Parameter optimization and test of harvesting device for digging and pulling green onions based on discrete element analysis

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Abstract: In green onion harvesting, the problems of easy dumping and low rate of clean digging can be encountered. In this paper, a kind of harvesting device for digging and pulling green onions, referred to simply as "the device", was designed. The device mainly consists of a digging shovel, screen bars, clamping conveyor belt, etc. This paper focuses on the analysis of the model forces of green onions and soil in the two states of the onion digging process without dumping and clamping. The key factors affecting the model state of onions and soil were identified as: screen bar length l_2, screen bar inclination angle β, and pulling point position x. Based on the discrete element simulation technology of EDEM, the mechanism-crop-soil model was established, and a single-factor simulation test was conducted to determine the range of values for each factor. Taking the advantages of field test and three-factor five-level orthogonal experimental design, the parameter combinations of green onion harvesting operation evaluation indices were optimized, including a pulling point position of 166 mm, screen bar length of 242 mm, and screen bar inclination angle of 14°. As the results of the field test show, the harvester operation was stable without congestion or damage, the harvesting effect of green onions was improved, and the clean digging rate reached 100%, which meets the agronomic requirements for onion harvesting and the expectations of users.

Keywords: green onions, digging and pulling, clamping, EDEM, test design
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1 Introduction

Green onion is an important specialty vegetable in China, with its planting area and production in China ranking first among all countries in the world[1]. To counteract the high labor cost during the harvest season, it is urgent to realize mechanized harvesting of green onions. Segmented harvesting is currently popular in China, that is, simple soil digging and shaking, with the advantages of high efficiency and low cost, but with disadvantages such as high labor intensity of manual work[2]. The onion combine harvester has to be improved to adapt to different onion varieties and planting modes. Such improvements are still in the experimental stage, and a breakthrough in the digging and conveying coordination technology is urgently needed. For the combine harvester used for the digging and pulling of green onions, harvesting missing may easily occur due to digging congestion and poor clamping during the working process[3].

The scale of onion planting is gradually increasing due to the increase of benefits, which in turn boosts the demand for combined harvesting equipment day by day. Europe and the United States focus on the harvesting of leeks and flat-grown onions, with more planted on large farms. This is distinct from China's planting pattern[4], which is better adapted to the use of the side-traction leeks combine harvester, such as the T110-PO845 side-traction leeks harvester produced by the Danish ASA-LIFT company. Though Japan's and South Korea's onion planting soil conditions are better, their harvesting operation efficiency is low. Their harvest method mostly uses small self-propelled green onion harvesting machines, such as the HL10 produced by the Japanese company YANMAR. These machines are used mainly for the harvesting of green onions planted in small plots, and they are not well-adapted to China's onion joint harvesting requirements[5]. In conclusion, foreign advanced harvesting technology and equipment are not promotable or applicable in China. China's green onion combine harvester mainly adopts the harvesting method of digging and pulling to meet the operational requirements of multifunctional integration. However, there is a lack of technology and theory on digging and pulling harvesting, and less mature equipment[6,7]. In this paper, the mechanism of the digging and pulling operation of the green onion combine harvester is studied, and the force and motion state of onions during the digging and pulling operation are analyzed in order to determine the necessary conditions for the harvester to be efficient in this operation[8]. On this basis, the onion combine harvester device is designed. Analysis based on EDEM simulation of the digging operation is conducted to verify the effect of the digging shovel and the screen bar. In the field test on the device, the green onion clean digging rate is taken as the evaluation index to verify the digging and pulling operation effect of the device in the actual operating situation.

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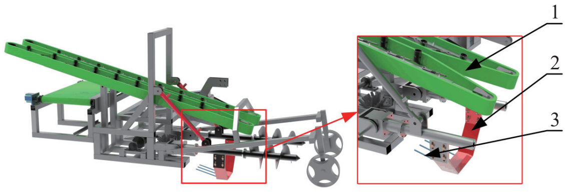
2 Harvesting processes and mechanical characterization of digging and pulling

2.1 Harvesting process of digging and pulling

Considering that the height of the onion ridge and the length of the onion scallion white are between 250-300 mm[9], a flat digging shovel, screen bars, and clamping conveyor belt with a V-shape opening are designed. The device is shown in Figure 1.



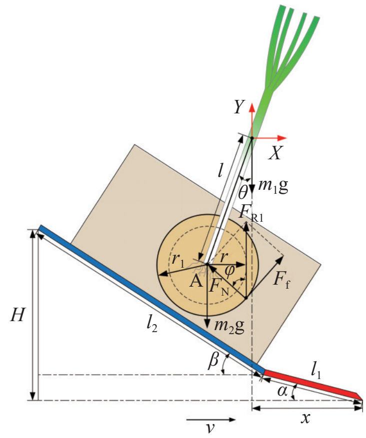
1. Clamping conveyor belt 2. Digging shovel 3. Screen bars

