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STRUCTURAL FORM AND FIELD OPERATION EFFECT OF CRAWLER TYPE BROCCOLI HARVESTER

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KEYWORDS

Broccoli, efficient harvesting, track self-propelled, low-loss cutting, structural component design.

ABSTRACT

Broccoli is increasingly favored by consumers as it is rich in vitamins and many other bioactive compounds. However, existing large tractor-drawn vegetable harvesting machinery is more suitable for large farmland and farm cultivation patterns. Therefore, this paper develops tracked broccoli harvesting equipment for small farmland and tests the ability to harvest broccoli. The tracked broccoli harvester developed in this paper is capable of traveling on its own in the field, cutting the stalks and transporting the broccoli bulbs. This paper analyses the working process of the cutting device and designs the working parameters. Through the cutting bench experiment, the optimal working parameters of the cutting device were determined as 456 r/min of rotational speed, 8.312 mm of overlap, and 0.255 m/s of pusher speed. In the field test, the broccoli leakage rate was 4.8%, the cutting qualification rate was 81.6%, the transport qualification rate was 95.62%, the damage rate was 3.96%, and the total loss rate was 8.55%. This structural model is an important technical support for broccoli harvesting equipment in China.

INTRODUCTION

Broccoli is increasingly favored by consumers because it is rich in vitamins and other bioactive compounds. According to FAO (Food and Agriculture Organization of the United Nations) statistics, the global production of broccoli and cauliflower in 2020 will be 25 million tons, with an area of 1.3 million hectares, and China's production will be the first in the world (Siomos et al., 2022). Broccoli in China is mainly harvested by hand, where broccoli florets are cut with a cutter and placed in baskets, which are collected on trucks at the edge of the field. After harvesting broccoli in the field, the broccoli needs to be sorted and boxed, which is a complicated harvesting process, consumes a lot of labor costs, has low working efficiency, and restricts the large-scale production of broccoli.

Stalk cutting is an essential part of the broccoli harvesting process. Stalk cutting is affected by many factors, and one of the most important factors is the cutter, such as the rotational speed of the cutter, the feed rate, and the area of the cutter. Scholars at home and abroad have researched how to reduce the energy consumption of stalk cutting. Researchers (Xiao & Lu, 2022) found that the cutting energy and maximum cutting force are directly proportional to the cross-sectional area and inversely proportional to the water content of the stalks. Experiments proved (Liu et al., 2012; Anderson et al., 2013) that different blades produce different cutting energy and cutting force during cutting. It is also possible to start with the cutting elements (Igathinathane et al., 2011; Igathinathane et al., 2010), to evaluate the effect of vertical, inclined and parallel placement of corn stover on cutting force, ultimate stress and energy consumption. In the process, the researchers found that it was cumbersome to conduct frequent cutting experiments. Therefore, they began to use simulation first, and then experimental methods to carry out the next study. The mechanical properties of plant stalks were studied (Maude et al., 2009; Li et al., 2020), and the stalks of corresponding plants were modeled. The process of cutting was simulated by finite element analysis software ANSYS/LS-DYNA simulation (Ali et al., 2019; Wang et al., 2023), and the range of values of operating parameters of the cutting device was finally obtained (Wang et al., 2023; Lu & Tu, 2023). The study shows that the design of cutting device based on the characteristics of specific crop stalks can meet the operational requirements (Wu et al., 2022; Irsel, 2022) and effectively improve the operational efficiency.

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FIGURE 1. Manual harvesting process of broccoli.

The structural integrity of the machine and the smoothness of the process is also an important aspect of broccoli harvesting. The components of a broccoli harvester need to be designed in conjunction with the broccoli harvesting process. Researchers have analyzed the four major processes of plucking, cutting, transporting, and defoliating (Li et al., 2020; Zhang et al., 2022 a; Zhang et al., 2022 b) to model and design the harvester. The components of the harvester were optimized and designed with the objectives of improving the harvesting efficiency and reducing the breakage rate of machine harvesting. To improve the accuracy of harvesting, some researchers also studied broccoli texture and color to achieve automated precision harvesting by identifying the location of broccoli (Zhao et al., 2023; Kusumam et al., 2017). Researchers (Birrell et al., 2020) developed a lettuce harvesting system that includes a vision system, customized end-effector, and software; the vision system for sorting and localization, and the end-effector for nondestructive harvesting. Harvesting methods that visually recognize broccoli locations are relatively accurate (Dixit & Rawat, 2022), but the harvesting process is time-consuming and inefficient.

In summary, the existing large tractor-drawn vegetable harvesting machinery is more suitable for large-scale farmland and farm planting mode, and it is difficult to adapt to the planting mode of small-scale farmland and family farms represented by China. Therefore, this paper designs a tracked broccoli harvester, that can walk on its own in the field, cut broccoli stalks, and complete the transportation, sorting and packing of broccoli, for the characteristics of small-field operation.

MATERIAL AND METHODS

Overall structural form

According to the cultivation characteristics and technical requirements of broccoli, single row one-time self-propelled harvesting is adopted as well as the mechanical harvesting process of cutting, conveying and manual sorting. The broccoli harvester should be able to realize the operational functions such as stalk cutting, conveying and lifting, auxiliary sorting and field handling. According to the scheme of the broccoli mechanized harvesting process, the overall structure of the self-propelled broccoli harvester designed by using the three-dimensional design software SOLIDWORKS is shown in Fig.2.

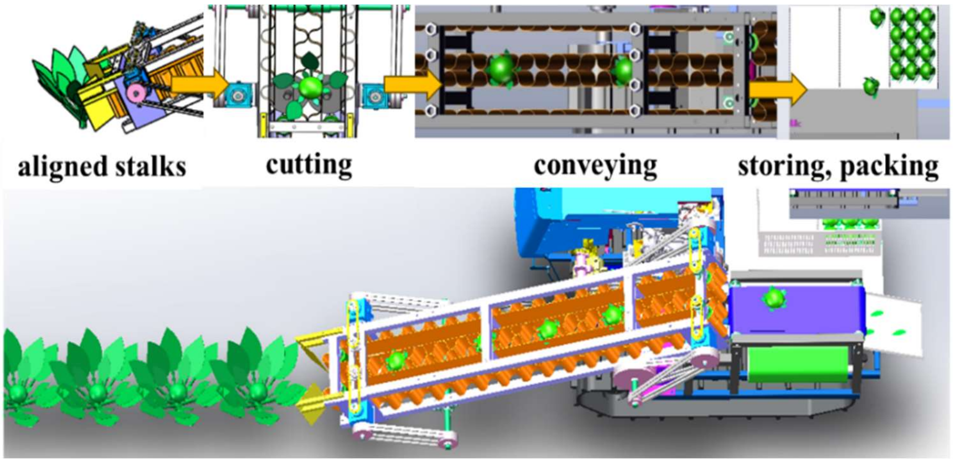


FIGURE 2 Broccoli harvester operation process.

During harvesting, the inclination angle is changed by adjusting the hydraulic cylinder so that the cutter is at the right height. During broccoli harvesting operation, the leaf-supporting device at the front end of the conveying unit holds the stalks in the middle of the front end of the double clamping conveyor belt. As the machine advances, the broccoli bulb and part of the leaves are held in place by the clamping conveyor belt. The double disk cutter below the clamping conveyor belt cuts off the broccoli stalks and leaves. Broccoli florets are conveyed under the gripping action of the conveyor belt. The conveyor transports the broccoli to the sorting table. Workers strip the remaining leaves and sort the broccoli into baskets. Broccoli leaves fall to the ground along the leaf discharge chute.

Cutting device design

Structural forms

The cutting device is one of the key components of broccoli harvesting equipment, and its main function is to remove broccoli stalks, and the cutting efficiency and cutting effect of the cutting device are of great significance to the operation quality and operation efficiency of the broccoli harvester. The research of scholars at home and abroad on the cutting device for kale, cabbage and other bulbous vegetables mainly focuses on the two structure types of serrated knife and circular knife (Jin et al., 2016; Du et al., 2014), and the experimental results show that the root-cutting operation can be better accomplished by a single or two relatively rotating circular cutting knives. Therefore, to balance the force when cutting broccoli stalks and meet the needs of cutting efficiency and speed, the structure of two symmetrically arranged double-disk cutting knives is adopted, as shown in Fig.3.

