OPTIMISATION BY COUPLED RECURDYN-EDEM SIMULATION: OPTIMISATION TESTS OF A THREE-STAGE LOW-LOSS SEPARATION DEVICE FOR POTATO SOIL /

RecurDyn-EDEM 耦合仿真优化：三段式薯土低损分离装置优化试验

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ABSTRACT

Aiming at the potato soil separation device of potato harvester, which generally has the problem of potato high damage in potato-soil separation, a three-stage potato soil low-loss separation device was developed, and orthogonal experiments were designed with the help of RecurDyn-EDEM coupled simulation method. A field bench was built for verification tests. The test proved that: when the lift transport chain speed was 1.40 m/s, travel speed was 0.60 m/s, amplitude was 32.0 mm, the impurity rate was 1.49% and the average force on potato was 1.801 N. The potato damage rate was 2.7%, indicating that the design of the three-stage potato soil low-loss separator device worked well.

摘要

针对马铃薯收获机薯土分离装置普遍存在的薯土分离损伤高等问题，研制出一种三段式薯土低损分离装置，借助 RecurDyn-EDEM 耦合仿真方法设计正交实验。并搭建田间台架进行验证试验，试验证明：当升运链速度为 1.40m/s、行进速度为 0.60m/s、振幅 32.0mm 时，含杂率 1.49%，马铃薯平均受力为 1.801N，伤薯率 2.7%，表明设计的三段式薯土低损分离装置工作性能良好。

INTRODUCTION

Native to South America and introduced to China in the 17th century, the potato, as the world's fourth-largest food, has played an important role in reducing poverty and achieving sustainable development of human society (*Ren et al., 2022*). As a key link in the mechanization of potatoes, potato harvester is of great significance in improving labour efficiency and increasing production and income in the potato industry. The structure of similar foreign machinery and equipment is complicated, which affects the effect of potato soil separation and potato harvesting damage and is not adapted to China's potato planting mode (*Li et al., 2020; Baritelle et al. 2000; Du et al., 2019*).

Given the problems of potato mechanised harvesting, experts and scholars mainly analyse the range of length of the lifting chain of potato harvester potato soil separation device, the structural parameters of the Jitter and the working condition of the agricultural equipment, and optimise them in combination with the field trials (*Hu, 2018; Zhou et al., 2019*). Roger C. Brook used the MSU-USDA Instrumentation Sphere (IS) to analyse the structure of seven different structures of potato harvesters with a total of 28 different potato harvesting machines, to optimise their performance, to measure the effects of chain speed, equipment travel speed, chain type and drop height on harvesting results for each harvester, providing a range of data for harvester testing and development (*Roger C.B., 2008*). In addition, Alexey Dorokhov et al research has shown that damage due to the operation of potato-soil separating devices during mechanized harvesting of potato tubers accounts for 95% of mechanized damage to potatoes (*Dorokhov et al., 2022*). In another paper, the researcher pointed out that vibratory soil breaking is more efficient due to the fact that the effect of the external force is constant in a specific (limited) area of the soil mass (*Dorokhov et al., 2022*). Yakov Lobachevsky et al. used Raman LIDAR to analyse the cut surface of impacted potato tubers in a study of potato damage to assess potato tuber damage (*Lobachevsky et al., 2022*). Matmurodov et al. proposed a potato harvester solution that can separate impurities from potato tuber components multiple times, and the transmission mechanism of a newly developed crochet potato harvester was a mathematical simulation (*Matmurodov et al., 2020*).