Figure 1 Structure of the digging and pulling device

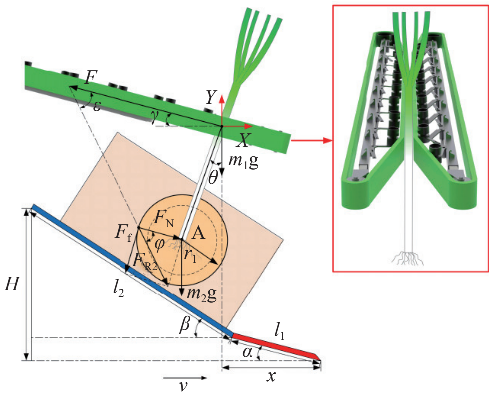
In operation, the digging shovel cuts the soil at the root of the onion, and lifts the soil excavation containing the green onion. The soil becomes fractured and misaligned as the lifting height increases, causing the onion to separate from the soil. When the mixture reaches a certain position of the screen bars, the onion is basically separated from the soil, showing a tendency to dump under the action of gravity and the like. At this time, the clamping belt comes into contact with the onion stems and leaves to pull out the loose onion in time, thereby completing the whole process of onion harvesting. In this process, the entry angle of the digging shovel determines the digging resistance and breakage of the soil, while the inclination angle of the screen bars affects the lifting height of the onion and the breaking effect of the soil. If the separation between onion and soil is poor, it is more difficult for the clamping belt to pull the onion, which is difficult to clamp and easily falls off. However, if the separation effect is good, the onion is easy to dump due to lifting, which is not conducive to the clamping and pulling by the clamping belt. Therefore, it is helpful to study the relationship between onion and soil loading and movement during the digging and pulling harvesting process. Only in this way can we determine the appropriate harvesting structure and parameter combinations and improve the quality and effect of onion harvesting.

2.2 Interaction between onion and soil

Green onion harvesting process is complicated by digging shovel, screen bars, clamping belt, and other factors. When the green onion is excavated, if the soil is too loose, the onion will be tipped over, resulting in the inability of the clamping conveyor belt to pull the onion. This is because the soil is too loose and the support force and friction are too small to support the positional state of the onion. which is an articulated rotating vise from the view of the root of the onion, and the use of this simplified model to study this problem, which can be well and correctly reflect the onion's motion state at this moment and the force characteristics. Considering the working principle of the device and the characteristics of the clamping belt lifting, it is assumed that the soil adhered to the onion root and the onion constitute a system together, and with the lifting of the mixture, the onion root soil is gradually loosened and dislodged until the onion is dumped or clamped and pulled out. The soil adhering to the roots of the onion is simplified as a soil ball, and the onion and surrounding soil together form an articulated model. To ensure the harvesting effect, the onion should be in the critical dumping state when it is pulled. The critical position of onion dumping and instantaneous state of onion pulling are selected for force analysis[10-16]. The coordinate system and forces are shown in Figure 2.



a. Instantaneous mechanical model of green onion dumping



b. Mechanical model of instantaneous state of green onion being pulled

Figure 2 Mechanical articulation model of green onion

The force on the articulated model of the onion is analyzed in conjunction with the working state of the device. If the green onion does not dump, assuming that the force balance condition and the torque balance requirements at Point *A* are balanced, the model of the onion system satisfies Equations (1) and (2):

$$m_1 g + m_2 g = F_{R1} \tag{1}$$

$$m_1 g \cdot l \cdot \sin\theta \le F_{R1} \cdot r \cdot \sin\varphi \tag{2}$$

where, m_1 refers to the mass of onion, kg; m_2 represents the mass of soil ball of onion root, kg; F_{R1} stands for the total reaction force of soil on the model during digging, N; l refers to the distance from the center of gravity of the onion to the center of gravity of the soil ball, m; θ stands for the angle of onion deflection, (°); r denotes the radius of friction circle, m; φ represents the friction angle, (°).

The mass of the soil ball at the root of the onion was calculated according to the formula for the mass of a sphere, and Equation (3) is obtained:

$$m_2 = \rho \cdot \frac{4}{3} \cdot \pi \cdot r_1^3 \tag{3}$$

where, ρ refers to the soil density, kg/m^3; r_1 is the radius of the soil ball at the onion root, m.

With the lifting of the mixture, the soil adhered to the onion root is less, and the radius correction factor of the soil ball is introduced. Setting the radius correction coefficient of the soil ball on the digging shovel as K_1 and the radius correction coefficient on the screen bars as K_2, the radius of the soil ball at the moment of clamping and pulling satisfies Equation (4):

$$r_1 = r_0 \cdot \frac{l_1 \cos\alpha}{v} \cdot K_1 \cdot \frac{x - l_1 \cos\alpha}{v} \cdot K_2 \tag{4}$$

where, r_0 refers to the initial radius of soil ball, m; l_1 stands for the digging shovel length, m; α denotes the inclination angle of the shovel surface, (°); v is the digging device forward speed, m/s; x represents the pulling point position (horizontal distance from the pulling point to the shovel tip), m; K_1 refers to the correction factor for the radius of the soil ball on the digging shovel; and K_2 denotes the correction factor for the radius of the soil ball on the screen bars.

From the relationship between onion lifting height and device structure, Equation (5) is obtained:

$$H = l_1 \cdot \sin\alpha + l_2 \cdot \sin\beta \tag{5}$$

where, H refers to the height of onion lifting, m; l_2 denotes the screen bar length, m; and β is the screen bar inclination angle, (°).

Associating Equations (1) to (5), Equation (6) is obtained as:

$$\begin{cases} F_{R1} = \left[m_1 + \dfrac{4}{3}\pi\rho \left(r_0 \cdot \dfrac{\sqrt{{l_1}^2 - (H - l_2 \cdot \sin\beta)^2}}{v} \cdot K_1 \cdot \right.\right. \\ \qquad \left.\left. \dfrac{x - \sqrt{{l_1}^2 - (H - l_2 \cdot \sin\beta)^2}}{v} \cdot K_2 \right)^3 \right] g \\ F_{R1} \geq \dfrac{m_1 g l \sin\theta}{r \sin\varphi} \end{cases} \tag{6}$$

At the instant of smooth onion pulling, the green onion system model shows an upward movement tendency, which should satisfy Equation (7):

$$F \cdot \sin\gamma \geq m_1 g + m_2 g + F_{R2} \cdot \cos\left(90^\circ - \varepsilon - \gamma\right) \tag{7}$$

where, F refers to the pulling force of clamping belt, N; γ stands for the clamping belt inclination angle, (°); F_{R2} denotes the total reaction force of soil on the model, N; and ε represents the angle between the pulling force and conveying direction, (°).