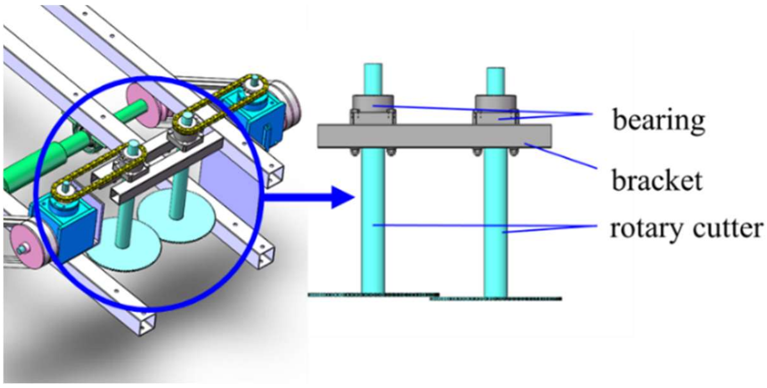


FIGURE 3. Structure of the cutting device.

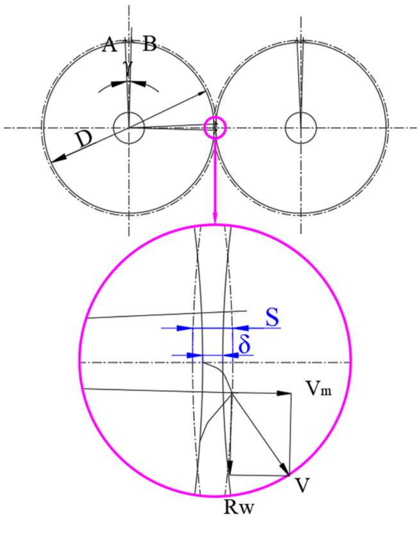


FIGURE 4. Velocity synthesized image of the circular knife in motion.

Cutting knife parameter design

The motion of the blade on the disc knife is analyzed, as shown in Fig.4. In Fig. 4, A and B, respectively, for the sawtooth disc on the top circle of any two connected sawtooth apexes, γ for the two connected sawtooth apex angle, that is, the cutting knife relative to the forward direction of the machine's angle of rotation, v, any disc apex motion combined speed, Rw and v_m for the corresponding to the disc apex of the tangential velocity and normal velocity.

The working width of the double disc cutter is

$$H = D(1 - \sin\gamma) + \delta - l' \quad (1)$$

Where:

H is the width of the working area of the double disc cutter, mm;

D is the diameter of the track circle at the midpoint of the top of the cutter, mm;

δ is the minimum distance between the diameter of the track at the midpoint of the top of the cutter and the other disc cutter, mm;

l' is the working length of the cutter, mm, and

γ is the angle of the two adjacent teeth of the disc cutter, °.

The diameter of the trajectory of the middle point of the top of the cutter needs to be determined according to the distance between the broccoli rows. To avoid cutting into the broccoli of the adjacent rows, the trajectory of the middle point of the top of the cutter needs to be spaced at a certain distance from the broccoli of the adjacent rows, i.e.

$$S \geq D + \Delta l + \frac{d_c}{2} \tag{2}$$

Where:

Δl is the spacing distance between the trajectory of the top midpoint of the cutter and the broccoli in the neighboring rows, mm,

d_c is the broccoli stalk, mm.

After determining the rotational speed of the cutting knife n and the forward speed of the machine v_{mmax}, make the value of δ equal to the value of l, i.e., the two cutting discs are just in contact, and in this way, the critical value of the critical cutting disc working area width H can be calculated. Under the condition of meeting the cutting quality, the cutting cutter disk rotational speed is large, and the width of the working area of the cutting cutter disk can be appropriately reduced. However, to avoid leakage, that is, in the root cutting process within the cutting width, there should not be harvested but not cut and harvested phenomenon, and at the same time to make the root can be cut off, need to meet the following conditions

$$\begin{cases} S_m \leq l' \\ S_m = \frac{60 v_m}{Zn} \\ l' \geq d_{max} \end{cases} \tag{3}$$

Where:

Z is the number of cut teeth,

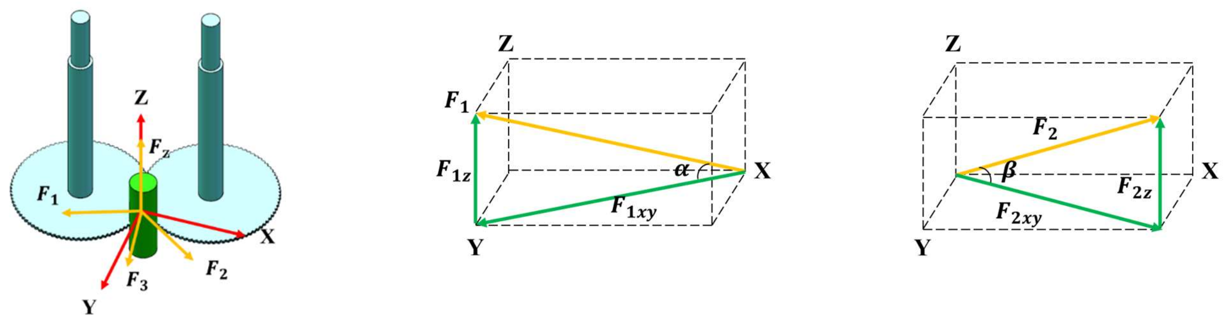
d_{max} is the maximum diameter of the root, mm.

In this paper, the broccoli field planted in Xiangshui County, Yancheng City, Jiangsu Province, China is taken as an example, the planting row spacing is S=400mm, and the average diameter of broccoli bulb d_c=38mm, and Δl=200mm, and it is obtained through a calculation that the diameter of the cutting disk D⩽281mm, and the value is used as the initial reference value for the design of the double disk cutter.

The average maximum diameter of broccoli stalks, d_{max}=38mm, was used as the minimum cutting knife working length. The maximum working speed of harvesting equipment advancing v_{mmax}=1.2m/s. According to the above calculation, take the reference cutting disk diameter D=220mm, the larger number of cutting teeth Z=88, the calculation can be obtained, the critical condition of no leakage of cutting disk speed n⩾22r/min, combined with the calculated value and the test value, to determine that the value of the cutting disk speed n take the value of the range of 100-500r/min.

Cutting force analysis

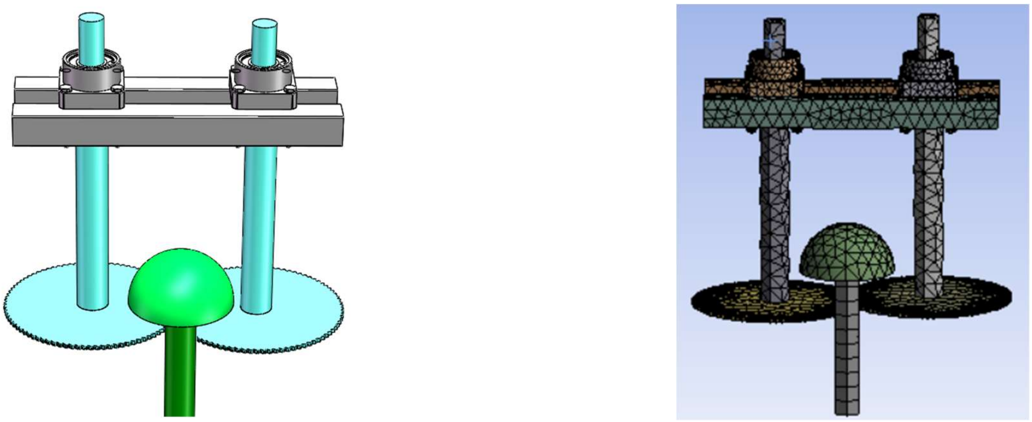
During the cutting process, the cutting position is analyzed by the force (shown in Fig. 5), the broccoli stalk receives cutting force F1, F2 and friction force F3 in X, Y and Z. During the actual cutting process, these forces change in real-time, which is difficult to monitor, and therefore can be tested with the help of the ANSYS software for its Simulation test.



