DESIGN AND EXPERIMENTATION OF ROOT-CUTTING DEVICE FOR HEAD-FORMING VEGETABLES

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结球类蔬菜切根装置设计与实验

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DOI: https://doi.org/10.35633/inmateh-75-71

Keywords: *head-forming vegetables, root-cutting device, virtual simulation, experiment*

ABSTRACT

In response to the current low level of mechanized harvesting for heading vegetables in China and the unsatisfactory harvesting results, this study focuses on the root-cutting operation during the harvesting process. A double-disk root-cutting device was designed to achieve low-power consumption and high-efficiency root cutting. Through LS-DYNA simulation experiments, the root-cutting process of the root-cutting device was simulated, and the cutting force and internal cutting energy of three different cutter combinations are compared. The simulation results show that the maximum cutting force of the double-serrated blade was the smallest, while the combination of a smooth blade and a serrated blade had the lowest internal cutting energy. Compared to smooth blades, serrated blades exhibited better clamping effects on the roots of head-forming vegetables. Considering both cutting force and internal cutting energy, the combination of a serrated blade and a smooth blade was found to be optimal. The quadratic rotary orthogonal combination test method was used to analyze the relationship between the main influencing factors of the root cutting device performance (rotational speed of the cutter, conveying speed, inclination angle of the cutter, and overlapping amount of the cutter) and the performance index (root cutting power) of the root cutting device. The bench test program was designed by applying regression analysis, response surface and multi-objective variable optimization methods. The bench test results show that the optimal parameter combination of the designed root cutting device were: cutter speed of 200 rpm, conveying speed of 0.3 m/s, cutter inclination angle of 10°, and cutter overlap of 20 mm. The predicted cutting power of the model was 51.19 W.

摘要

针对现阶段我国结球类蔬菜机械化收获水平低下，收获效果不理想等问题。本文重点研究结球类蔬菜收获过程中的切根作业，设计一种双圆盘切根装置，可实现低功耗、高效率切根。过 LS-DYNA 仿真实验，模拟了切根装置的切根工作过程并比较了三种切刀组合的切根力和切根内能，仿真实验结果双锯齿刀的最大切根力最小，光刀与锯齿刀的组合切根内能最小。光刀与锯齿刀相比，锯齿刀对结球类蔬菜根的钳持效果更好，综合切根力和切根内能，选择锯齿刀加光刀的组合更优。采用二次旋转正交组合试验方法，分析切根装置性能的主要影响因素（切刀转速、输送速度、切刀倾角、切刀重叠量）与性能指标（切根功率）的关系，应用回归分析、响应曲面和多目标变量优化方法设计了台架试验方案。台架试验结果表明，所设计切根装置的最优参数组合为：切刀转速 200r/min，输送速度 0.3m/s，切刀倾角 10°，切刀重叠量 20mm；模型预测的切根功率为 51.19W。

INTRODUCTION

Heading vegetables is one of the important vegetables consumed by the Chinese residents, which is important for ensuring the balanced supply of vegetable market, balancing the price of vegetables and ensuring the income of farmers (*Sheng et al., 2021; Yan et al., 2024*). The relevant agronomic data show that in the whole process of heading vegetable production, the harvesting operations accounted for more than 40% of the entire heading vegetable production operations *(Li, 2020)*. At present, China's heading vegetable mechanized harvesting level is low, still completely rely on manual completion, harvesting process farmers need to constantly bend down and cut vegetables from the roots. Then remove the package and picking up the vegetable bulb. Finally load, with trucks. Thus, harvesting operations is a long time, labor-intensive process (*Li et al., 2023; Wen et al., 2024*).

Heading vegetables mechanized harvesting can reduce the labor intensity for vegetable farmers, eliminating the constantly bending over to cut and pick up of the manual processes. With the promotion of China's urbanization process and the rural labor force to the city to transfer, it is imperative to improve the level of mechanized harvesting for heading vegetables *(Wang et al., 2018; Zhou, 2013; Wang et al., 2014).*

Heading vegetables belong to a class of vegetables harvested without root, the quality of its cut root (whether the cut is flat, whether the cut is biased, whether there is damage, etc.) has a great impact on its subsequent storage. Therefore, many experts and scholars have conducted a lot of research on disk cutting device, most of them focus on the mechanical properties of crops, crop cutting mechanism, slip cutting theory, cutting device structure and other aspects of the study. *(Jang et al., 2021; Jing et al., 2021)*.