Equation (8) is obtained based on the force polygon and the sine theorem:

$$\frac{F_{R2}}{\sin\left(90^\circ + \gamma\right)} = \frac{m_1 g + m_2 g}{\sin\varepsilon} = \frac{F}{\sin\left(90^\circ - \varepsilon - \gamma\right)} \tag{8}$$

Associating Equations (3) (4) (5) (7) (8), Equation (9) is obtained as:

$$F \geq \frac{\left[m_1 + \dfrac{4}{3}\pi\rho \left(r_0 \dfrac{\sqrt{l_1^2 - (H - l_2 \sin\beta)^2}}{v} K_1 \dfrac{x - \sqrt{l_1^2 - (H - l_2 \sin\beta)^2}}{v} K_2 \right)^3 \right] g}{\sin\gamma - \dfrac{\cos\gamma}{\tan\left(90^\circ - \varepsilon - \gamma\right)}} \tag{9}$$

Based on a comprehensive analysis of the above, the green onion harvesting effect is affected by a variety of factors such as l_1, l_2, α, β, v, γ, x, φ, etc. According to experience, the digging depth of the flat shovel is less than 150 mm, the inclination angle of the shovel surface α is 10°, the operation speed is relatively stable at 0.3-0.5 m/s, and the parameters such as γ and φ tend to be stable. Because the digging shovel is mainly used to cut and loosen the soil and separate the onion from the soil, the onion is clamped at the screen bars' position. Therefore, to ensure that the onion is smoothly pulled by the clamping belt without dumping, we focus on analyzing the influence of the screen bar length l_2, screen bar inclination angle β, and pulling point position x on harvesting.

3 Discrete element simulation analysis

The mechanism-crop-soil model was established by using EDEM simulation software[17]. Using the number of bond breaks in EDEM simulation as an evaluation index of soil loosening and fragmentation, the parameter range of the key factors affecting harvesting was determined, which lays the foundation for the determination of the best parameter combination for the subsequent field experiments.

3.1 Construction of the model for discrete elements

3.1.1 Model of digging and pulling device

Using SolidWorks, the device was modeled, saved as a STEP format file, and imported into EDEM software. The material of the digging device was selected as 65Mn, with a Poisson's ratio of 0.35, a shear modulus of 7.27×10^{10} Pa, and a density of 7830 kg/m^3, which is in line with the requirements of the actual production and harvesting environment[18]. Figure 3 shows the 3D model of the device.

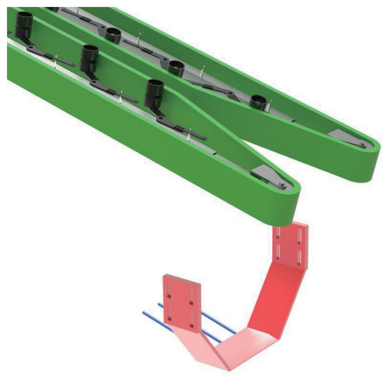


Figure 3 Digging and pulling device

3.1.2 Modeling of soils

In view of the fact that the soil particles under the actual growing conditions of onions are small, it is impractical to model the soil particles in equal proportions, taking into account the computer computational performance and other factors. According to the existing research basis and the soil environmental conditions under the actual growth conditions of onions, the radius of soil particles was increased appropriately without affecting the simulation accuracy and efficiency. The radius of soil unit was set to 6 mm, and four common, typical soil particles were obtained by appropriate combination. Four types of soil particles were established in EDEM, namely, Single Sphere, Straight Four, Square Four, and Tetrahedral Four[19,20], with a physical radius of 6 mm, as shown in Figure 4.

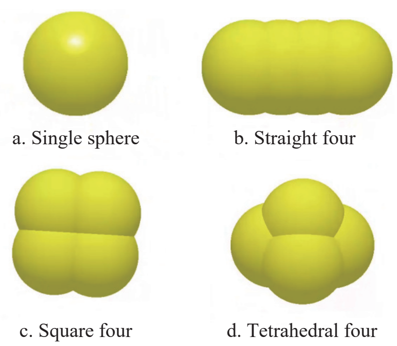


Figure 4 Modeling of soil particles

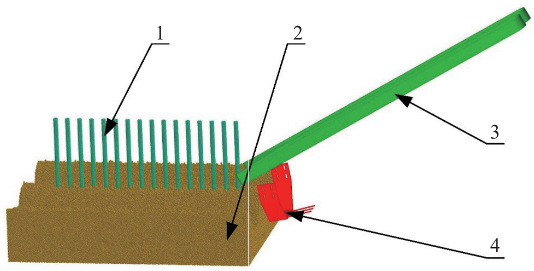
To accurately simulate the mechanism-crop-soil interaction characteristics and ensure the realism and timeliness of the simulation analysis, Hertz-Mindlin with Bonding was selected as the contact model between soil particles[21], and Bonding V2 model was introduced to accelerate the calculation[16].