(a) stress analysis (b) Decomposition of F1 (c) Decomposition of F2

FIGURE 5. Stalk force analysis.

As shown in Fig. 6, the broccoli stalk model (Zhao et al., 2022) is established, and the broccoli stalk consists of three parts: epidermis, xylem, and pith, and the material attributes are set separately for meshing. To simulate the broccoli harvesting state, fixed support constraints are added to the upper and lower sections of the stalk entity, and remote displacements are added to the two disk knives to produce feed displacements and relative rotational constraints in the plane of the disk knives. Click Solution to solve the model, and the stalk cutting and fracture model is shown in Fig.6.



(a) Simulation cutting schematic (b) Broccoli stalk cutting model meshing

FIGURE 6. Cutting simulation.

The broccoli stalk-cutting process has more influencing factors, to study the influence of each factor on the cutting effect of broccoli stalk, a one-factor simulation is carried out by controlling variables. The feed rate of the disk cutter, the coincidence length of the two cutter disks, and the rotational speed of the disk cutter are selected as variables, and five level values are selected for each variable, as shown in Table 1.

TABLE 1. Factors and levels of broccoli stalk cutting simulation.

Level	Factor		
	Feedrate /m/s	Coincidence length /mm	Rotational speed/rpm
1	0.01	1	100
2	0.11	6	200
3	0.21	11	300
4	0.31	16	400
5	0.41	21	500

Cutting Experiment

According to the actual working conditions of the broccoli harvester field operation, a stalk-cutting test bench was built as shown in Fig. 7. The test bench consists of a switching power supply, a cutting device, and a stalk propulsion device. The cutting device includes a rotary cutter, a motor, and a motor speed controller, and the stalk propulsion device includes a slider slide, an electric actuator, an actuator and a governor.

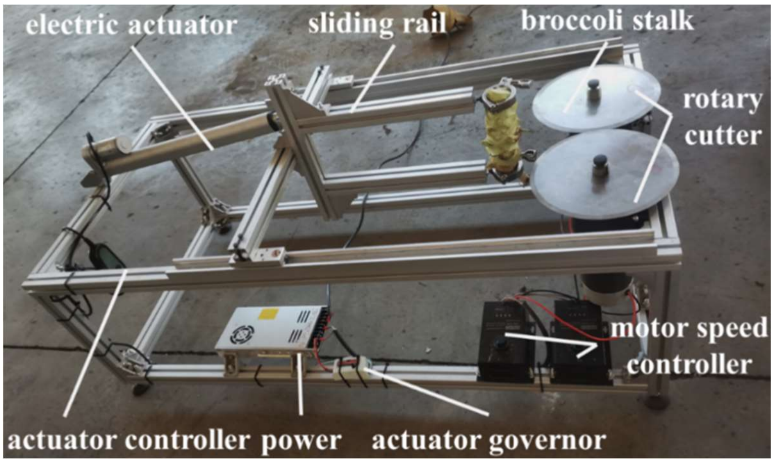


FIGURE 7. Broccoli stalk cutting test stand.

In the broccoli stalk cutting test, the stalks are fixed on the bracket by clamps, and the motor mounting position is adjusted so that the overlap of the two-disc cutter knives reaches the specified value. The cutting effect was scored according to the cutting breakage and the morphology of the stalk section, etc., and the scoring values were from 1 to 10.

Design of working parts

Conveyor design

The broccoli clamping conveyor designed in this paper adopts double conveyor belts in longitudinal rows, and to reduce the damage to broccoli and provide a stable clamping effect, the surface of the conveyor belts is equipped with arc-shaped grooves made of PVC to ensure the stable conveyance of broccoli balls without sliding.

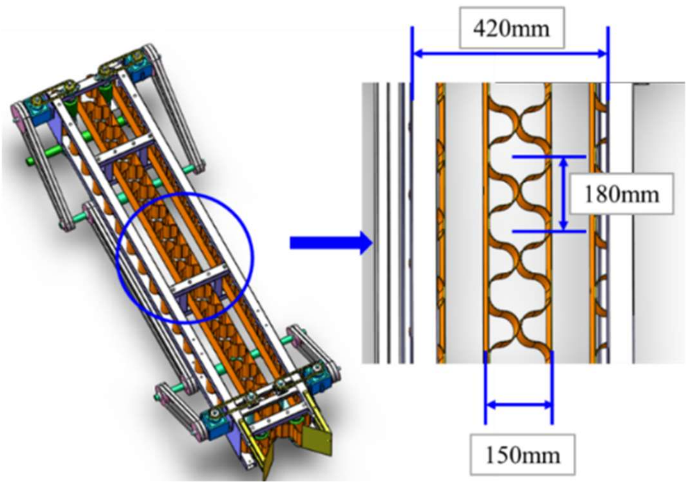


FIGURE 8. Conveyor model.

The Broccoli harvester conveying device is shown in Fig. 8, the row spacing of broccoli planting is 400mm, so the width of the broccoli harvester conveying device is designed as 420mm. The diameter of a broccoli bulb is generally 130mm, due to the harvesting process of the leaves wrapped with the bulb into the clamping conveyor, so the distance between the inner surface of the clamping conveyor belt is designed as 150mm, and the elasticity of the conveyor belt can adapt to different diameter of broccoli bulb, so the width of the conveyor belt is designed as 420mm. The elasticity of the conveyor belt can make it adapt to different diameters of broccoli bulbs.

Conveying speed

Conveying needs to be coordinated with the machine walking and stalk cutting process, if the conveying speed is too slow, it will lead to the broccoli plant tilting forward before cutting, and at the same time the cut broccoli bulbs gathering in the conveying device will cause the load to increase and clogging; if the conveying speed is too fast, it will affect the stability of the cutting and conveying, and reduce the quality of the operation. Therefore, as shown in Fig. 9, the conveying line speed of the clamping conveyor belt should be equal to the forward speed of the harvester, i.e.:

$$v_m = v_a \tag{4}$$

Where:

v_m is the travel speed of the harvester, m/s;

v_a is the linear speed of the clamping conveyor belt, m/s.

The overall dimensions of the conveyor unit are shown in Fig.9 and conform to the following relationships:

$$h = l \cdot \sin\alpha \tag{5}$$

Where:

h is the height of the articulation point of the conveying device from the ground, m;

l is the length of the conveying device, m;

α is the angle between the conveying device and the ground, degrees.

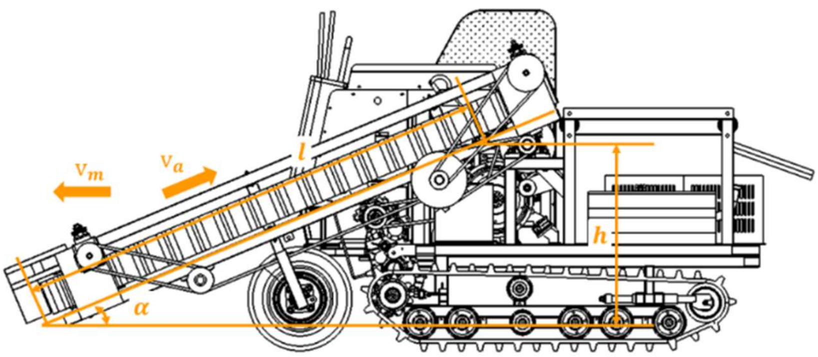


FIGURE 9. Conveying speed analysis

Transmission system

The power transmission schematic diagram of the broccoli harvester is shown in Fig.10, and the power system consists of mechanical transmission and electrical transmission. The mechanical transmission includes the engine, belt drive, chain drive, gearbox and conveyor roller and other components, and the power source is the engine. The electrical transmission includes the battery, the cutter motor and the sorting table conveyor motor.