El et al., (2020), developed and tested a cabbage root cutting device and investigated the effects of cutter shape, cutter speed and cutter angle on the performance of the harvester. *Xu et al., (2009)*, investigated the shear characteristics of cabbage roots and stems using different conditions such as cutting speed, blade curve, blade thickness and blade smoothness. The effect of cutting speed, blade shape and blade smoothness on the shear force was tested. *Li et al., (2020)*, designed an adjustable root-cutting device, and obtained the influence law of individual factors on root-cutting reaction force through one-factor test and orthogonal test; then they conducted second-order orthogonal rotary combination multifactorial test to study the influence of cutter speed, cutting position, walking speed, cutter overlap and pitch angle on the maximum root-cutting reaction force, and at the same time, they used the response surface method for the optimization of the parameters to obtain the best parameter combination. *Du et al., (2017)*, carried out the cutting part test, cutting force orthogonal test, cutting and splitting breakage test and stem using the universal material testing machine. The test results showed that both the maximum cutting force and the average cutting force were linearly related to the crude fiber content, and the interval of 30-35 mm in diameter of kale rhizome was the optimal root cutting area.

Based on the above research, this paper designs a root cutting device for heading vegetables, applies LS-DYNA software to simulate and analyze the root cutting characteristics of different blade combinations, confirms the blade combinations according to the results, and optimizes the structure and working parameters of the root cutting device.

MATERIALS AND METHODS

Design of key components

Root cutting mechanism is an important part of the root cutting operation of heading vegetables. While operating, the root cutting mechanism needs to clamp and excise the roots of heading vegetables. Its performance will directly affect the results of the root cutting operation. Root cutting mechanism diagram is shown in Figure 1 and it mainly consists of: cutter, *4*; cutter plate, *5*; bracket, *1*; cutter shaft, *6*; universal joint coupling, *2*; T-type commutator, *7*; hexagonal shaft, **8** and hydraulic motor and other components, *3*.

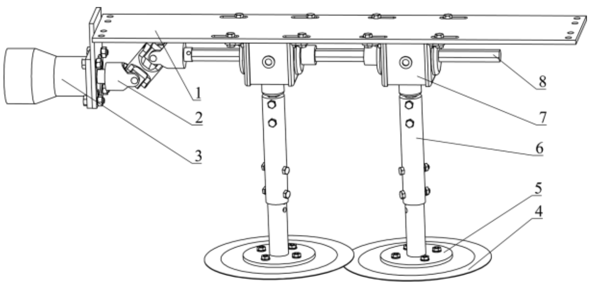
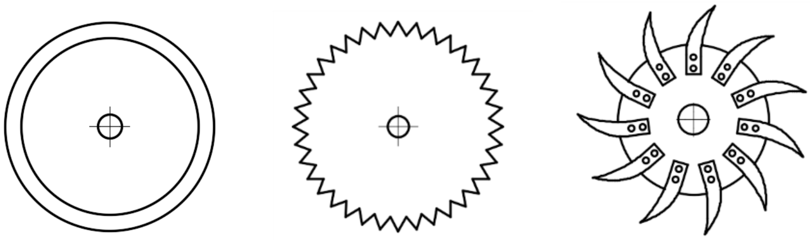


Fig. 1 – Structure diagram of heading vegetables root cutting mechanism

The design of the root cutting mechanism in this paper mainly focuses on the selection of the cutter and the design of the main parameters of the two cutters. There are generally two types of cutting mechanisms used for crop harvesting: the reciprocating type and the disk type. The reciprocating type is typically employed for harvesting crops with relatively fine stems, such as rice and wheat, while the disk type is commonly used for harvesting crops with thicker stems, such as sugarcane and cabbage. Since the roots of heading vegetables are relatively thicker, the type of cutter designed in this paper utilizes the disk type cutter.

