Development and test of a spring-finger roller-type hot pepper picking header

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Abstract

This study developed a spring-finger roller type hot pepper picking header to increase picking efficiency, performance, and lower harvesting costs. The picking header was mainly composed of a roller, spring-fingers, a steel frame, an upper cover plate, and transmission parts. Based on SolidWorks, a picking structure model for hot peppers was created in accordance with their mechanical properties. The movement law of the picking spring-finger was analyzed based on the working principle to select appropriate motion parameters of main factors. Based on these chosen parameters, a prototype hot pepper picking header was created, and field tests were conducted to investigate the primary factors influencing the harvesting effect. The rotation speed of the roller and the travel speed of the picking machine were monitored by setting sensors. Using Design Expert, the test results were examined and optimized in accordance with a central composite design. The orthogonal test results showed that when the roller rotation speed was 215.00 r·min^{-1}, and travel speed was 3.59 km·h^{-1}, the hot pepper picking header had the best harvest effect. The picking rate was 98.47%, and the breakage rate was 3.87%. The hot pepper picking header with a spring-finger roller type and good picking effect were demonstrated by the field experiment.

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Key words: hot pepper; picking header; roller spring-finger; central composite design; picking test.

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Introduction

Hot pepper is a kind of vegetable and economic crop with rich vitamins, capsaicin, pigments, and other nutrients. Hot pepper is not only a popular vegetable with a spicy taste among people but also an industrial raw material used in cosmetics, medical treatment, industrial pigments, and other fields. Hot pepper is widely distributed in many countries such as the United States, China, India, Korea, Bangladesh, Vietnam, Thailand, Peru, and Myanmar (Food and Agriculture Organization & World Health Organization, 2022). In China, pepper is widely distributed in Xinjiang, Guizhou, Hunan, Shandong and other provinces. The planting area is growing rapidly. From 2018 to 2022, the average annual planting area of pepper reached 2.0 million hm^2 in China. In 2020, the planting area of pepper reached 31,146 ha in Korea (Statistics Korea, 2022). At present, hot pepper is harvested mainly by manual picking in China, as shown in Figure 1.

Every pepper harvesting requires a lot of labor, which is labor-intensive, and manual harvesting pepper efficiency is low (Wang, 2021). If the hot pepper is not harvested and dried in time, the quality of the hot pepper will be affected, and the commodity conversion rate will be reduced (Dai *et al.*, 2005). With the aging population and a large number of rural laborers moving to cities to engage in non-agricultural work, labor will be in short supply, and hot pepper picking has become a bottleneck for the sustainable development of the hot pepper industry. It is worth mentioning that the mechanization of harvesting pepper can reduce the labor utilization rate by 51% and cost by 38% (Bidhan *et al.*, 2017). The current situation of mechanized harvesting of pepper is that pepper harvesters have been researched and developed in many countries such as the United States, China, Korea, Israel, and other countries (Hu *et al.*, 2012; Chen *et al.*, 2013). However, the difficulties of mechanized picking of pepper are as follows: the planting patterns (planting density, row spacing) of pepper are different in different regions, the growth status of peppers is inconsistent, and the varieties of pepper are different in diverse regions. Therefore, the picking link of pepper has become the biggest bottleneck restricting the large-scale cultivation of pepper (Chen *et al.*, 2013). For these reasons, it is of great significance to develop a high-performance hot pepper harvester to harvest pepper and promote mechanized harvesting of pepper. Relevant studies on picking machines of pepper are as follows: hot pepper picking machine was developed by the United States and some developed countries in the 1970s (Funk *et al.*, 2010; 2011), the picking efficiency of which was high but it is not suitable for the planting patterns of other countries. Paul *et al*. designed a system approach to analyze the factors affecting the picking effect for harvest mechanization (Wall *et al.*, 2003). Kang *et al.* (2016) developed a helix type picking head to study the optimal working conditions for a self-propelled pepper harvester by factorial experiments considering the type of helix rod, the rotation speed and the direction of a helix rod. Kim *et al*. (2020) designed and produced two small helix-type hot pepper harvesters to comparatively analyze of the harvest performance by field tests. Nam *et al*. (2018) carried out a study to investigate the mechanical and physical properties of a kind of red pepper in South Korea, and the research results will help to analyze the particle behavior of red pepper and red pepper stem while being picked and separated for a self-propelled pepper harvester. Nam *et al*. (2017) and Shin *et al*. (2021) conducted factorial experiments to evaluate the performance of separation device separating branches, leaves, and soil from hot pepper. In China, several authors (Qin *et al.*, 2012; Chen *et al.*, 2013; Lei *et al.*, 2015) developed a line pepper harvester, and the machine was experimented and used in the Xinjiang Uygur Autonomous Region of China. However, there was no relevant research on picking header for hot pepper. In addition, the existing line pepper harvesting machines have huge volumes and are not suitable for working in pepper fields in hilly and mountainous areas. The plots where hot peppers are planted are not all large areas; most of them are small plots, and there are also many plots in hilly and mountainous areas. Therefore, it is necessary to develop a hot pepper-picking machine based on the combination of agricultural machinery and agronomy in hilly and mountainous areas. In order to achieve the above objectives, the following research work needs to be carried out. First, the planting patterns and mechanical properties of pepper need to be investigated. Second, a three-dimensional model of the spring-finger roller type picking header is established and its picking principle is analyzed. Then, a large number of field tests are conducted to obtain factors affecting the picking effectiveness. Finally, analysis of experimental data based on response surface design methodology, and obtain the best working parameters of the picking machine.