3.1.3 Setting of simulation parameters

The onion ridge model was established in SolidWorks and imported into EDEM soil trough with dimensions of 2000×1400×600 mm (Length×Width×Height). A particle factory was created and particles were statically generated, so that they completely filled the onion ridge model and formed the onion ridge by settling, stacking, and generating bonding bonds. Vertical loads required to calibrate the soil density were applied to its upper part, so that the model was compacted and consistent with the actual soil density. Referring to the existing literature and studies, the basic parameters of the discrete element model are listed in Table 1[22-24], and the simulation model is shown in Figure 5.

Table 1 Basic parameters of the discrete element simulation model

Parameter	Value
Soil trough size/mm×mm×mm	2000×1400×600
Depth of digging/mm	250
65Mn density/(kg·m^{-3})	7830
65Mn Poisson's ratio	0.35
65Mn shear modulus/Pa	7.27×10^{10}
Density of soil particles/(kg·m^{-3})	1340
Poisson's ratio of soil particles	0.4
Soil particle shear modulus/Pa	1×10^{6}
Soil-soil coefficient of restitution	0.2
Soil-soil coefficient of rolling friction	0.3
Soil-soil coefficient of static friction	0.4
65Mn-soil coefficient of restitution	0.3
65Mn-soil coefficient of rolling friction	0.05
65Mn-soil coefficient of static friction	0.4
Physical radius/mm	6
Soil particle number	283 701
Gravity/(m·s^{-2})	9.81
Total simulation time/s	10



1. Green onion 2. Ridge of green onion 3. Clamping conveyor belt 4. Digging device

Figure 5 Simulation model

A simulation test of the soil model's compactness was conducted to compare the soil compactness of the simulated soil tank with the actual measured soil compactness. This was undertaken to verify the quality of the soil simulation model. When the cone head of the soil compactness meter is inserted vertically at a depth of 150 mm, the resultant compactness of the soil particles is 0.63 MPa, and the actual measured soil compactness is 0.6 MPa, with an error of 5%. Consequently, the established simulated soil model is in close proximity to the actual soil compactness, thus rendering it suitable for the purpose of conducting a simulation test for the harvesting of onions.

3.2 Simulation test

3.2.1 Test design

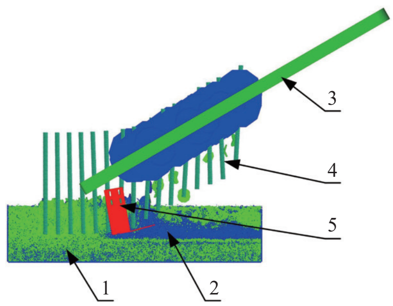
To explore the main factor level range of the performance of the device, a single-factor simulation test was conducted with the screen bar length l_2, screen bar inclination angle β, and pulling point position x as the test factors, and the bond breakage was measured and analyzed. Based on the previous preliminary tests and considering the spatial location relationship between the main influencing factors, the following test ranges were selected for each of the three factors: screen bar length l_2 (40-360 mm), screen bar inclination angle β (–35° to 65°), and pulling point position x (–350 to 650 mm). Five test points were selected in each range for the single-factor simulation test. In the EDEM analysis, the bond breakage can be visualized through the fracture cloud diagram, the number of bond breakages in each group of simulation test can be exported, and the data can be processed by using SPSS software and Origin 2024.

3.2.2 Simulation settings

Based on the onion harvesting conditions, the digging depth is set to 250 mm, and the width of the shovel shanks on both sides of the digging shovel is 580 mm. For timeliness and continuity of the simulation, the fixed time step is set to be 1.465×10^{-4} s, which is 20% of the Rayleigh time step. The total time of the simulation is 10s, and the target save interval is 0.1 s.

3.3 Analysis of results

At the completion of the simulation, bond breakage is shown in Figure 6, and the change of the total number of bonds is shown in Figure 7. Bonds continue to be generated, and the number of bonds reaches a peak at 2 s. As the device enters the soil, bonds are gradually broken, and the total number of bonds gradually decreases until the end of the simulation. In the EDEM analysis, the experimental data of each group were exported, and the difference between the maximum number of bonds and the minimum number at the end of the simulation was calculated as the number of bond breaks. The result was imported into SPSS 26.0 for the test of significance and analysis of variance (ANOVA), and plotted on a significance bar graph using Origin 2024. The ANOVA of each factor on bond breakage is shown in Table 2, and the significance is shown in Figure 8.



1. Complete bonds 2. Broken bonds 3. Clamping conveyor belt 4. Green onion 5. Digging device

Figure 6 Condition of bond breaks

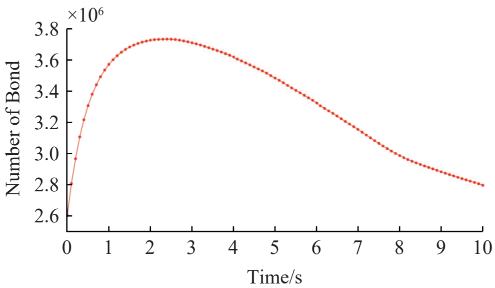
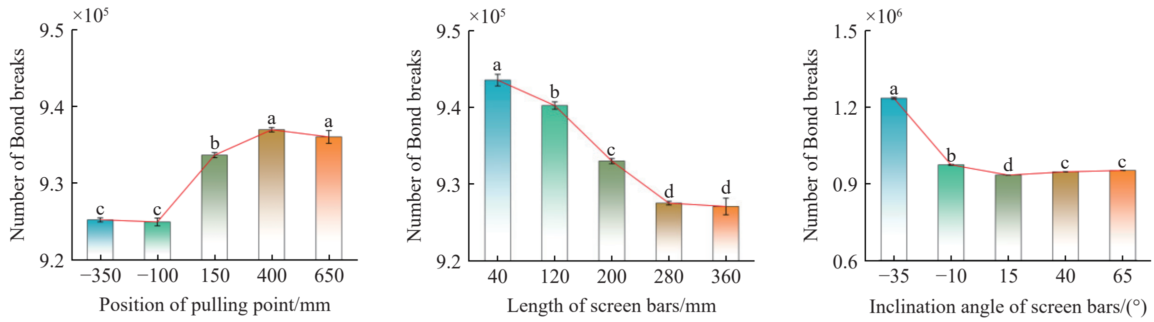