According to the number of cutters used in the cutting process is divided into single disk cutting mechanism and double disk cutting mechanism.

Among them, the single disk cutting mechanism cutter needs a larger diameter, the rotational speed set is also relatively high. This situation can unbalance the force of the root cutting process; while the diameter of the double disk knife does not need to be too large, the rotational speed does not need to be too high, you can reduce the energy consumption in the work process, eliminate the force imbalance during root cutting. Therefore, the cutting mechanism designed in this paper selects double disk cutter. In order to ensure the integrity of the cut root, there is a certain overlap area between the double disk cutter. Common disk cutter shape mainly has a smooth edge type, serrated type and extra-blade type three types, as shown in Figure 2 *(Li, 2018; Liu et al., 2021)*.



a) smooth edge type b）serrated type c）extra-blade type

Fig. 2 – Different style cutters

Under the same working conditions, the cutting effect and power consumption of the disk cutter with different edges and structures are different. The smooth-edge cutter has the lowest power consumption and small force, while the extra-blade-type disk cutter is subject to the largest force and the highest cutting power consumption. *Du Dongdong* found that it was difficult to clamp cabbage roots for stable cutting by a separate smooth-edged disk cutter through mechanical analysis, therefore, this paper chooses the combination of smooth-edged and serrated cutter for root cutting *(Du et al., 2011; Du et al., 2015; Du et al., 2017)*.

The root cutting device designed in this paper has overlapping upper- and lower-disk knives, and during the root cutting process, the double disk knives will clamp and cut off the heading vegetable roots. As the clamping force and shear force are in the rotating plane of the disk knives, only the force on the heading vegetable roots in the rotating plane of the disk knives is analyzed. The force on the heading vegetable roots is shown in the schematic diagram in Fig. 3:

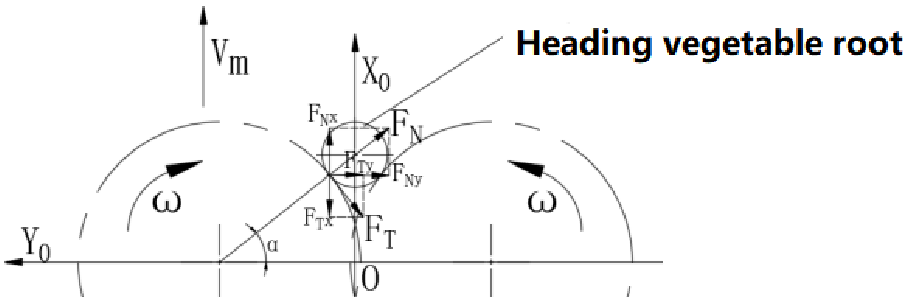


Fig. 3 – Stress analysis of heading vegetable root during root cutting process

The force analysis leads to the equation (1):

$$\begin{cases} F_C = F_{Ty} + F_{Ny} = F_T \sin\alpha + F_N \cos\alpha \\ F_S = F_{Tx} + F_{Nx} = F_T \cos\alpha - F_N \sin\alpha \\ F_T = f F_N \end{cases} \tag{1}$$

F_C - clamping force, N;

F_S - shear force, N;

F_N - normal reaction force of the disk cutter acting on the heading vegetable root, N;

α - angle between F_N and Y_0 axis direction, (°);

F_T - friction force of the disk cutter on the heading vegetable root, N;

f - friction coefficient between the disk cutter and the heading vegetable root, generally take 0.4~0.7.

From the force analysis, it can be seen that the disk cutter can clamp the heading vegetable root under the condition that: $F_T \cos\alpha > F_N \sin\alpha$, therefore, at $f > \tan\alpha$, the disk cutter can clamp the heading vegetable root.

$$\alpha = \sin^{-1}\frac{A_1/2}{(D+d)/2} = arccos\frac{A_1}{D+d} \quad (2)$$

A₁ - center distance between two disk cutters, mm;

D - diameter of the disk cutter, mm;

d - diameter of cabbage root cutting place, generally take 25~35 mm.