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Murodov et al. proposed a scheme of potato harvester with screw lift separator and verified the main parameters of centrifugal separation screw lift separator *(Murodov et al., 2022)*. Wei Zhongcai et al. designed a potato harvester based on the vibration separation section and wave separation section and analysed the separation sieve and potato movement characteristics of the equipment, and it was difficult to reflect the real chain movement state because the simulation model did not see the coupled simulation (*Wei et al., 2018*). In addition, the team designed a crawler self-propelled sorting potato harvester for the hilly mountainous operating environment, which has a large adhesion force, high-frequency and low-amplitude vibration soil crushing, it has technical advantages such as high adhesion force, high-frequency and low-amplitude vibration soil crushing, automatic row-to-row digging, manually-assisted sorting and hydraulic drive mode (*Wei et al., 2023*). Zhao Xiang et al. used the gliding motion vibration equation to model the mechanics of the oscillating separating screen of the potato digger and carried out the theoretical analysis of the motion, but there was no analysis of the lifting chain and jitter wheel of the transport sub-mechanism (*Zhao et al., 2021*). Li Yanbin et al. designed a potato harvester multi-stage conveying and separating device, analysed the multi-stage conveying and separating device and the motion characteristics of the potato-soil mixture and verified that the conveying and separating sieve produces a "high-frequency and low-amplitude" cyclic motion, but did not analyse the shaking wheel and chain (*Li et al., 2021)*. Zhang Zhaoguo et al. designed a multistage separation buffer potato harvester for potato mechanisation in Yunnan mountainous clay conditions, analysed the collision characteristics of the soil in the conveying and separation process, and determined the factors affecting the effect of separation and crushing, but did not analyse the vibration of the lifting chain (*Zhang et al., 2021*). Wang Xingdong et al. simulated the collision effect between potato and lifting chain based on the results of ADAMS dynamics rigid-flexible collision calculations, and proposed a method to assess the impact of collision on tubers to predict the effect of tuber desliming and damage rate, but did not study the interaction between the soil and potato of the lifting chain in-depth *(Wang et al., 2018)*. Currently, EDEM software is increasingly being used in the agricultural field. Jun-Hee Byum et al. designed and fabricated an experimental setup to simulate the analytical factorization of a chili pepper harvester and conducted analytical factorization experiments to determine the card-cleaner type of the chili pepper harvester that can be mounted in the chili pepper harvester with the help of EDEM software (*Jun-Hee, 2018*). *Je Lim et al. (2016)* used EDEM software to simulate the conveyance performance of the separating system of a peanut harvester.

In summary, there are more studies on potato soil separation devices in China, but the depth of the analysis of the role of potato soil separation structure on the material is not deep enough, and there is no vibration analysis of the lifting chain as well as coupling simulation analysis.

To solve the above problems, this paper designs a three-stage potato soil separation device based on kinetic analysis and sieving principle analysis, and with the help of the method of response surface experimental design and RecurDyn-EDEM coupled simulation as a means of structural optimization and parameter design, finally builds a field bench test to verify the working effect of the three-stage potato soil separation device.

MATERIALS AND METHODS

System architecture

The three-stage low-loss potato soil separation device designed in this paper has main parts including guide wheel, Jitter wheel, positioning wheels, side plate, lifting chain with bar, driving wheel and so on. As the main core component of the potato harvester, the three-stage low-loss potato soil separation device can vibrate, crush, sieve and transport the potato soil mixture on the lifting chain, and its structure and motion parameters are directly related to the effect of potato soil separation and operation quality. The working width of the three-section potato soil low-loss separation device is 900 mm, the structure is shown in Figure 1,2, divided into three working sections: material feeding section, vibration crushing section and screening section, the material feeding section is 400 mm long, the vibration crushing section is 500 mm long, and the screening section is 300 mm long, to satisfy the requirements of material transport, the inclination angle of the lifting chain should be less than the friction angle of the material, and the design manual of agricultural machinery has shown that the potato soil separation effect and operation quality are directly related to its structure and motion parameters. According to the design manual of agricultural machinery, the rolling friction angle of potato on 65Mn is 9 º ~ 37 º, the rolling friction angle of sand and sandy loam (cohesion) on 65Mn is 26 º 30 ´ ~ 35 º, the rolling friction angle of sand and sandy loam (loose) on 65Mn is 14 º ~ 26 º 30 ´. Therefore, it can be concluded that the inclination angle of the three working section of the lifting chain $\alpha_1 \le 26$ º, $\alpha_2 \le 14$ º, $\alpha_3 \le 9$ º, to facilitate the processing and installation of parts, take $\alpha_1 = 22$ º, $\alpha_2 = 12$ º, $\alpha_3 = 8$ º.