Figure 7 Changes in the number of bonds

Table 2 ANOVA for single-factor model

Source		Sum of squares	*df*	Mean square	*F*-value	Significance
Pulling point position	Intergroup	411 005 819.333	4	102 751 454.833	140.546	0.000
	Within group	7 310 870.000	10	731 087.000		
	Total	418 316 689.333	14			
Screen bar length	Intergroup	659 677 210.667	4	164 919 302.667	128.816	0.000
	Within group	12 802 671.333	10	1 280 267.133		
	Total	672 479 882.000	14			
Screen bar inclination angle	Intergroup	193 949 733 915.333	4	48 487 433 478.833	4156.604	0.000
	Within group	116 651 556.000	10	11 665 155.600		
	Total	194 066 385 471.333	14			



a. Effect of position of pulling point on Bond breaks
b. Effect of length of screen bars on Bond breaks
c. Effect of inclination angle of screen bars on Bond breaks

Figure 8 Influence of factors on bond breaks

As can be seen fromTable 2, there are significant differences in the effects of different pulling point positions x, screen bar lengths l_2, and screen bar inclination angles β on the number of bond breaks, and the model is significant (p<0.05).Figure 8ashows that the number of bond breaks has an overall increasing trend with the increase of the pulling point position, and the difference in the influence of the pulling point position between –350 mm and –100 mm and between 400 mm and 650 mm on the model is non-significant. Seen fromFigure 8b, the number of bond breaks shows an overall decreasing trend with the increase of screen bar length, and the difference in the length of screen bars between 280-360 mm on the model is non-significant.Figure 8cshows that the number of bond breaks first decreases and then slightly increases with the increase of screen bar inclination angle, and the difference of the model is non-significant when the screen bar inclination angle is between 40°-65°.

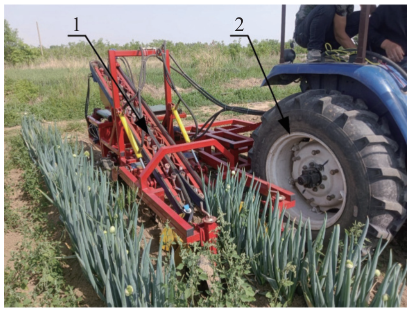
In summary, considering the single-factor simulation test and the agronomic requirements of green onion harvesting, the pulling point position x (–100 to 400 mm), the screen bar length l_2 (120-280 mm), and the screen bar inclination angle β (–10° to 40°) were selected as the experimental factors, which provided the theoretical basis for the subsequent multifactorial field test of the parameter optimization of the device.

4 Field tests

4.1 Test scheme

The field test was conducted on June 22, 2024 at the onion planting base in Jiaolai Town, Jiaozhou City, Qingdao City, Shandong Province, China. The test variety was Japanese steel onion, planted in single rows with a spacing of 80 cm between rows and 6 cm between plants. The field test is shown in Figure 9.

Based on the results of single-factor simulation test and harvesting agronomic requirements, the pulling point position X_1, screen bar length X_2, and screen bar inclination angle X_3 were selected as test factors, and onion clean digging rate Y was selected as the test index. Design-Expert was adopted to design a three-factor five-level orthogonal test, for which the test factor levels are listed in Table 3.



1. Green onion digging and pulling harvesting device 2. Tractor

Figure 9 Field test

Table 3 Table of coding levels of the test factors

Code	Test factors: Position of pulling point X_1/mm	Length of screen bars X_2/mm	Inclination angle of screen bars X_3/(°)
–1.682	–100	120	–10
–1	0	150	0
0	150	200	15
1	300	250	30
1.682	400	280	40

4.2 Test results and analysis

The experimental design and analysis were carried out by using Central Composite Design of Design-Expert 13 software[25-27], with the experimental results listed in Table 4 and the ANOVA table in Table 5.

As can be seen from the analysis, the fit of the model was enormously significant (p<0.01), the effect of the terms X_1, X_2, X_3, X_1X_2, X_1X_3, X_1^2, and X_3^2 on the clean digging rate was significant, and that of the terms X_1, X_2, X_3, X_1^2, and X_3^2 was enormously significant. Excluding the non-significant regression terms, the regression equation for the clean digging rate of onion Y was[28,29]:

$$Y = 94.86 + 11.99X_1 + 10.50X_2 + 8.87X_3 + 5.19X_1X_2 - 7.12X_1X_3 - 28.88X_1^2 - 5.55X_3^2 \quad (10)$$