When A_1 increases or D decreases, α decreases, which is beneficial for the two disk blades to clamp the root of heading vegetables for cutting. However, due to structural constraints such as the center distance A_1 between the two disk blades and the disk cutter diameter D, the angle α is typically limited to a range of 35° to 40°. Additionally, the friction coefficient f between the root of heading vegetables and the blade edge generally ranges from 0.4 to 0.7. As a result, it is difficult for two smooth-edged disk blades to effectively clamp the root of heading vegetables for cutting. In this paper, the ability of the cutter to clamp the root is improved by using a combination of a smooth-edged disk cutter and a serrated disk cutter.

According to the analysis results, in the case of the root cutting mechanism, conveying mechanism and frame do not interfere with each other, while meeting the requirements of the two pieces of the cutter have a partial overlap, the diameter of the outer end of the cutter is set to 270 mm, the diameter of the inner hole in the middle is set to 25 mm, and the design of the cutter parameters is shown in Figure 4.

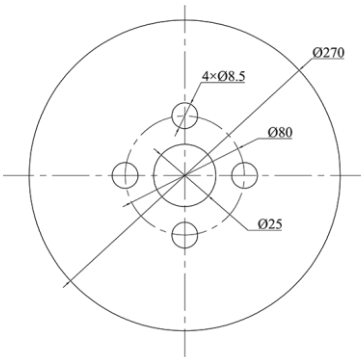


Fig. 4 – Design diagram of cutting tool structure

MATERIALS AND METHODS

Simulation experiment

In order to study the effect of different knife combinations on the maximum root cutting force and internal energy of root cutting, three knife combinations of double smooth-edged knife, double serrated knife and smooth-edged knife + serrated knife were simulated and analyzed using LS-DYNA software, and the root cutting characteristics of different knife combinations were analyzed according to the simulation results.

SolidWorks was used to establish three kinds of root cutting model, and then the model mesh was imported to Workbench/LS-DYNA in order to reduce the amount of calculation. In this study, the disk cutter will be defined as a rigid body. The mesh at the contact area between the roots of heading vegetables and the disk cutter in the root cutting process was finely divided, and the mesh size could be coarsened in other positions. The meshed root-cutting model is shown in Figure 10, and the number of nodes of the knotty vegetable root and disk cutter meshes are 42036 and 12960, the number of cells are 39510 and 6199, respectively.

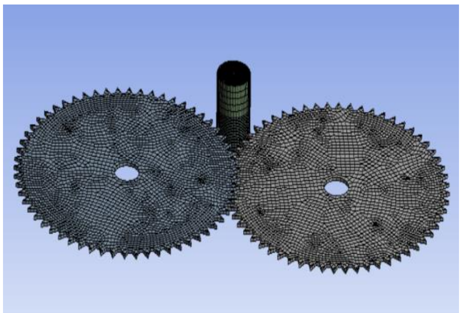


Fig. 5 – Grid division results

In the simulation model, the relative motion between the heading vegetable root and the cutter is used to simulate the actual root-cutting process. Select the upper end surface of the heading vegetables as fixed; the movement of the cutter is divided into forward motion and rotary motion around the axis, therefore, when constraining the cutter, it is necessary to set the X, Y, Z direction of the velocity component and X, Y, Z direction of the angular velocity component. The end time depends on the distance between the root of the heading vegetables and the cutter and the rotational speed of the cutter; the default safety factor of the time step is 0.9, and in the case of cutting simulation where the unit will be destroyed, it is possible to generate a negative volume, at this time, you can change the safety factor to a smaller one and set it to 0.6, and at the same time, the Minimum Time Step should be greater than 10^{-10} s *(Li ,2013; Mohammod et al., 2019)*.

Bench Test

In order to optimize the key structural parameters and working parameters of the root cutting device, the root cutting performance test was carried out. The quadratic rotary orthogonal combination test method was adopted to analyze the relationship between the main influencing factors of root cutting performance (rotational speed of the cutter, conveying speed, inclination angle of the cutter, and the overlap amount of the cutter) and the performance index of the root cutting (cutting power). Regression analysis, response surface, and multi-objective variable optimization were applied to optimize the performance index of the root cutting device (cutting power).