The three working sections of the three-stage potato soil low-loss separation device: material feeding section, vibration crushing section and screening section. In the work, the potato mixture first arrives at the material feeding section, at the same time the portion of the potato mixture with dimensions smaller than the spacing of the conveyor bars falls through the gap in the conveyor bars of the lifting chain, most of the remaining material continues to be transported along the lifting chain; in the vibration of the broken soil section, the Jitter wheel rotationally impacts conveyor bars, while driving the potato mixture to do a certain frequency and amplitude of reciprocating vibration, crushing the larger pieces of soil, so that the soil attached to the potato off. The soil falls to the ground along the gap between the bars, and the remaining material is transported to the screening and de-soiling section for further screening, which ultimately achieves the functions of material transport, vibration soil crushing and material screening.

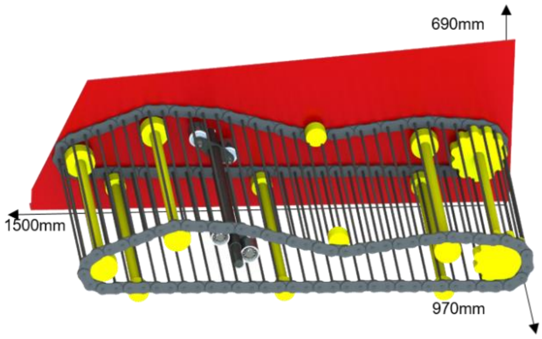


Fig. 1 - Side sectional view of the three-stage potato soil separation device

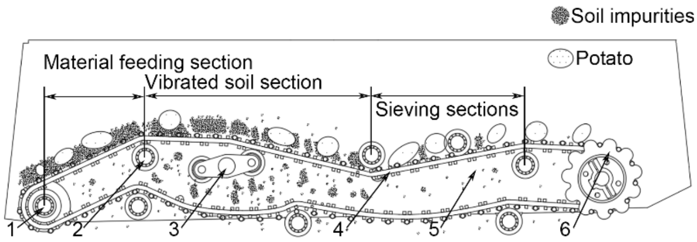


Fig. 2 - Working principle of three-stage potato soil separator

1 Guide wheel; 2 Positioning wheels; 3 Jitter wheel; 4 Lifting chain with bar; 5 Side plate; 6 Drive wheel

Orthogonal test of coupled simulation of potato soil separation device

To explore the optimal operating parameters, as well as the relationship with the potato force and potato soil separation ability, it is necessary to carry out the response surface test on the lifting chain with the help of a simulation test. Through the parameter design and analysis of the device, the lifting chain linear speed, the harvester travel speed (hereinafter referred to as travel speed) and the Jitter wheel from the lifting chain straight line distance (hereinafter referred to as the Jitter wheel distance) range were initially determined. The RecurDyn-EDEM coupled simulation model of the potato harvester soil separation device is established and then the simulation test of potato soil separation is carried out to deeply analyse the influence of the above three parameters on the effect of potato soil separation and tuber damage, in order to come up with the optimal parameter combination.

The discrete element model calibration object used in the experiment was taken from the experimental field of Qingdao Hongzhu Agricultural Machinery Co., Ltd. in Qingdao City, Shandong Province (120.06811°N, 36.43653°E), and the soil in the planting area was yellow loam, with loose surface soil and small lumps, and the subsoil had a certain degree of adhesion, and there were large lumps after excavation. To simulate the soil during the potato harvesting period, two kinds of particles, surface (loose) - and subsoil (cemented), were established to construct the potato harvesting granular bed. As shown in Figure 3.