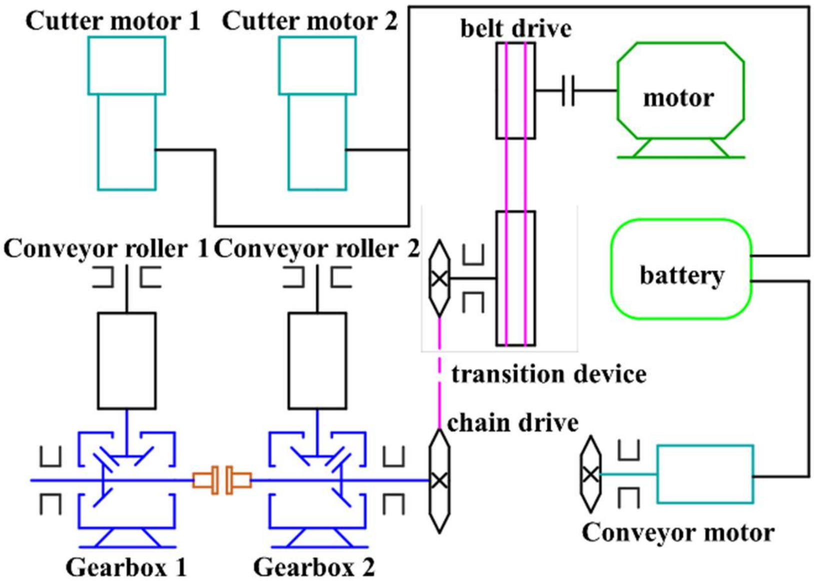


FIGURE 10. Broccoli harvester drive train.

During the harvesting operation, it is usually driven at low speed, at this time, the rated speed of the output shaft of the engine is 2050rpm, and the maximum travel speed is 4.04km/h. The linear speed of the clamping conveyor belt is the same as the travel speed of the machine, so the linear speed of the clamping conveyor belt is 1.14m/s, and the diameter of the conveying rollers is 100mm, so the rotational speed of the conveying rollers is 217.8rpm. The reduction ratio of the selected three-axis gearbox is 1:1, so the input speed of the gearbox is 217.8rpm. The rotational speed distribution is shown in Fig.12. The reduction ratio of the selected three-axis gearbox is 1:1, so the input speed of the gearbox is 217.8 rpm. The speed distribution is shown in Fig.11.

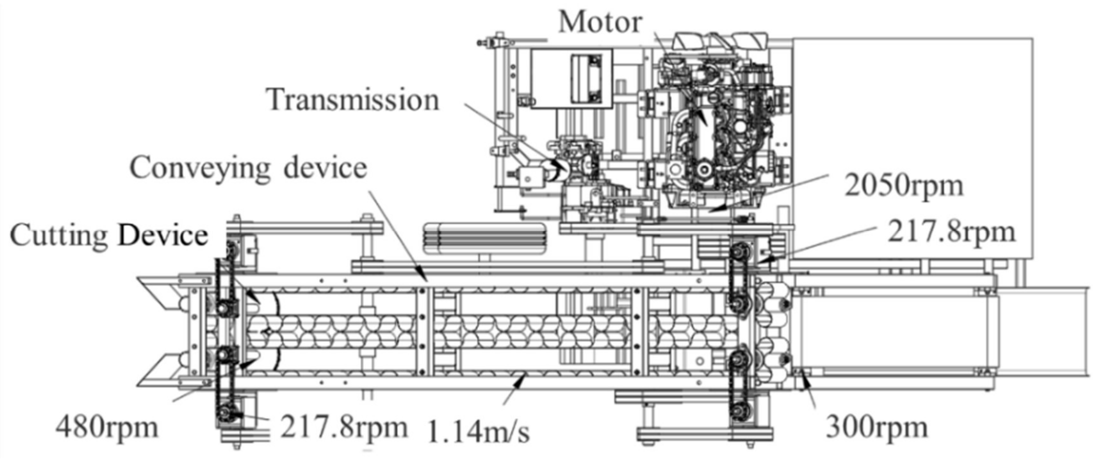


FIGURE 11. Schematic diagram of rotational speed.

The ratio i_1 of the belt drive is

$$i_1 = \frac{d_2}{d_1} = \frac{n_1}{n_2} = 2.82 \tag{6}$$

Where:

d_1 is the diameter of the engine output shaft pulley, 83mm;

d_2 is the diameter of the transition device pulley, 234mm;

n_1 is the speed of the engine output shaft, 2050rpm;

n_2 is the speed of the transition device shaft, rpm.

Thus the transition device shaft speed n_2 is 726 rpm.

The ratio i_2 of the chain drive is:

$$i_2 = \frac{z_1}{z_2} = \frac{n_2}{n_2} = 3.33 \tag{7}$$

Where:

z_1 is the number of teeth of the gearbox sprocket, 50;

z_2 is the number of teeth of the transition device sprocket, 15;

n_2 is the rotation speed of the transition device shaft, 726 rpm;

n_2 is the rotation speed of the gearbox input shaft, 217.8 rpm.

Indoor trial

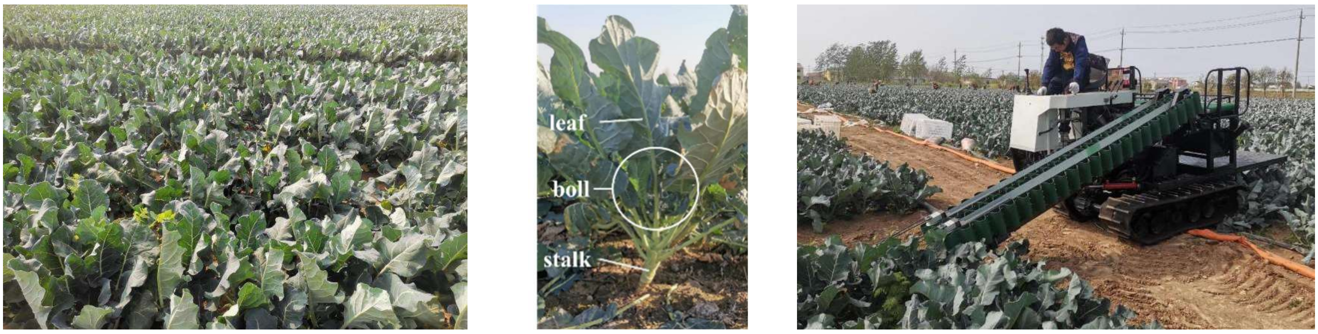
To preliminarily explore the operating effect of the whole machine, field trials were simulated indoors. Mature broccoli planted at the same time and grown in the same plot were selected. The broccoli plants were fixed on the ground through jigs, and the plants were spaced about 38 cm apart, which was consistent with the spacing of the plants planted in the field, as shown in Fig.12. Morphological parameters of the broccoli plants were measured before the start of the trial, and at the end of the trial, the shape parameters of the flower bulbs and stalk stubble after harvest were counted.

(a) Broccoli plant samples (b) Broccoli mechanical harvesting indoor trials

FIGURE 12. Indoor trial.

Field trial

To further test the operation effect of the broccoli harvester, it went to the broccoli planting base in Xiangshui County, Yancheng City, Jiangsu Province, to conduct a field trial. The broccoli mechanical harvesting test field is shown in Fig.13(a), the broccoli planted in the field is shown in Fig. 13(b), and the field trial process is shown in Fig. 13(c).



(a) Broccoli mechanical harvesting test field (b) Broccoli in the field (c) Self-propelled broccoli harvester field trial

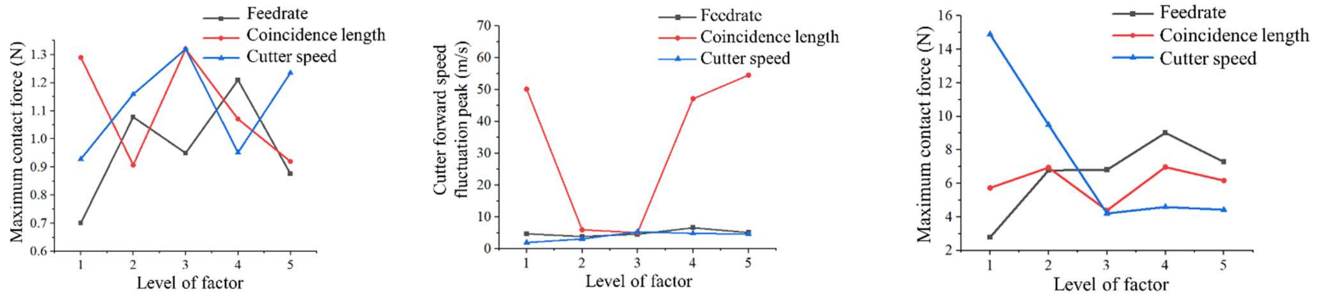
FIGURE 13. Field trial.