Table 4 Scheme and results of test

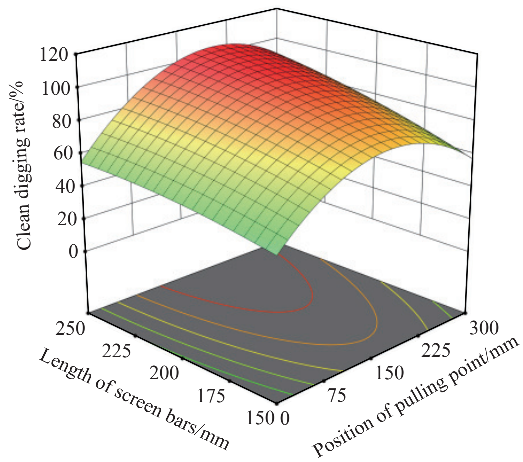
Serial No.	Experimental factors			Y/%
	X_1/mm	X_2/mm	X_3/(°)	
1	150	200	15	95
2	300	250	30	87
3	150	280	15	100
4	–100	200	15	0
5	400	200	15	30
6	150	200	15	98
7	300	250	0	90
8	300	150	30	52
9	0	250	0	40
10	150	200	40	100
11	0	150	30	53
12	150	120	15	77
13	150	200	15	100
14	150	200	15	87
15	0	250	30	58
16	150	200	15	96
17	150	200	15	92
18	150	200	–10	62
19	300	150	0	49
20	0	150	0	13

Table 5 Field test ANOVA table

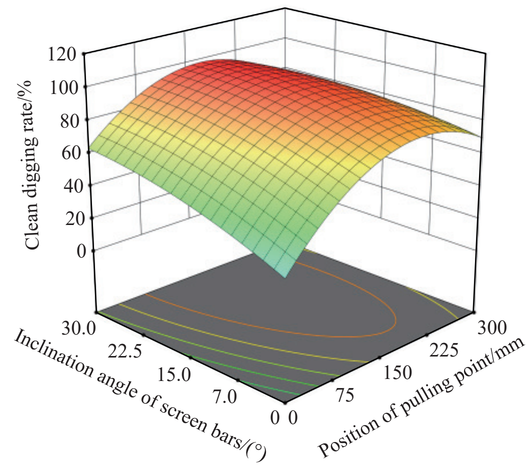
Source	Sum of squares	df	Mean square	F-value	p-value	Significance
Model	17 739.50	9	1971.06	44.25	< 0.0001	enormously significant
X_1	1984.13	1	1984.13	44.54	< 0.0001	enormously significant
X_2	1598.10	1	1598.10	35.88	0.0001	enormously significant
X_3	1086.03	1	1086.03	24.38	0.0006	enormously significant
X_1X_2	242.00	1	242.00	5.43	0.0420	significant
X_1X_3	420.50	1	420.50	9.44	0.0118	significant
X_2X_3	98.00	1	98.00	2.20	0.1688	non-significant
X_1^2	12 171.09	1	12 171.09	273.23	< 0.0001	enormously significant
X_2^2	131.84	1	131.84	2.96	0.1161	non-significant
X_3^2	449.35	1	449.35	10.09	0.0099	enormously significant
Residual	445.45	10	44.55			
Lack of fit	338.12	5	67.62	3.15	0.1168	non-significant
Pure error	107.33	5	21.47			
Cor total	18 184.95	19				

The sequence in terms of effect size of each factor on the clean digging rate is: pulling point position > screen bar length > screen bar inclination angle. According to the results of regression analysis, the pulling point position, the screen bar length, the screen bar inclination angle in any one of the zero levels, and the significant interaction response surface plot, the influences of the test factors on the law of the clean digging rate were analyzed, with the response surface shown in Figure 10[30-32].

As shown in Figure 10a, when the screen bar inclination angle is 15°, in the case of a fixed screen bar length, the clean digging rate first increases and then decreases with the increase of the pulling point position. At the same screen bar inclination angle, if the pulling point is positioned excessively forward, the digging shovel will not yet have dug the soil before the clamping belt pulls the onion, and the clean digging rate is low. On the contrary, if the pulling point is positioned excessively backward, it will result in the onions being dug out without being clamped. With the pulling point located, more onion will be dumped before it is clamped after digging, which will also result in a lower clean digging rate. In the case of the position of the pulling point, the clean digging rate increases with the increase of length of the screen bars. At the same screen bar inclination angle and pulling point position, the longer the screen bar length, the larger the amount of soil contacted by the screen bars, the more obvious the effect of loosening and crushing of the soil, and the higher the clean digging rate.



a. Clean digging rate when X_3 is equal to 15°



b. Clean digging rate when X_2 is equal to 200 mm

Figure 10 Influence response surface of test factors on test indices

As shown in Figure 10b, when the length of the screen bar reaches 200 mm, the clean digging rate first increases and then decreases with the increase of the screen bar inclination angle. In the case of a fixed pulling point position and at the same screen bar length, the smaller the screen bar inclination angle, the worse the disturbance effect on the soil, which leads to difficulties in extracting the onions from the clamping belt and a low clean digging rate. A larger screen bar inclination angle will lead to the direct action of the bar on the onion root, affecting the balance of the onion force and causing a low clean digging rate. The larger the screen bar inclination angle, the more likely it will lead to the direct action of the bar on the onion root, which will affect the balance of the onion force and the tipping phenomenon, and also make the clean digging rate lower. In the case of a fixed screen bar inclination angle, the clean digging rate first increases and then decreases with the increase of the pulling point position. The more forward the pulling point position, the lower the clean digging rate; likewise, the more backward the pulling point position, the lower the clean digging rate.