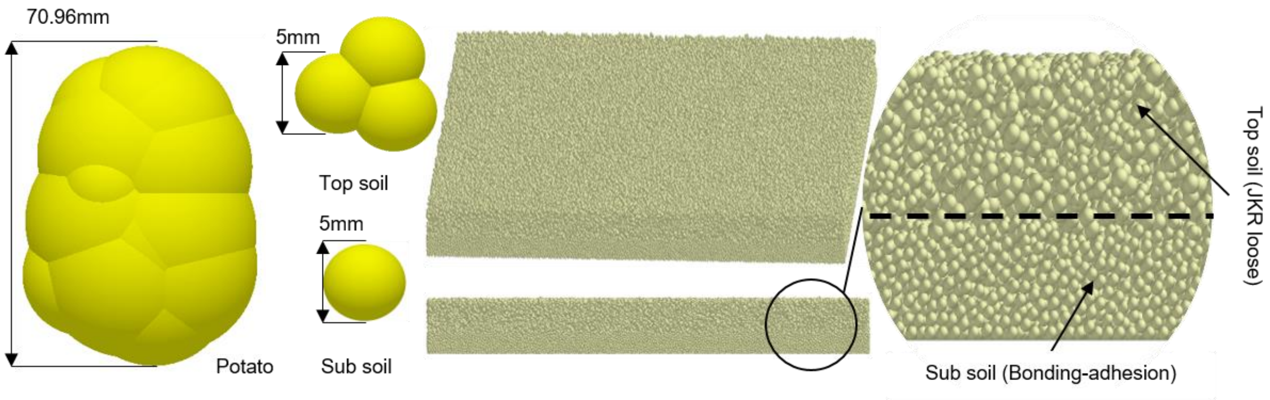


Fig. 3 - Discrete element simulation particle modelling

The surface particles were tri-spherical, bonded by the Hertz Mindlin with the JKR model, with diameters ranging from 2.5-5.0 mm. The bottom particles were based on the Hertz Mindlin with bonding model, using single-spherical particles with a diameter of 2.5 mm, and were bonded by the Hertz Mindlin with JKR model between the two types of soil particles, and between the soil particles and the potato, with JKR parameters set at 12 J/m3 between the soil and 7.5 J/m^3 between the soil and the potato. According to the JKR model, the JKR parameter was set at 12 J/m^3 between the soils and 7.5 J/m^3 between the soils and the potatoes.

The overall size of the particle bed was 1000mm*200mm*900mm, the bottom particles were generated by static particle factory in EDEM with a thickness of 100 mm, and the surface particles were generated dynamically with a thickness of about 65 mm, and the intrinsic parameters and contact parameters of each discrete elemental cell are shown in Tables 1 to 3.

Table 1

Particle intrinsic parameters

Material	Densities/kg·m^{-3}	Poisson's ratio	Shear modulus/Pa
Sub-soil	2400	0.25	1e+07
Top-soil	2400	0.25	1e+07
Potato	1058	0.48	1.58e+08
Steel	7800	0.3	7.984e+10

Table 2

Bonding parameters of particles

Parametric	Sub-soil-sub-soil
Unit normal stiffness / N·m^{-3}	1.8e+06
Unit tangential stiffness / N·m^{-3}	1.4e+06
Normal strength / Pa	189000
Shear strength / Pa	106000
Bonding radius / mm	3

Table 3

Discrete element material contact parameters

Parametric	Crash recovery factor	Static friction factor	Kinetic friction factor
Sub-soil-sub-soil	0.15	0.8	0.05
Sub-soil-top-soil	0.61	0.5	0.2
Sub-soil-potato	0.25	0.21	0.013
Sub-soil-steel	0.7	0.6	0.015
Top-soil-top-soil	0.6	0.5	0.4
Top-soil-potato	0.206	0.2	0.13
Top-soil-steel	0.6	0.5	0.05
Potato-potato	0.313	0.36	0.1
Potato-steel	0.36	0.41	0.06

Simulation model construction based on RecurDyn-EDEM

Constructing the three-dimensional model of the key components of the potato soil separation device of the potato harvester is an important part of the simulation, the design and modelling of the lifting chain rod of the potato soil separation device is carried out in SolidWorks, and imported into RecurDyn in STEP format to add the moving and fixed vice and the contact between the parts. The External SPI is further exported to the EDEM through the RecurDyn software coupling interface, and the modeling rendering diagrams are shown in Figures 4 and 5.