The test is carried out on an independently designed double-disk heading vegetables root cutting test bench. This bench is mainly composed of double-disk cutting device, root cutting motor, clamping and conveying device, conveying motor, dynamic torque sensor, elastic pin coupling, frame, control and information acquisition system, etc. The test is carried out on a double-disk heading vegetables root cutting test bench. During the working process, the heading vegetable is stably clamped by the clamping and conveying device and conveyed in the direction of the cutting device, and the root of the heading vegetable is removed by the high-speed rotating double-disk cutter at the bottom.

Test Indicators

Referring to the national standard General Provisions on Measurement Methods for Test Conditions of Agricultural Machinery (GB/T 5262-2008) and the agricultural industry standards Test Methods for Sugar Beet Harvesting Machinery (JB/T 6276-2007) and Operational Quality of Sugar Beet Harvester (*NY/T 1412-2007*), the root cutting power P during the cabbage root cutting process was used as the test index.

$$P = \frac{(T_1 - T_0) \cdot n}{9550} \tag{3}$$

P - cutting power, W;

T_1 - total working torque, N·m;

T_0 - idling torque, N·m.

Test Design

According to the previous experimental research, the factors that have a greater impact on the performance of root cutting mainly include the rotational speed of the cutter, conveying speed, inclination angle of the cutter, and overlap of the cutter. Therefore, in order to obtain a better combination of root cutting parameters, this experiment refers to the results of simulation tests and related literature, with the rotational speed of the cutter (A), conveying speed (B), cutter inclination (C) and the amount of overlap of the cutter (D) as the test factors, and with the root cutting power (R) as the response index, to carry out a four-factor, three-level quadratic rotary orthogonal test, the four factors of the Chinese cabbage cutting test level coding as shown in Table 1.

Table 1

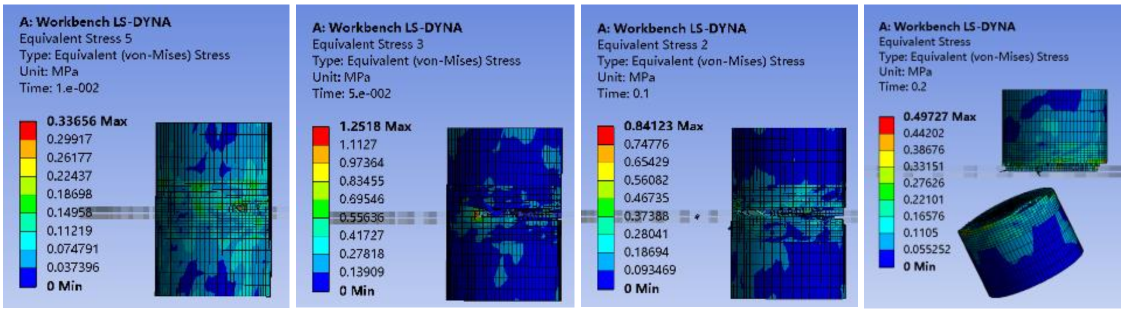
Factors and level of orthogonal test

Level	Factors			
	A. The rotational speed of the cutter (rpm)	B. Conveying speed (ms^{-1})	C. Cutter inclination (°)	D. Cutter overlap (mm)
1	200	0.3	5	15
2	300	0.4	10	20
3	400	0.5	15	25

RESULTS

Analysis of simulation test results

According to the above operation steps, the root cutting process in three types of cutting combinations was simulated and analyzed, and the root cutting process and the change curve of root cutting force were obtained through simulation analysis, as shown in Figure 6.



a) 0.01 s b) 0.05 s c) 0.1 s d) 0.2 s

Fig. 6 – Simulation process of root cutting

The heading vegetables root and the cutter began to contact, the cutter approached the heading vegetables root and contacted the outer skin of the cabbage root, and the outer skin of the heading vegetables root was gradually deformed, as shown in Figure 6a. As the cutter continued to go deeper into the interior of the heading vegetables root, the cutter exerted a vertically acting cutting and friction force on the root resulting in the cutting of the root as shown in Figure 6b. The cutter continued to penetrate deeper into the root, and the root started to fracture, as shown in Figure 6c. Eventually, the cutter severed the cabbage root, as shown in Figure 6d.