RESULTS AND DISCUSSION

Simulated cutting effect

Single-factor test

In the single-factor simulation of broccoli stalk cutting, according to Table 1, the relevant parameters are set for solving, and the data results obtained from solving are exported and processed to obtain the simulation results of broccoli stalk cutting by disc knife shown in Fig. 14. During the cutting process, the cutter will be subjected to resistance, and the unbalanced impact will lead to unstable operation of the cutter, and the forward speed of the cutter will vary with ups and downs around the set value, which is defined as the fluctuation of the forward speed of the cutter.



(a) Maximum equivalent force on the stalk

(b) Peak fluctuations in the forward speed of the cutter

(c) Maximum contact force between the cutter and the stalk

FIGURE 14. Simulation results of cutter cutting stalks.

As can be seen from Fig.14: To ensure that the cutting force is large enough, the best cutter operating parameters for the feed speed of 0.31m/s, the amount of overlap of 1mm and the speed of 300rpm. In conclusion, to produce a larger equivalent force and larger shear force of broccoli stalks, and at the same time to ensure the smooth operation of the disc knife and cutting efficiency, the operating parameters of the cutter knife are the feed speed of 0.21-0.31m/s, the amount of overlap of the two discs of the cutter knife is 1-11mm, and the rotational speed of the cutter knife is 300-500rpm.

Multifactor test

The Broccoli stalk cutting process is subject to the simultaneous action of several factors, to investigate the effect of multi-factor interaction on the cutting effect of broccoli stalk, according to the results of single-factor simulation, design a three-factor three-level simulation orthogonal test. The factor levels and responses are shown in Table 2.

TABLE 2. Broccoli stalk cutting simulation factors, levels and responses.

Factor	Unit	Level			Responsive	Unit
A: Feedrate	m/s	0.21	0.26	0.31	R1: Maximum equivalent force on the stalk	MPa
B: Coincidence length	mm	1	6	11	R2: Peak fluctuations in the forward speed of the cutter	mm/s
C: Cutter speed	r/m	300	400	500	R3: Maximum contact force between the cutter and the stalk	N

The three-factor, three-level orthogonal test simulation of Box-Behnken design using Design-Expert software was carried out for 17 simulations and the maximum equivalent force of the cutter to cut the stalks, the peak of the fluctuation of the forward speed of the cutter, and the maximum contact force of the cutter on the stalks were counted during the simulation, as shown in Table 3.

TABLE 3. Simulation data.

Sequences	Factor			Responsive		
Run	A/m/s	C/mm	D/rpm	R1/MPa	R2/mm/s	R3/N
1	0.21	6	500	0.99954	39.96	7.4476
2	0.21	1	400	0.91304	36.77	6.8834
3	0.21	11	400	0.8303	38.26	7.3324
4	0.21	6	300	0.82254	38.54	7.2396
5	0.26	1	500	1.2541	36.4	7.7459
6	0.26	11	500	1.1674	38.77	7.7599
7	0.26	6	400	1.1449	33.29	6.9225
8	0.26	6	400	1.2013	34.28	6.9046
9	0.26	6	400	1.2498	32.88	6.8081
10	0.26	6	400	1.1449	30.68	6.9143
11	0.26	6	400	1.2498	32.56	6.8122
12	0.26	11	300	0.92397	37.47	8.3645
13	0.26	1	300	0.91348	37.33	9.184
14	0.31	1	400	1.2632	37.28	9.1501
15	0.31	11	400	0.85783	38.66	6.6314
16	0.31	6	300	0.95669	39.64	9.6033
17	0.31	6	500	1.083	40.86	6.8667

Mathematical equations obtained by fitting the experimental data may produce inaccurate results, so it is necessary to use analysis of variance (ANOVA) to test the significance and accuracy of the models (Chen et al., 2022; Rashidi et al., 2021; Sarkar & Raheman, 2023). The ANOVA for the maximum equivalent force model of the stalk, the peak fluctuation model of the forward speed fluctuation of the cutter, and the maximum contact force model are shown in Tables 4-6 below.

TABLE 4. Analysis of variance of the maximum allelopathic force model for stalks.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.3780	9	0.0420	6.49	0.0110	significant
A-A	0.0443	1	0.0443	6.85	0.0346	
B-B	0.0398	1	0.0398	6.15	0.0422	
C-C	0.0984	1	0.0984	15.22	0.0059	
AB	0.0260	1	0.0260	4.02	0.0849	
AC	0.0006	1	0.0006	0.0993	0.7618	
BC	0.0024	1	0.0024	0.3651	0.5648	
A^2	0.1156	1	0.1156	17.87	0.0039	
B^2	0.0186	1	0.0186	2.87	0.1342	
C^2	0.0189	1	0.0189	2.92	0.1310	
Residual	0.0453	7	0.0065			
Lack of Fit	0.0343	3	0.0114	4.15	0.1015	not significant
Pure Error	0.0110	4	0.0028			

TABLE 5. Analysis of variance of the model for the peak fluctuation of the forward speed of the cutter.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	128.83	9	14.31	12.38	0.0016	significant
A-A	1.06	1	1.06	0.9153	0.3706	
B-B	3.62	1	3.62	3.13	0.1202	
C-C	1.13	1	1.13	0.9793	0.3553	
AB	0.0030	1	0.0030	0.0026	0.9606	
AC	0.0100	1	0.0100	0.0086	0.9285	
BC	1.24	1	1.24	1.08	0.3343	
A^2	55.21	1	55.21	47.74	0.0002	
B^2	7.83	1	7.83	6.77	0.0353	
C^2	47.85	1	47.85	41.38	0.0004	
Residual	8.09	7	1.16			
Lack of Fit	0.8088	3	0.2696	0.1480	0.9258	not significant
Pure Error	7.29	4	1.82			

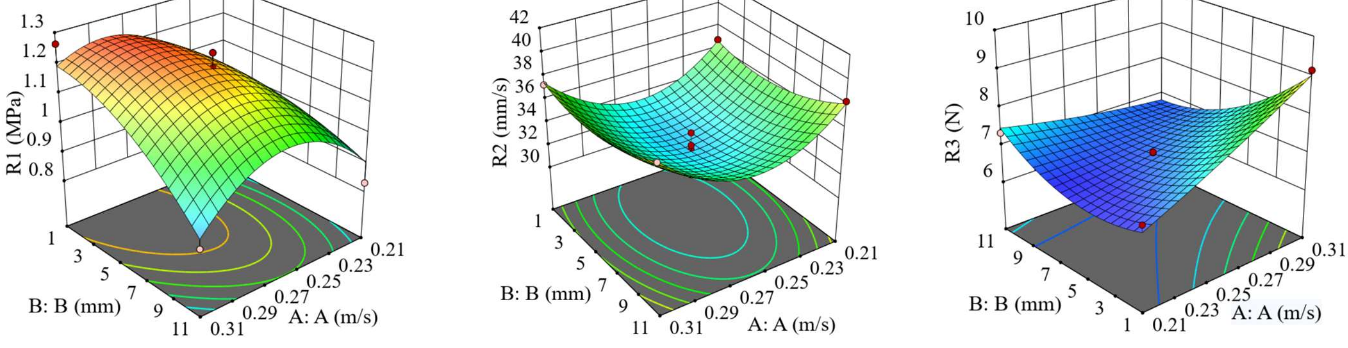
TABLE 6. Analysis of variance for the maximum contact force model.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	14.16	9	1.57	44.38	< 0.0001	significant
A-A	1.40	1	1.40	39.54	0.0004	
B-B	1.03	1	1.03	29.15	0.0010	
C-C	2.61	1	2.61	73.69	< 0.0001	
AB	2.20	1	2.20	62.11	0.0001	
AC	2.17	1	2.17	61.15	0.0001	
BC	0.1738	1	0.1738	4.90	0.0624	
A^2	0.0245	1	0.0245	0.6920	0.4329	
B^2	1.28	1	1.28	36.01	0.0005	
C^2	2.98	1	2.98	83.93	< 0.0001	
Residual	0.2482	7	0.0355			
Lack of Fit	0.2351	3	0.0784	24.00	0.0051	significant
Pure Error	0.0131	4	0.0033			

TABLE 7. Model fitting effects.