The optimization module in Design-Expert 13 software was used to obtain the best combination of parameters with the objective of maximizing the clean digging rate Y[33,34]. The objective function is expressed as follows:

$$\begin{cases} \max Y(X_1, X_2, X_3) \\ \text{s.t.} \begin{cases} 0\ \text{mm} \leq X_1 \leq 300\ \text{mm} \\ 150\ \text{mm} \leq X_2 \leq 250\ \text{mm} \\ 0^\circ \leq X_3 \leq 30^\circ \end{cases} \end{cases} \tag{11}$$

According to the actual operation, the best parameter combination is determined as follows: a pulling point position of 166 mm, a screen bar length of 242 mm, and a screen bar inclination angle of 14°. With this parameter combination, all the onions can be dug clean.

5 Discussion

In this paper, the interactions between onion and soil were theoretically analyzed and simplified into an articulated model, which is innovative when applied to the optimal design of agricultural equipment. The key factors affecting the harvesting index were obtained through the theoretical analysis of the model. The discrete element simulation method was utilized to simulate and analyze the key factors affecting the harvesting indices. This approach enabled the establishment of a realistic model of the onion groove and the determination of the number of bond breaks at each test level. This process enabled a response to the loosening and pulling effect of the device, and facilitated the determination of the range of influence of the key factors. Based on the simulation results, a field orthogonal test was designed to optimize the parameter combination to meet the harvesting requirements.

The most challenging issue currently is the harvesting of different varieties of target crops and different soil conditions by a digging and pulling onion harvesting device. The proposed method of digging and pulling onion harvesting can be applied to harvesting other varieties and soil qualities as well. Subsequent research will focus on the adaptability and stability of the onion harvesting device for different regions and varieties of onions.

6 Conclusions

1) In this paper, a digging and pulling type onion harvesting device was designed, which can realize the digging and pulling operation for onions. Through theoretical and experimental analysis, the motion characteristics of the onion harvesting process were obtained, the influencing factors of the onion not tipping and smooth clamping were clarified, and the structural arrangement parameters of the key components were determined, which solves the problems of easy dumping and low rate of clean digging of the onion in the process of onion harvesting.

2) Based on the soil discrete element simulation test, the influencing law of the screen bar length l_2, screen bar inclination angle β, and pulling point position x on the soil-crushing effect was determined, and the significance and value range of the key factors were obtained, which lays the foundation for the optimization of the mechanism parameter combinations for the field test.

3) Through field experiments, a three-factor five-level orthogonal test was designed. Design-Expert 13 data analysis software was utilized to establish a mathematical model between the screen bar length l_2, screen bar inclination angle β, and pulling point position x with the harvest indices, and the best parameter combination was determined. When the pulling point position is 166 mm, the screen bar length is 242 mm, and the screen bar inclination angle is 14°, the onion clean digging rate is 100%, which meets the agronomic requirements of onion harvesting.

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[References]

[1] Wang F Y. Production technology and harvesting equipment of green Chinese onion. Agricultural Engineering, 2017; 7(5): 1–4. (in Chinese)

[2] Zhang D X, Zhang J Q, Min L Q, Li Q J, Liu X F, Ren D M. Overview of the whole mechanization process and related equipment of scallion production. Journal of Chinese Agricultural Mechanization, 2020; 41(1): 197–204. (in Chinese)

[3] Hou J L, Chen Y Y, Li Y H, Wang W, Li G H. Development of quantitatively-laying and self-propelled green onion combine harvesters. Transactions of the CSAE, 2020; 36(7): 22–33. (in Chinese)

[4] Zhang D X, Zhang J Q, Liu X F, Qin X T, Li Q J, Min L Q, et al. Design of 4CZ-1 type caterpillar self-propelled integrative machine for scallion harvesting. Journal of Agricultural Mechanization Research, 2022; 44(4): 71–79. (in Chinese)

[5] Hou J L, Chen Y Y, Li Y H, Li T H, Li G H, Guo H E. Design and experiment of shovel-screen combined green onion digging, shaking, and soil tillage device. Transactions of the CSAE, 2021; 37(18): 29–39. (in Chinese)

[6] Wang F Y, Qiu Z C, Pan Y F, Sun G Q. DEM-based parameter optimization and tests of digging green onions. Int J Agric & Biol Eng, 2023; 16(4): 126–133.

[7] Wang F Y, Sun G Q, Shang S Q. Development of 4CL-1 self-propelled combine harvester for green onion. Transactions of the CSAE, 2019; 35(24): 39–47. (in Chinese)

[8] Wang C, Yang Y, Kou T X, Hou S, Hu G F. Theoretical and experimental study on excavation resistance of green Chinese onion harvester. Journal of Agricultural Mechanization Research, 2020; 42(9): 32–38. (in Chinese)

[9] Sun G Q, Pan Y F, Wang F Y. Study on physical and mechanical properties of green onion. Journal of Agricultural Mechanization Research, 2022; 44(11): 159–165, 172. (in Chinese)

[10] Hou J L, Li C, Zhang Z L, Li T H, Li Y H, Wu Y Q. Design and test of double-row walking garlic combine harvester. Transactions of the CSAE, 2021; 37(12): 1–11. (in Chinese)

[11] Li J W, Li X Y, Hu B, Gu T L, Wang Z J, Wang H L. Analysis of the resistance reduction mechanism of potato bionic digging shovels in clay and heavy soil conditions. Computers and Electronics in Agriculture, 2023; 214: 108315.

[12] Liu L, Wang X L, Zhang X C, Cheng X P, Wei Z C, Zhou H, et al. The impact of 'T' -shaped furrow opener of no-tillage seeder on straw and soil based on discrete element method. Computers and Electronics in Agriculture, 2023; 213: 108278.

