, so the grading accuracy decreased. When the forward speed of the unit was fixed, the grading accuracy Y_1 tended to increase and decrease as the conveyor chain speed increased. The reason was that the conveyor chain line speed affected the residence time of potatoes on the conveying and grading device. When the conveyor chain line speed was too low, the potatoes stayed too long, which would cause the potatoes to be blocked. When the conveyor chain line speed was large, the potato residence time was too short, and some potatoes were transported to the large potato collection box without grading.

When the forward speed of the unit x_1=1m/s, the response surface between the conveyor chain line speed and the conveyor chain elevation angle is shown in Figure 8(b). When the conveyor chain elevation angle was certain, the potato damage rate Y_2 showed a gradual increase as the speed of the conveyor chain increased. The reason was that when the conveyor chain line speed was larger, the potato from lifting stage, I was thrown to lifting stage II. The greater the fall speed, the more likely to cause damage to potatoes. When the conveyor chain line speed was certain, the potato damage rate gradually increased as the conveyor chain elevation angle decreased. The reason was that when the conveyor chain elevation angle was small, potatoes were prone to accumulation, increasing the friction between the potatoes and the conveyor chain, while the potatoes stayed on the conveyor chain for a longer time, thus increasing the potato damage. Among them, the effect of conveyor chain line speed on potato damage rate was greater than that of conveyor chain elevation angle.

Parameter optimization

To obtain the best combination of test factors with higher grading accuracy and lower injury rate of potatoes, Design-Expert 13.0 was used for parameter optimization, and the optimization constraints were selected as follows:

$$\left\{\begin{array}{l} \max Y_1\left(x_1, x_2, x_3\right) \\ \min Y_2\left(x_1, x_2, x_3\right) \\ s.t.\left\{\begin{array}{l} 13° < x_1 < 23° \\ 0.7 m/s < x_2 < 1.3 m/s \\ 0.7 m/s < x_3 < 2.1 m/s \end{array}\right. \end{array}\right. \tag{14}$$

The optimization result was that the best grading effect was achieved when the conveyor chain elevation angle, unit forward speed, and conveyor chain line speed were 21.0°, 0.8 m/s, 1.3 m/s, the grading accuracy was 91.9%, and the damage rate was 1.4%.

Experimental validation

During the test, each test index of the potato conveying and grading device was adjusted to the optimal parameters. The potatoes' grading accuracy and the potato damage rate were measured several times under the same test conditions as above to obtain the results shown in Table 8.

Table 8

Grading accuracy and damage rate of potatoes at optimal parameters

No.	test factors			Y_1 (%)	Y_2 (%)
	x_1 (°)	x_2 (m/s)	x_3 (m/s)		
1	21.0	0.8	1.3	90.35	1.1
2	21.0	0.8	1.3	90.88	1.34
3	21.0	0.8	1.3	91.28	0.89
4	21.0	0.8	1.3	91.22	0.68
5	21.0	0.8	1.3	92.4	0.83
6	21.0	0.8	1.3	92.1	0.45
average value	21.0	0.8	1.3	91.4	0.88

As can be seen from Table 8, the conveyor chain elevation angle, unit forward speed, and conveyor chain line speed were 21.0°, 0.8 m/s, and 1.3 m/s, respectively. Through six tests, the average grading accuracy and potato damage rate were 91.4% and 0.88%, respectively, which met the agronomic requirements of potato harvesting machinery (grading accuracy ≥ 85%, damage rate ≤ 3%).

CONCLUSIONS

(1) A variable space potato conveying and grading device was designed in this study by measuring the potato size distribution in the field and referring to the structure and relevant parameters of the conveying and grading device. The clearance and structure parameters of the rotating plate were determined, and the conveyor chain elevation angle was determined by dynamics analyzing the potatoes on the conveying and grading unit. The inclined plane test determined the inclination angle of the potato guide plate. The main factors affecting the mechanical damage of potatoes were determined by analyzing the damage of potatoes from the end of lifting stage I to lifting stage II.

(2) Through the field test of the prototype, the regression model of test indexes and test factors was established, and the parameters were optimized. The test results showed that when the conveyor chain elevation angle, unit forward speed, and conveyor chain line speed were 21.0°, 0.8 m/s, and 1.3 m/s, respectively, the grading accuracy was 91.4% and the rate of potato damage was 0.88%. Hence, the grading effect was the best. The operational performance of the prototype was stable, and all the test evaluation indicators could meet the agronomic requirements of the potato harvester. It can effectively solve the problem of damage to potatoes caused by multiple mechanical operations in the harvesting process, shorten the time for handling potatoes after harvesting operations and improve operational efficiency.

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