The effects of different cutter combinations on the maximum root cutting force and internal energy of root cutting during root cutting were further analyzed and the statistical simulation results are shown in Table 2.

Table 2

Data of maximum root cutting force and internal energy under different cutter types

Cutter types	Maximum root cutting force (N)	Internal energy (mJ)
Double smooth blade	22.797	1854.56
Double serrated blade	20.499	1751.4
Smooth + serrated blade	20.97	1653.53

From the data in Table 2, it can be concluded that the maximum root cutting force of the double serrated knife is the smallest, and the root cutting internal energy of the combination of smooth knife and serrated knife is the smallest. Compared to the smooth knife, the serrated knife has a better clamping effect on the cabbage root. The combination of serrated knife and smooth-edged knife is more optimal by combined analysis of the results of maximum root-cutting force and internal energy.

Analysis of bench test results

The experiments were designed in accordance with the BBD experimental design method, and the experimental program and results are shown in Table 3.

Table 3

Orthogonal test scheme and test results

Factor				Response indicators
A (r/min)	B (m/s)	C (°)	D (mm)	R (W)
-1 (200)	-1 (0.3)	0 (10)	0 (20)	52.5
1 (400)	-1	0	0	90.8
-1	1 (0.5)	0	0	71.6
1	1	0	0	123.3
0 (300)	0 (0.4)	0	0	92.3
0	0	-1 (5)	-1 (15)	98.2
0	0	1 (15)	-1	92.2
0	0	-1	1 (25)	92.7

Factor				Response indicators
A (r/min)	B (m/s)	C (°)	D (mm)	R (W)
0	0	1	1	94
0	0	0	0	88.5
-1	0	0	-1	68.6
1	0	0	-1	102.3
-1	0	0	1	60.7
1	0	0	1	109.6
0	0	0	0	84.6
0	-1	-1	0	75.5
0	1	-1	0	107.6
0	-1	1	0	82
0	1	1	0	95.6
0	0	0	0	85.9
-1	0	-1	0	68.6
1	0	-1	0	107.7
-1	0	1	0	62.4
1	0	1	0	111
0	0	0	0	89.5
0	-1	0	-1	69
0	1	0	-1	101.5
0	-1	0	1	70.2
0	1	0	1	102.8

The quadratic polynomial response surface regression model of the root cutting power (R) on the rotational speed of the cutter (A), conveying speed (B), cutter inclination (C) and the amount of overlap of the cutter (D) was established by using Design-Expert 8.06 to fit the multivariate regression to test results in Table 4. In this table, df means degree of freedom. F-value is the ratio of the variance between the group means to the variance within the groups. A higher F-value indicates a greater difference between group means relative to the variation within the groups. The P-value is the probability of obtaining an F-value as extreme as the one calculated, assuming the null hypothesis is true. A small P-value (typically < 0.05) suggests that the observed differences between group means are statistically significant, leading to the rejection of the null hypothesis.

Table 4

Results of variance analysis of orthogonal test

Source	Root cutting power					
	Sum of Squares	df	Mean Square	F value	P value	Significant
Model	8324.53	14	594.61	63.97	<0.0001	**
A	5646.34	1	5646.34	607.45	<0.0001	**
B	2197.81	1	2197.81	236.45	<0.0001	**
C	14.30	1	14.3	1.54	0.2352	
D	0.27	1	0.27	2.9E-2	0.8671	
AB	44.89	1	44.89	4.83	0.0453	*
AC	22.56	1	22.56	2.43	0.1415	
AD	57.76	1	57.76	6.21	0.0258	*
BC	85.56	1	85.56	9.21	0.0089	**
BD	2.5E-3	1	2.5E-3	2.7E-4	0.9871	
CD	13.32	1	13.32	1.43	0.2511	
A2	73.92	1	73.92	7.95	0.0136	*
B2	19.04	1	19.04	2.05	0.1743	
C2	99.89	1	99.89	10.75	0.0055	**
D2	3.29	1	3.29	0.35	0.5617	
Residual	130.13	14	9.3			
Lack of Fit	93.3	10	9.33	1.01	0.5424	
Pure Error	36.83	4	9.2			
Cor Total	8454.66	28				