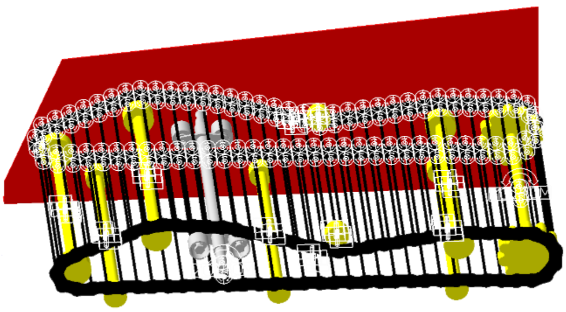


Fig. 4 - Multibody dynamics model motion pair added

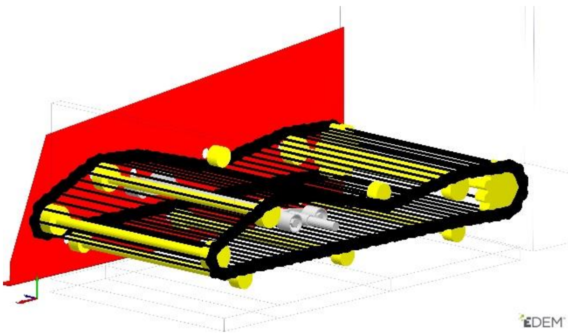


Fig. 5 - EDEM model

Considering the large particle velocity, to guarantee the reliability of the results, 1% of Rayleigh time is used as the minimum simulation step. A single simulation requires 746,250 soil particles, including 59 potatoes, and the simulation time is 5-7 s. It is estimated that the simulation takes 136-172 hours.

SIMULATION OF ORTHOGONAL TESTS

Design of test programme

The test program is shown in Table 4, taking the lifting chain linear speed, travel speed and jitter wheel position as the test factors, and the impurity content rate and average potato force as the evaluation indexes. According to "NY/T648-2015 Technical specification for quality evaluation of potato harvester", the impurity rate Y_1 is calculated as follows:

$$Y_1 = \frac{Q_2}{Q_2 + Q_1} \times 100\% \tag{1}$$

where Q_2 is the mass of impurities (soil in this paper), Q_1 is the mass of harvested potatoes, the experimental test factors coded as shown in Table 5. The test programme and results are shown in Table 5.

Table 4

Test factor coding

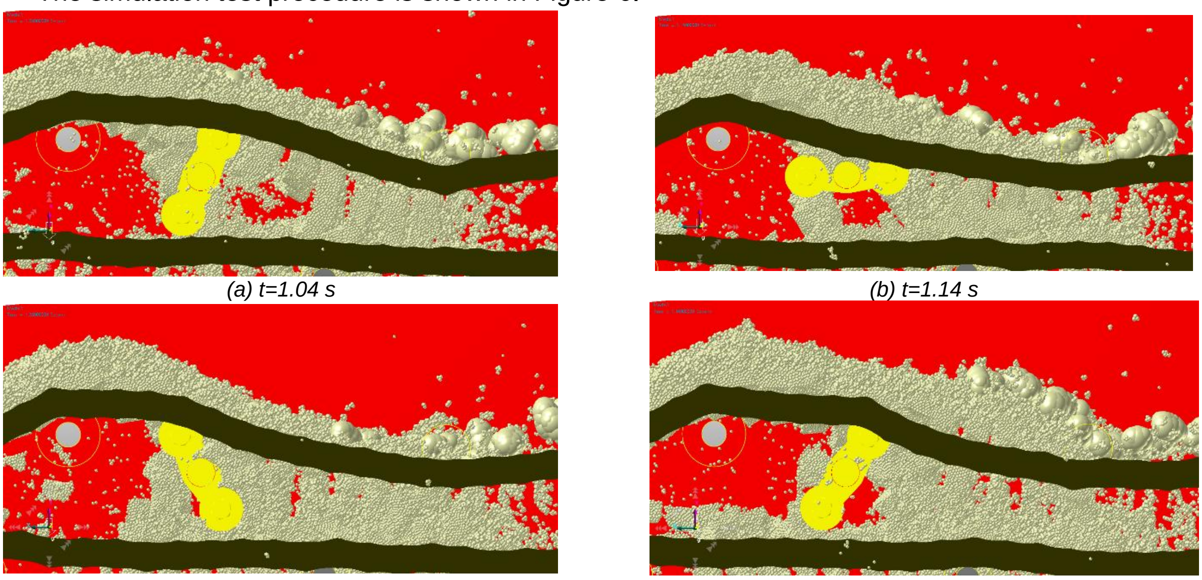
Encodings	Experimental factors		
	A: Lifting chain linear speed / m·s^{-1}	B: travel speed / m·s^{-1}	C: Jitter wheel position / mm
-1	0.8	0.6	30
0	1.1	0.9	65
1	1.4	1.2	100