Model	Standard deviation	Average	Coefficient of variation /%	Goodness of fit	Signal-to-noise ratio
R1:Maximum equivalent force on the stalk	0.0804	1.06	7.61	0.9020	8.1553
R2:Peak fluctuations in the forward speed of the cutter	1.08	36.69	2.93	0.9409	9.3141
R3:Maximum contact force between the cutter and the stalk	0.1883	7.56	2.49	0.9828	19.5088

The fitting statistics of the three models are shown in Table 7, and the ratio of the standard deviation to the mean is called the coefficient of variation, which is less than 10% for all three models. The goodness-of-fit is >0.9, indicating that the regression equations are in good agreement with the simulation results, and the established models can reflect the simulation data well. In Design-Expert software, a signal-to-noise ratio (Adeq Precision) greater than 4 is desirable, and the signal-to-noise ratios of the three models fitted are all >4, therefore, all three models are reliable.



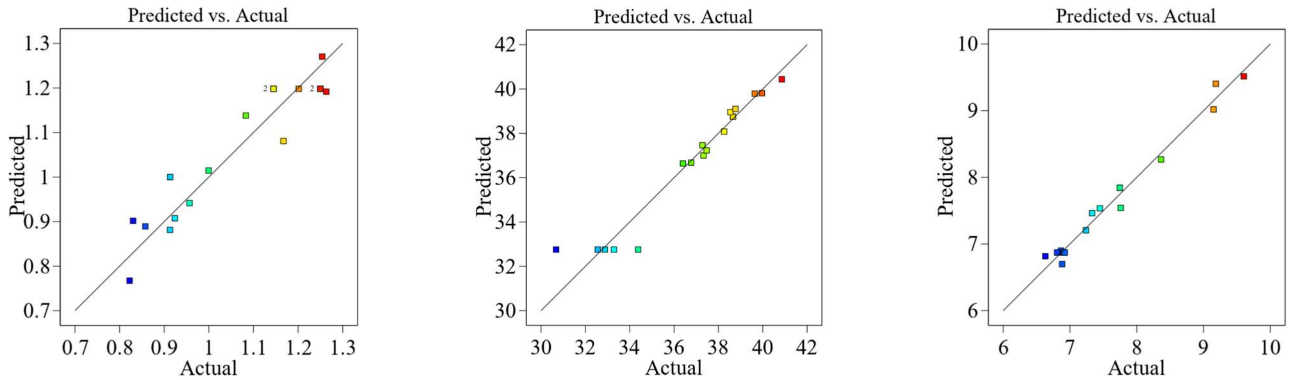
(a) Maximum equivalent force on the stalk

(b) Peak fluctuations in the forward speed of the cutter

(c) Maximum contact force

FIGURE 15. Response surface.

From Fig. 15(a), it can be seen that, when the degree of overlap is certain, the maximum equivalent force of the stalk increases and then decreases with the acceleration of the feed speed; when the feed speed is certain, the equivalent force decreases with the increase of the degree of overlap. From Fig. 15(b), too much or too little overlap with the feed rate can lead to large speed fluctuations and an unsteady cutting process.,. From Fig.15(c), too much or too little overlap with the feed rate can lead to excessive contact forces and increased cutter wear.



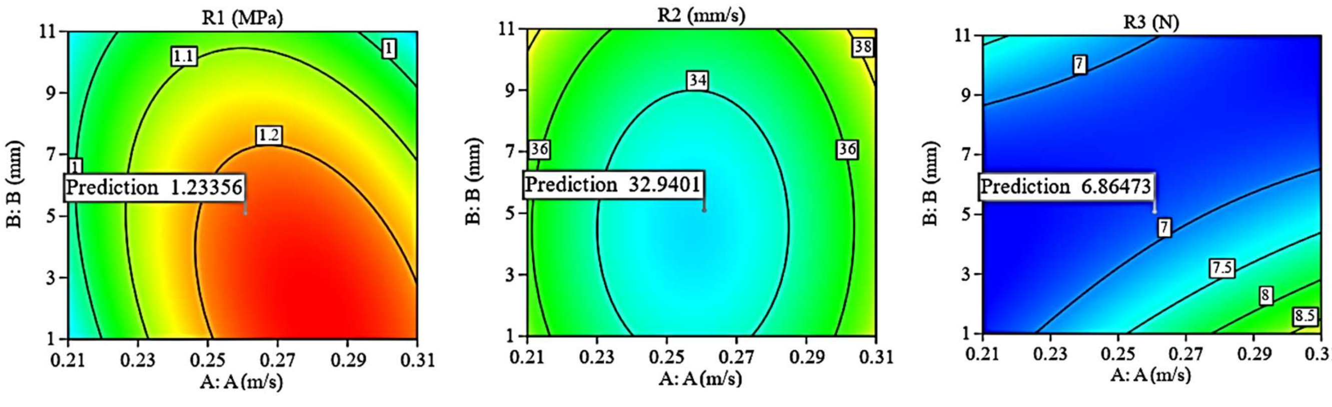
(a) Maximum equivalent force on the stalk

(b) Peak fluctuations in the forward speed of the cutter

(c) Maximum contact force

FIGURE 16. Comparison of model prediction and simulation results.

A comparison of model prediction and simulation results is shown in Fig. 16, in which the horizontal coordinates are the actual values and the vertical coordinates are the model prediction results and the closer the horizontal and vertical coordinates of the data points are, the more points fall on the solid line in the figure, the more points indicate that the true value of the point is close to the predicted value with a smaller error. Figure b has the best fit, figure c is better, and figure a is worse.



(a) Feedrate

(b) Coincidence length

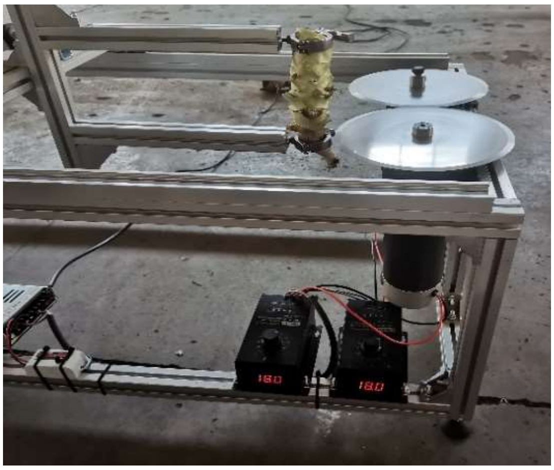
(c) Cutter speed

FIGURE 17. Optimal parameter solution results.

Based on the above prediction model, the optimal parameter solution results were calculated as shown in Fig. 17, with the optimal parameters: feed speed 0.261 m/s, overlap 5.1 mm, and rotational speed 423.5 r/min. Under these conditions, the maximum equivalent force of the stalk was 1.23356 MPa, the peak of the fluctuation of the cutter forward speed was 32.9401 mm/s, and the maximum contact force was 6.86473 N. The optimal parameters are shown in Fig. 21.

Cutting experiment results

The broccoli stalks were fixed on the constructed experimental table as shown in Fig.18(a) for the cutting test. The cut stalks are shown in Fig.18(b), and the stalk sections were relatively flat.