Materials and Methods

Physical and mechanical parameters of hot pepper

The physical and mechanical parameters of hot pepper are the theoretical basis for designing the picking header. Therefore, they are of great significance to the successful picking of hot pepper for a picking header. In order to get the planting pattern and the growth status of hot pepper, a flexible rule and vernier calipers were used to measure the data of the distance between pepper plants, the row spacing, the height of pepper plants, the length of hot pepper, respectively in a pepper field and laboratory (Figure 2). During these measurements, each physical quantity was measured three times, and then the average of the three measured values was taken as the result.

Figure 1. Manual picking pepper in a field.

Figure 2. Measurement of peppers and pepper plants.

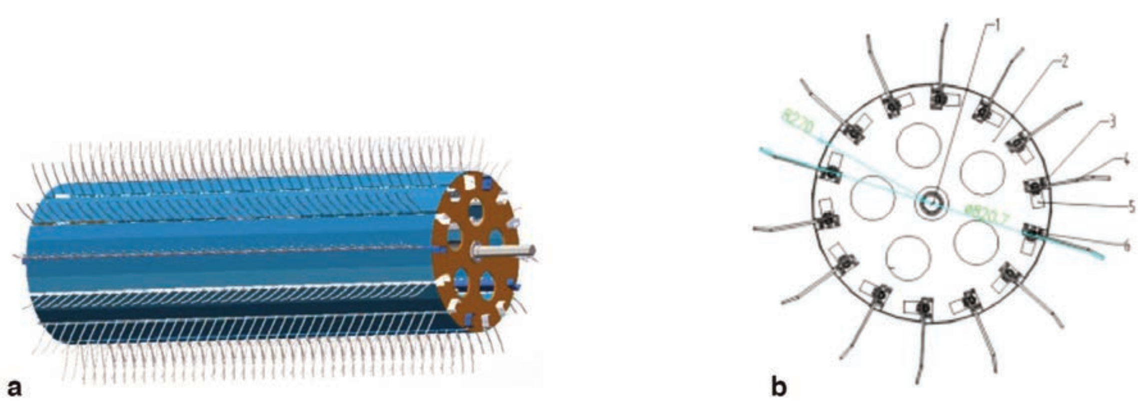

Figure 3. The spring-finger type picking roller. a) Three-dimensional model; b) Sectional view of the roller. 1) Drive shaft of the picking roller, 2) flange plate; 3) U-shaped steel groove; 4) spring finger; 5) angle iron; 6) bolt and nut..

Design of picking header

The structure of a spring-finger roller type hot pepper picking header is mainly composed of a steel frame, a roller with spring-fingers, an imitate terrain roller, a roller for bending branches, a driving shaft, a screw conveyor, two side plates (left and right), and two dividers (left and right). Among these parts, the spring-finger type picking roller is the key working component, which is composed of a drive shaft, three flange plates, and many U-shaped steels, spring-fingers, angle irons, bolts, and nuts (Figure 3).

The main parameters of the picking roller are: roller diameter, roller width, axial and radial spacing of spring-fingers installation, height of the roller for bending branches from the ground, rotation speed of the picking roller, and travel speed. These parameters are the key factors affecting the picking effect of pepper. Therefore, these key parameters need to be determined based on the combination of agricultural machinery and agronomy taking into account the planting pattern, and physical and mechanical characteristics of the hot pepper. According to the analysis of relevant data in the early stage and the field survey results (Chen *et al.*, 2013; Duan, 2014), the key parameters are preliminarily determined (Table 1).

Based on the main parameters of a picking roller, the structure of a spring-finger roller type hot pepper picking header was designed as shown in Figure 4.

Working principle of the picking header

Among these components in the picking header, the steel frame is a basal body for every component. The left and right dividers comb hot pepper plants for the spring-finger roller conveniently picking hot pepper. The roller for bending branches is used to bend the branches of hot pepper for convenient picking operation. The imitate terrain roller is used to make the picking header follow the fluctuation of the terrain. The spring-finger roller is a key part of the picking header to pick hot pepper. The upper cover plate not only prevents the newly picked hot pepper from flying out of the picking header but also guides the newly picked hot pepper to move backward. The left side plate and right side plate are used to prevent the hot pepper from being thrown out of the picking header. When the picking header is working to pick hot pepper, the roller for bending branches is installed on the left and right dividers to push the hot pepper plants to bend forward. Then the spring-finger type roller scrapes the hot pepper and some branches and leaves from bottom to top by the rotation movement in a clockwise direction. Under the interaction between the spring-fingers and hot pepper, hot peppers are picked down and thrown to the rear by the spring-fingers.