Table 5

Test scheme and results

Serial number	Experimental factors			Y_1 / %	Y_2 / N
	A	B	C		
1	0	0	0	1.30	2.15
2	1	0	-1	1.10	2.59
3	0	1	-1	1.50	2.59
4	0	0	0	1.20	2.17
5	0	0	0	1.30	2.31
6	0	0	0	1.20	2.41
7	-1	0	1	0.96	2.93
8	1	0	1	1.60	0.90
9	0	-1	1	1.59	1.72
10	0	0	0	1.30	2.18
11	1	1	0	1.73	1.26
12	1	1	0	1.12	2.13
13	-1	1	0	0.85	3.34
14	0	1	1	1.51	1.23
15	-1	1	0	0.96	2.99
16	-1	0	1	0.79	3.68
17	0	-1	1	0.91	3.19

The simulation test procedure is shown in Figure 6.



(a) t=1.04 s (b) t=1.14 s

(c) t=1.24 s (d) t=1.34 s

Fig. 6 - Coupled simulation process

RESULTS

Analysis of test results

Using Design-Expert software to analyse the test results, to get the regression equations of the impurity rate and average force, the results of ANOVA are shown in Table 6. For the regression model of impurity rate A, B, C, AB and A^2 for the impact of impurity rate is extremely significant (P<0.01), and the effects of AC and BC on this index were significant (P<0.05). The order of influence of the main terms of impurity rate is A, B, C. For the regression model of the average force on potatoes, A, B, C, AC and A^2 for the impact of impurity rate is extremely significant (P<0.01), AC and BC for this indicator is significant (P<0.05). The order of influence of the main terms of the average force on potatoes is A, C and B. The regression model was fitted using the software.

Using the software to carry out multiple regression fitting analysis, excluding the insignificant items, to establish the regression equation between the impurity rate, the average force and the significant factors:

$$\begin{aligned} Y_1 &= 2.54914A - 1.31972B + 0.003827C \\ &+ 1.38889AB + 0.007934AC - 0.008938BC \\ &- 1.58583A^2 - 0.534829 \end{aligned} \tag{2}$$

$$\begin{aligned} Y_2 &= -6.22968A + 2.02115B + 0.001663C \\ &- 1.44444AB - 0.002619AC \\ &+ 2.93611A^2 + 7.14033 \end{aligned} \tag{3}$$

The regression equations for impurity rate and average force are highly reliable, and the optimal parameter combinations for each factor can be solved based on the above two regression models.

Table 6

Impurities and Average Force Variance Analysis

Variance (statistics) Source	Impurity rate / % F	Impurity rate / % P	Average force / N F	Average force / N P
models	36.84	< 0.0001	96.17	< 0.0001
A	142.90	< 0.0001	425.63	< 0.0001
B	84.08	< 0.0001	61.85	< 0.0001
C	40.75	0.0004	321.89	< 0.0001
AB	18.18	0.0037	6.27	0.0408
AC	8.07	0.0250	20.48	0.0027
BC	10.25	0.0150	0.2805	0.6128
A^2	24.95	0.0016	27.26	0.0012
B^2	3.10	0.1216	2.39	0.1660
C^2	0.0579	0.8168	0.1095	0.7504
lost proposal	1.34	0.3795	0.6671	0.6149

Analysis of the effect of interaction on the test indexes

Through the software, as shown in Figures 7 and 8, the response surface of the interaction of the three factors on the influence of impurity rate Y_1 and average force Y_2 were obtained.