(a) Broccoli cutting bench test

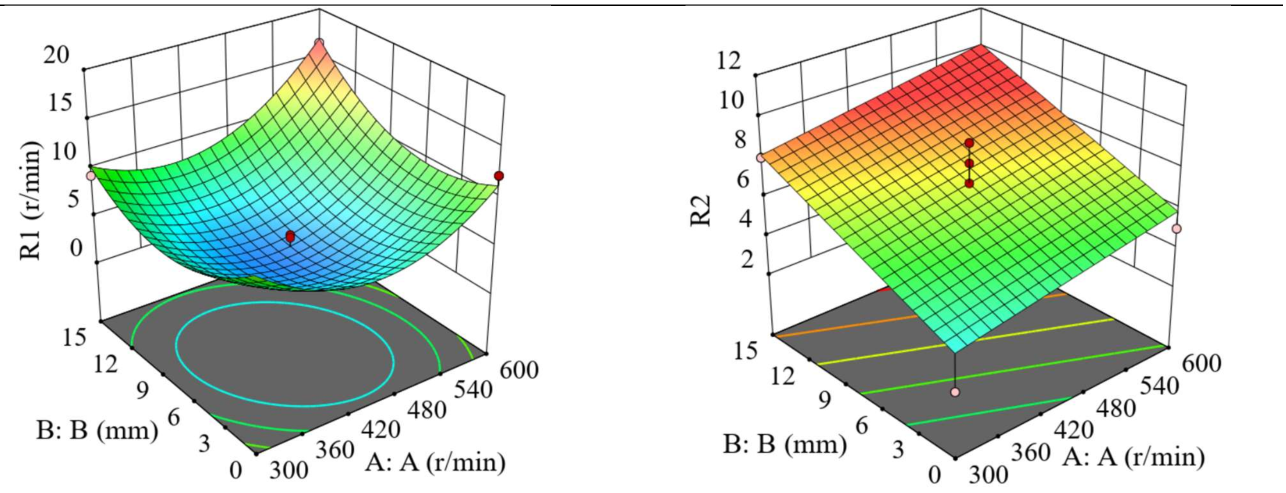
(b) Cut stalk sections

FIGURE 18. Cutting experiment results.

In Design-Expert software, 17 tests were conducted using the three-factor, three-level orthogonal test method, and the test conditions and results are shown in Table 8.

TABLE 8. Experimental data.

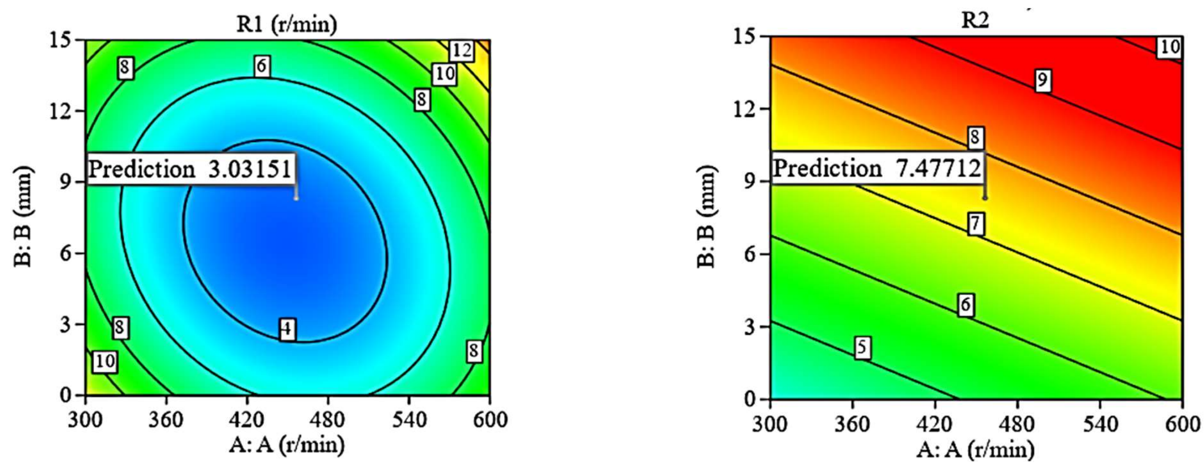
Sequences	X_1:Rotational speed/rpm	X_2:Coincidence length /mm	X_3: Putter forward speed /m/s	R1: Fluctuation of cutter speed/rpm	R2: Cutting effect score
1	300	7.5	0.1	8.5	7
2	600	0	0.2	12.2	5
3	450	0	0.3	4.7	6
4	600	7.5	0.1	16.2	9
5	450	7.5	0.2	4.6	6
6	300	0	0.2	11.5	2
7	600	15	0.2	16.4	8
8	450	7.5	0.2	1.9	8
9	600	7.5	0.3	8.8	9
10	450	7.5	0.2	1.5	7
11	300	15	0.2	9.3	8
12	450	7.5	0.2	4.3	9
13	300	7.5	0.3	10.9	6
14	450	7.5	0.2	6.7	8
15	450	15	0.3	8	9
16	450	0	0.1	11.5	3
17	450	15	0.1	15..9	8



(a) Fluctuation of cutter speed (b) Cutting effect score

FIGURE 19. Response surface.

From Fig. 19(a), too much or too little overlap with the rotational speed can lead to large speed fluctuations and an unsteady cutting process. And the unsteady phenomenon is more serious when the speed is too large. From Fig. 19(b), both the overlap and the increase in rotational speed improve the cutting results and result in higher cutting scores.



(a) Fluctuation of cutter speed (b) Cutting effect score

FIGURE 20. Optimal parameters.

According to the above prediction model, the optimal parameter solution is calculated as shown in Fig. 20. The optimal parameters: the rotational speed of 456r/min, the overlap of 8.312mm, and the actuator speed of 0.255m/s. Under this condition, the minimum value of rotational speed fluctuation is 3.03151r/min, and the value of the cutting effect is 7.47712.

Indoor work effect

The tracked broccoli harvester includes four main devices: a cutting device, a conveyor belt, a sorting table, and tracked undercarriage, as shown in Fig.21. Mechanically harvested broccoli bulbs are shown in Fig.22. Both stalks and leaves were neatly severed, and the cutting pattern was the same as that of the stalks on the flower bulbs.

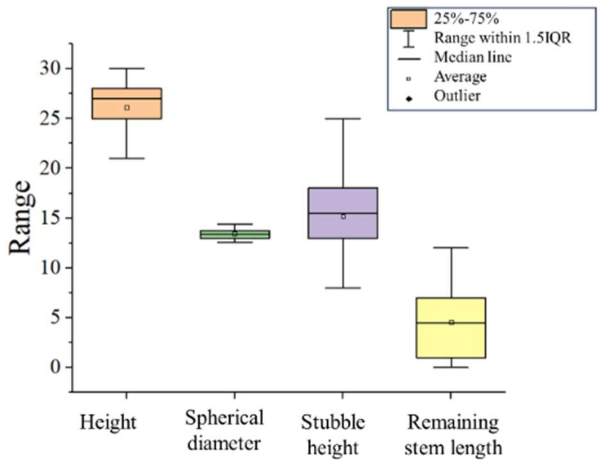
FIGURE 21. Caterpillar broccoli harvester.

(a) Broccoli mechanically harvested stubble

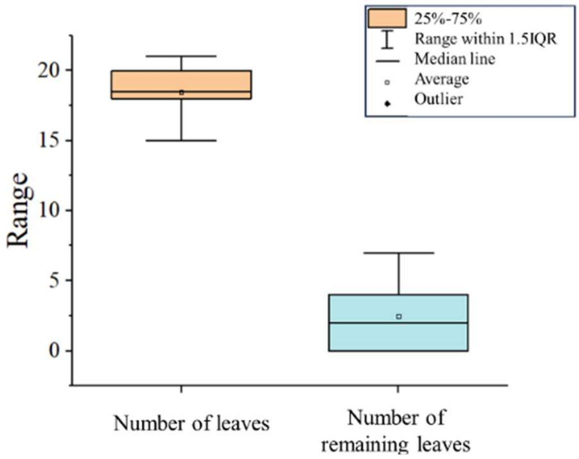
(b) Broccoli bulbs after mechanical harvesting

FIGURE 22. Mechanically harvested broccoli.