[13] Lü J Q, Yang X H, Lü Y N, Li Z H, Li J C, Du C L. Analysis and experiment of potato damage in process of lifting and separating potato excavator. Transactions of the CSAM, 2020; 51(1): 103–113. (in Chinese)

[14] Sun J F, Chen H M, Wang Z M, Ou Z W, Yang Z, Liu Z, Duan J L. Study on plowing performance of EDEM low-resistance animal bionic device based on red soil. Soil & Tillage Research, 2020; 196.

[15] Wang F A, Ni C, Zhang Z G, Xu H W, Xie K T, Wang B Y. Analysis and experiment on drag reduction characteristics of digging shovel of *Panax notoginseng* harvester. Transactions of the CSAM, 2024; 55(7): 179–190, 199. (in Chinese)

[16] Zhang P C, Li F G, Wang F Y. Optimization and test of ginger-shaking and harvesting device based on EDEM software. Computers and Electronics in Agriculture, 2023; 213: 108257.
[17] Wang J W, Li X, Gao P X, Na M J, Wang Q, Zhou W Q. Design and experiment of high efficiency drag reducing shovel for carrot combine harvester. Transactions of the CSAM, 2020; 51(6): 93–103. (in Chinese)
[18] Xia C, Shang S Q, Wang D W, Liu Y G, He X N, Zhao Z, et al. Design and research of bionic scallop peanut excavation shovel. Journal of Agricultural Mechanization Research, 2024; 46(3): 114–119. (in Chinese)
[19] Ma W N, Song Q, Gao X Y, Zhao J G, Ma C Y. Design and experiment of saposhnikovia divaricata bionic digging shovel. Journal of Agricultural Mechanization Research, 2024; 46(7): 64–72. (in Chinese)
[20] Sun N, Shi X L, Chen Y, Li J L, Yang G. Design and testing of potato digging device based on EDEM. Journal of Agricultural Mechanization Research, 2024; 46(11): 29–34, 44. (in Chinese)
[21] Zhang Z G, Xue H T, Wang Y C, Xie K T, Deng Y X. Design and experiment of *Panax notoginseng* bionic excavating shovel based on EDEM. Transactions of the CSAM, 2022; 53(5): 100–111. (in Chinese)
[22] Chen M D, Liu X T, Hu P X, Zhai X T, Han Z L, Shi Y L, et al. Study on rotor vibration potato-soil separation device for potato harvester using DEM-MBD coupling simulation. Computers and Electronics in Agriculture, 2024; 218: 108638.
[23] Li J W, Gu T L, Li X Y, Wang Z J, Hu B, Ma Y H. Analysis and experiment of the bionic drag reduction characteristics of potato digging shovels on clayey black soil conditions. Transactions of the CSAE, 2023; 39(20): 1–9. (in Chinese)
[24] Zou L L, Yan D W, Niu Z R, Yuan J, Cheng H, Zheng H. Parametric analysis and numerical optimisation of spinach root vibration shovel cutting using discrete element method. Computers and Electronics in Agriculture, 2023; 212: 108138.
[25] Tao G X, Zhang Z H, Yi S J, Xia C L, Ma Y C. Design and test of combined swing radix isatidi root-soil separation device. Transactions of the CSAM, 2022; 53(4): 109–119. (in Chinese)
[26] Xiao X, Xie F P, Zhao Z Q, Wang X S, Liu D W, Zhao Y. Optimized design and experiment of the tassel gathering mechanism for 4BL-1 type white radish combine harvester. Transactions of the CSAE, 2024; 40(11): 38–47. (in Chinese)
[27] Zhang J, Wang J, Du D D, Long S F, Wang Y W, Han C J, et al. Optimization and validation of root-cutting device for Chinese cabbage harvester based on discrete element method. Computers and Electronics in Agriculture, 2023; 214: 108314.
[28] Dai Z W, Wu M L, Fang Z C, Qu Y B, Liu Y F. Design and test of a throwing roller type lily bulb harvester. Transactions of the CSAE, 2023; 39(12): 20–29. (in Chinese)
[29] Zhang G Z, Zhang Q H, Liu W R, Li Z H, Zhou Y, Liu H P. Spring roller device for soil-corm separation for a water chestnut harvester. Transactions of the CSAE, 2024; 40(2): 164–175. (in Chinese)
[30] Chen Q Y, Zhang S X, Wei N S, Li P H, Hu G R, Chen J, Chen Y. Design and optimization of torsion harvester of *Lycium barbarum* L. Int J Agric & Biol Eng, 2024; 17(4): 109–115.
[31] Wang F Y, Zhang Q, Zhang Z Y, Huang X P. Development of comb type leaves clearing and top cutting machine for beets. Transactions of the CSAE, 2021; 37(4): 69–79. (in Chinese)
[32] Wang F Y. Optimization and field experiment of an adjustable device for sugar beet digger. Int J Agric & Biol Eng, 2021; 14(6): 68–74.
[33] Yang R B, Tian G B, Shang S Q, Wang B J, Zhang J, Zhai Y M. Design and experiment of roller group type potato soil separator for potato harvester. Transactions of the CSAM, 2023; 54(2): 107–118. (in Chinese)
[34] Yang S D, Qiu T Y, Ma C, Li X Q, Wang L L, Liu Y. Design and test of sugar beet combine harvester separation and conveying device. Transactions of the CSAM, 2023; 54(S1): 191–200. (in Chinese)