*Note: ** indicates a highly significant effect (P<0.01) and * indicates a significant effect (P<0.05)*

As can be seen from Table 4, the root cutting power regression model P<0.01 and the misfit term P>0.05, indicating a high degree of goodness of fit and a highly significant fitting effect.

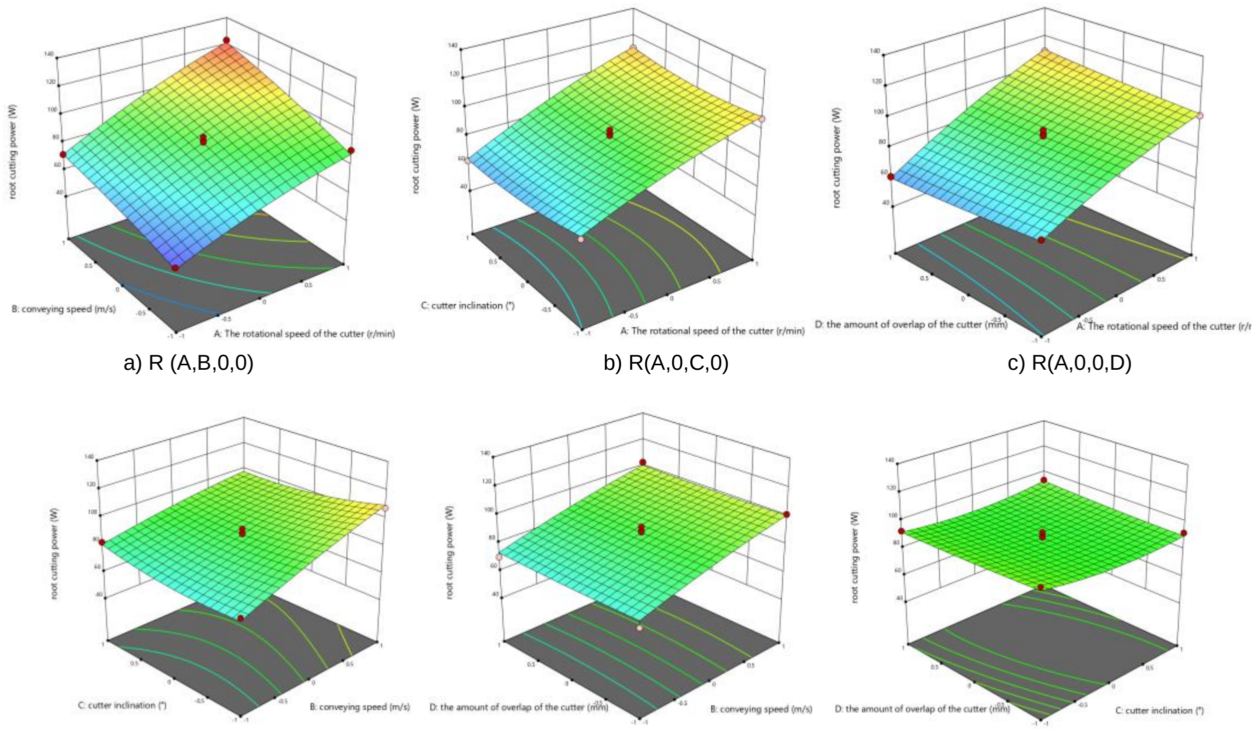
From the value of F-value in Table 4, it can be seen that the factors affecting the root cutting power (R) of the root cutting device are, in order of priority: the rotational speed of the cutter (A), conveying speed (B), cutter inclination (C), the amount of overlap of the cutter (D). From the value of P in Table 3, it can be seen that the effect of A, B, BC, and C2 on the root cutting power is highly significant, the effect of AB, AD, and A2 on root cutting power is significant, and the rest of the items do not have a significant effect on the root cutting power.