(1) Analysis of the effect of interaction on impurity rate

As can be seen from Fig. 7, there is a positive correlation between the impurity rate Y_1 and the lifting chain linear speed A, travelling speed B, and Jitter wheel position C. The interaction of the three factors on the impurity rate Y_1 is shown in Fig. 7. For the interaction of AB factors, when the travelling speed B is at a low level, the change of the impurity rate Y_1 with the lifting chain linear speed A is slower, mainly because when the travelling speed is slower, the feeding amount is lower, and the lifting chain can deal with the current soil, and vice versa, the impurity rate Y_1 will be increased accordingly; for the interaction of AC factors, when the jittering wheel position C is at a high level, the effect of the lifting chain linear speed A on the impurity rate Y_1 is more significant than that at the low level, and this is because the simulation shows a positive correlation between the speed of the lifting chain line and the impurity rate Y_1. This is because the soil particles of the simulation have a large degree of adhesion, and the amplitude of the shaking wheel of the lifting chain is related to the crushing of the soil, which helps the lifting chain to sieve the soil. The impurity rate is minimized when the shaking wheel is positioned and moves at a low level.

(2) Analysis of the effect of interaction on the average force on potato

The potato average force response surface is shown in Figure 8, and the lifting chain linear speed A, travelling speed B and Jitter wheel position C are negatively correlated with the average force Y_2. For the AB interaction, travelling speed at a high level of the lifting chain linear speed changes on the average force effect is smaller, due to the faster travelling speed, so that the feeding volume is larger, while the lifting chain linear speed is faster, the potato in the lifting chain residence time is less, the number of collisions is less, and the soil protection effect is better, the Jitter effect makes the potato force be reduced, so the two factors are at a high level, the average force is the lowest. AC interaction effect is more significant than that of AB, but the lowest average force is still at a high level. This is due to the fact that the shaking wheel is farther away from the position of the lifting chain, the amplitude of the forced vibration of the lifting chain is smaller, so that the force is smaller, and at the same time the linear speed increases, the potato stay in the lifting chain time decreases, further reducing the number of collisions, the two together reducing the average force on the potatoes.

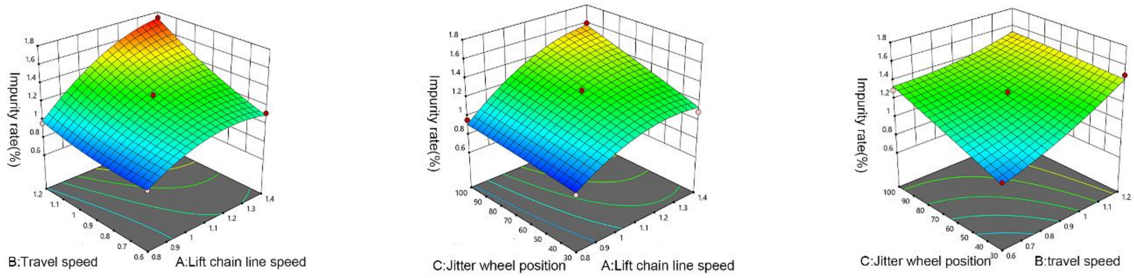


Fig. 7 - Response surface of factor interactions on impurity rate

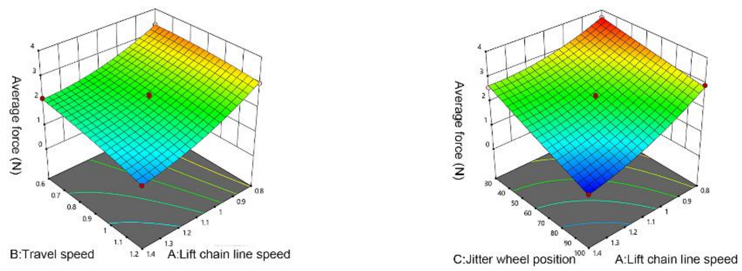


Fig. 8 - Response surface of factor interactions to the average force applied

Combination solution of the optimal value of experimental factors

According to the above test results and regression equation, the minimum impurity rate and average force are taken as the optimization objectives, and the linear speed, travel speed and jitter wheel position of the lifting chain are taken as the optimization objects, the regression model is optimized, and its objective function and constraint conditions are:

$$\begin{cases} \min Y_1(A, B, C) \\ \min Y_2(A, B, C) \\ X_1, X_2, X_3 \subseteq (-1, 1) \end{cases} \tag{4}$$

Finally, when the lifting chain linear speed is 1.40 m/s, the travel speed is 0.60 m/s, when the jitter wheel position is 70.701 mm (the theoretical amplitude is 32.299 mm), the impurity content is 1.151 %, and the average force is 1.942 N.