The morphological parameters of broccoli plant samples and post-harvest are shown in Fig. 23. The average distance between the top of the floral bulb and the ground of the selected broccoli plants was 26.14 cm, the average number of leaves was 18.45, and the diameter of the floral bulb was 13.43 cm. As can be seen from Fig. 23(a), the three sets of data were within the range of 1.5 IQR, and none of them had any outliers, the growth and maturity of the selected broccoli samples were consistent.



(a) Parameters of height, spherical diameter, stubble height, residual stalk length



(b) Parameters of number of leaf blades, number of residual leaf blades

FIGURE 23. Indoor work effect.

As can be seen from Fig.23(b), the mean value of post-harvest stalk stubble height was 15.82 cm, the mean value of residual stalk length was 4.55 cm, and the mean value of the number of residual leaves was 2.5. The three sets of data were all within the range of 1.5 IQR, with no outliers, indicating that the tracked broccoli harvester designed in this paper had consistent cutting effects on different broccoli samples.

Field operation effect

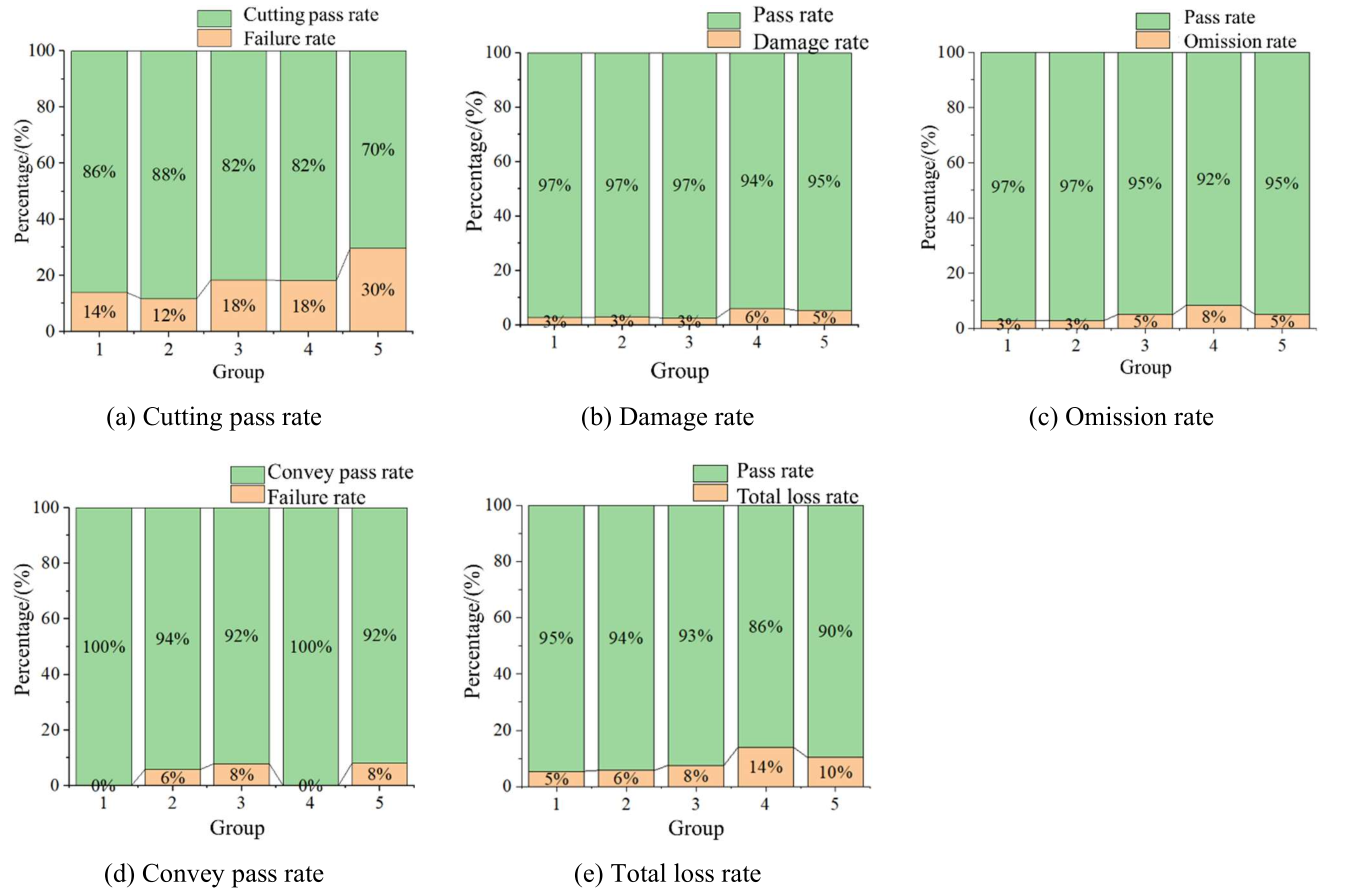
Broccoli harvester field trials were conducted five times, and the number of broccoli plants in each trial area ranged from 35 to 40, and the results are shown in Table 9.

FIGURE 24. Field operation process and effect of self-propelled broccoli harvester.

TABLE 9. Results of broccoli harvester field performance tests.

Test indicators	Number					Average
	1	2	3	4	5	
Number of broccoli/plant	37	35	40	36	39	37.4
Traveling speed/km • h^{-1}	1.52	1.80	2.13	2.88	3.74	2.42
Number of missed cuts/plant	1	1	2	3	2	1.8
Number of qualified cutting/plant	31	30	31	27	26	29
Number of qualified conveyors/plant	36	32	35	33	34	34
Operating efficiency/hm^2/h	0.061	0.072	0.085	0.115	0.150	0.097

Table 10 was analyzed to obtain the results of broccoli harvester performance as shown in Fig.25, and the indexes of productivity, root-cutting pass rate, conveyor success rate, and total loss rate for the harvester operation were calculated by counting the total number of broccoli in the test area, the amount of missed harvests, and the number of losses.



(a) Cutting pass rate (b) Damage rate (c) Omission rate

(d) Convey pass rate (e) Total loss rate

FIGURE 25. Field operation effect.

From Fig. 25, it can be seen that the conveying pass rate of each test is high, indicating that the conveying device has good working performance. From the average values of the operational performance indexes, it can be seen that the broccoli leakage rate of 4.8%, the cutting pass rate of 81.6%, the conveying pass rate of 95.62%, the damage rate of 3.96%, and the total loss rate of 8.55% are all in line with the expected indexes.

CONCLUSIONS

To reduce the labor intensity of manual broccoli harvesting, tracked broccoli harvesting equipment was developed and the ability of the machine to harvest broccoli was tested. Cutting tests and field tests were conducted separately to check the operating effect.

(1) The tracked broccoli harvester developed in this paper can walk on its own in the field, cut broccoli stalks, and transport broccoli bulbs for crating. Through mechanical characteristic analysis, the dimensional parameters of each key component are clarified, and the transmission ratios between each component of the drive system are designed.

(2) The optimal working parameters of the cutting device were determined by a coupled design-expert. The simulation of stalk cutting showed that the optimal working parameters of the cutting device were feed speed 0.261m/s, overlap 5.1mm, rotational speed 423.5r/min, and desirability 0.782883. The experimental results of stalk cutting show that the optimal working parameters of the cutting device are 456r/min of rotational speed, 8.312mm of overlap, 0.255m/s of feedrate, and the desirability is 0.722. Under this condition, the minimum value of rotational speed fluctuation is 3.03151r/min, and the value of the cutting effect is 7.47712.

(3) The results of the field test show that the tracked broccoli harvester design operates smoothly and can complete the operations of broccoli cutting, transportation and harvesting well. In the field test, the broccoli leakage rate was 4.8%, the cutting qualification rate was 81.6%, the transportation qualification rate was 95.62%, the damage rate was 3.96% and the total loss rate was 8.55%, and all the performance indexes met the relevant working standards and agronomic operation requirements.

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