In summary, the optimized regression fitting equation about root cutting power obtained after eliminating the insignificant terms is shown in equation (4), and the optimized model is reliable with P<0.01 and the out-of-fit term with P>0.05.

$$R = 87.61 + 21.69A + 13.53B - 1.09C - 0.15D + 3.35AB + 3.8AD - 4.63BC - 3.22A^2 + 4.08C^2 \quad (4)$$

Discussion

In order to further explore the factors affecting the experimental results and the degree of influence, this paper chooses to use the response surface method to analyze the influence of the rotational speed of the cutter (A), conveying speed (B), cutter inclination (C) and the amount of overlap of the cutter (D) on the root cutting power (R). The design of the root-cutting device is based on a set of objective function and constraints. By establishing the objective function and constraints, the optimal parameter combinations of the designed root cutting device are found.



a) R (A,B,0,0) b) R(A,0,C,0) c) R(A,0,0,D)

d) R(0,B,C,0) e) R(0,B,0,D) f) R(0,0,C,D)

Fig. 7 – Three-dimensional response surface analysis of root cutting power interaction factors

As can be seen from Figure 7, the rotational speed of the cutter (A) and other factors response surface slope is larger, that is, the rotational speed of the cutter (A) on the root cutting power R has the greatest impact, conveying speed (B) is the next largest, while cutter inclination (C) and the amount of overlap of the cutter (D) on the root cutting power ® has a smoother impact, that is, the interaction factors in the C and D have the smallest impact on the root cutting power.

In order to achieve low-power and high-efficiency root cutting, this paper takes the root cutting power as the optimization index, and carries out parameter optimization analysis on the influencing factors such as the rotational speed of the cutter, conveying speed, tilting angle of the cutter, and overlapping amount of the cutter. The regression model is optimized and solved using the optimization module in Design Expert 8.0.6 software, and the established optimization model is shown in equation (5).

$$\min R$$
$$s.t.\begin{cases}200 \le A \le 400 \\ 0.3 \le B \le 0.5 \\ 5 \le C \le 15 \\ 15 \le D \le 25\end{cases} \quad (5)$$

CONCLUSIONS

(1) In order to improve the efficiency of mechanized harvesting of heading vegetables, a root cutting device for heading vegetables was designed. Through the LS-DYNA simulation experiments, the root cutting process of the root cutting device was simulated and the root cutting force and root cutting internal energy of three knife combinations were compared. The simulation results of the maximum root cutting force of the double serrated knife is the smallest, and the combination of the smooth-edged knife and the serrated knife has the smallest root cutting internal energy. Compared with the smooth-edged knife and serrated knife, the serrated knife has a better clamping effect on the heading vegetables root. The combination of serrated knife and smooth-edged knife is more optimal by combined analysis of the results of maximum root-cutting force and internal energy.

(2) In order to obtain the optimal structural parameters and operating parameters of the root cutting device, a quadratic rotary orthogonal combination test method was used to analyze the relationship between the main factors affecting the performance of the root cutting device (rotational speed of the cutter, conveying speed, inclination angle of the cutter, and overlap amount of the cutter) and the performance index (root cutting power), and the regression analysis, response surface, and multi-objective variable optimization methods were applied to design the bench test program. The results of the bench test showed that the optimal parameter combinations of the designed seed dispenser were: cutter speed of 200 rpm, conveying speed of 0.3 ms^{-1}, cutter inclination angle of 10°, and cutter overlap volume of 20 mm; and the model-predicted root-cutting power was 51.19W.

ACKNOWLEDGEMENT

The authors were funded for this project by the National Natural Science Foundation of China (Grant no. 52205273) and the Key Laboratory of Modern Agricultural Equipment, Ministry of Agriculture and Rural Affairs（2023007）.

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