Bench validation experiments

Testing material

According to the design parameters of the device and the factors optimized by the simulation test, a three-stage potato-soil separation performance test bench was built. The test equipment was modified and processed by Qingdao Hongzhu Agricultural Machinery Co., Ltd. according to the test requirements. The test equipment is shown in Figures 9, 10, 11. The test equipment includes an electronic potato, frequency converter, horizontal conveyor belt, potato test bench and tachometer.

Bench test

The test site was the test field of Qingdao Hongzhu Agricultural Machinery Co., Ltd, Qingdao City, Shandong Province (120.06811°N, 36.43653°E), and the test bench was modified by an amplitude of 32 mm, with working parameters following a travelling speed of 0.6 m/s, and lifting chain linear speed of 1.4 m/s for the test. The acceleration sensor of the electronic potato was used to record the acceleration of the electronic potato when the equipment was working, and the force was calculated by multiplying the mass of the electronic potato. As the test results show in Table 7, after five repetitions, the average force of electronic potato is 1.801 N, impurity rate is 1.49%. The impurities rate in the test was higher than in the simulation tests due to the presence of weeds and other impurities such as rhizome stones. However, the protective effect of the soil resulted in less damage to the potato block in the test compared to the simulation. The results are consistent with the optimisation and prediction of the simulated response surface test. For the index of potato damage rate, the result of this test is 2.7%, which is better than the results of other studies *(Lv et al., 2020)*.

Fig. 9 - Electronic potato

Fig. 10 - Rotating speed meter

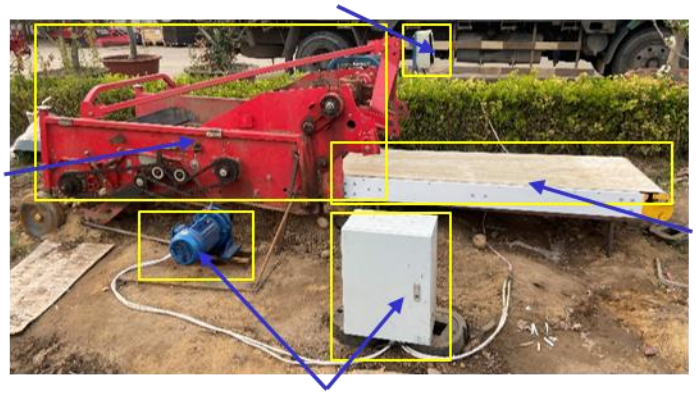


Fig. 11 - Three-stage potato soil separation performance test bench

Table 7

Bench test results

Num	1	2	3	4	5	Average
Average Force(N)	1.790	1.770	1.793	1.840	1.812	1.801

CONCLUSIONS

(1) In this paper, a three-stage potato-soil separation device is designed by analysing the working principle of the device and the forced vibration analysis of the lifting chain. The device is divided into three working sections: material feeding section, vibrating soil crushing section and screening soil removal section, and the mechanism of each working section is analysed.

(2) The multi-body dynamics model of potato-soil mixed granular bed and potato-soil separation device was established. The response surface simulation test of a three-stage potato-soil separation device based on RecurDyn-EDEM coupling simulation was designed with impurity rate and average force as evaluation indexes, and the linear speed of the lifting chain, travel speed and position of shaking wheel as factors. The results were optimized by regression. The results showed that when the speed of the lifting chain was 1.40 m/s, the travel speed was 0.60 m/s, and the distance between the shaking wheel and lifting chain was 70.70 mm (theoretical amplitude was 32.30 mm), the impurity rate was 1.151 %. The average force was 1.942 N.

(3) In this paper, the three-stage potato-soil separation device is designed and optimized, and a three-stage potato-soil separation performance test bench is built to verify the simulation results. Five repetitions are made and the average force of electronic potato is 1.801 N, impurity rate of 1.49%, the potato damage rate is 2.7%. The test results are similar to the simulation test results, which verifies the reliability of the simulation test.

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