Simulation of the movement track

Theoretical model

In the process of picking hot pepper, assuming that the field is flat, the spring-fingers move forward with the whole machine at a uniform speed in the horizontal direction while rotating with the picking roller around the driving shaft, so the motion state of spring-fingers can be regarded as plane motion. The motion trajectory of any point M on the spring-fingers can be expressed as formula (1), which is a trochoid.

$$\begin{cases} x = (R+L)\cos\theta + vt \\ y = (R+L)\sin\theta + H \\ \theta = \omega t \end{cases} \tag{1}$$

where, the rotation speed of the spring fingers is n (rpm), in this case, the angular velocity is ω (rad/s), $\omega = (\pi/30)*n$, and v (km/h) is the forward travel speed of the whole machine. The horizontal displacement of point M is x. The longitudinal displacement of point M is y. The radius of the spring-finger type picking roller is R. The radial distance of the spring-finger out of the picking roller is L. The distance from the driving shaft to the ground is H.

The velocity equation of point M can be obtained by making a first-order derivative of the trajectory equation of point M, which is expressed as formula (2).

$$\begin{cases} v_x = x' = -\omega(R+L)\sin(\omega t) + v \\ v_y = y' = \omega(R+L)\cos(\omega t) \\ v_M = \sqrt{v_x^{\ 2} + v_y^{\ 2}} \end{cases} \tag{2}$$

Table 1. The main parameters of picking roller.

Parameter	Unit	Value
Roller width	mm	1800
Roller radius	mm	270
Rotation radius of the tip of the spring finger	mm	410
Number of U-shaped steels	row	14
Height of the roller for bending branches	mm	600
Rotation speed	r/min	200-240
Travel speed	km/h	3-6

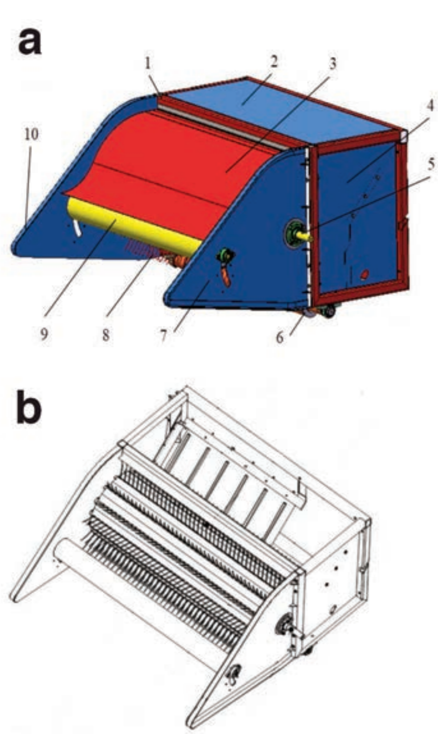

Figure 4. Structure model of the hot pepper picking header. **a**) Three-dimensional model; **b**) 2D model; 1) steel frame, 2) upper cover plate; 3) shield cover plate; 4) left side plate; 5) driving shaft; 6) imitate terrain roller; 7) left divider; 8) spring finger cylinder; 9) roller for bending branches; 10) right divider.

Validation of the model

According to equation (1), the motion trajectory of any point M on the spring-fingers is a trochoid, the shape of the displacement trajectory depends on the ratio δ of the rotation speed to the forward travel speed ($\delta = (R+L)\ \omega/v$), that is, the motion trajectory curves of M point change with the different values of δ. The motion trajectories of point M are shown in Figure 5.

According to equation (2), the velocity curves of point M with the different values of δ are drawn in Figure 6. It can be seen from Figures 5 and 6 that δ with different values have a great influence on the motion trajectories and the velocity curves of point M. If δ<1, the motion trajectory of point M is the solid curve with red color in Figure 5, and the velocity in the horizontal direction is the red color curve in Figure 6, which is always greater than 0. If δ=1, the motion trajectory of point M is the dotted curve with black color in Figure 5, and the velocity in the horizontal direction is the dotted curve with black color in Figure 6. In this case, when the point M on spring finger moves to the highest point, the horizontal velocity is just equal to 0. If δ>1, the motion trajectory of point M is the solid curve with blue color in Figure 5, and the velocity in the horizontal direction is the solid curve with blue color in Figure 6. In this case, the horizontal velocity is less than 0 periodically, which means the horizontal speed opposite to the forward direction of the machine, and hot peppers and the mixture of leaves and broken stems can be conveyed backward by spring fingers. After the comprehensive analysis of the change curves in Figures 5 and 6 and the actual movement of the spring-finger type picking mechanism, it can be concluded that the theoretical model is correct.

Two simulation examples

When the rotation speed n is 180 rpm, the forward travel speed v is 1.39 m/s, and the number of U-shaped steel grooves distributed in the circumferential direction N is 12, the motion trajectory of any point M on the spring fingers is shown in Figure 7a. When the rotation speed n is 220 rpm, the forward travel speed v is 1.39 m/s, and the number of U-shaped steel grooves distributed in the circumferential direction N is 14, the motion trajectory of any point M on the spring fingers is shown in Figure 7b. By comparing the motion trajectories of Figure 7a and b, it can be seen that the motion trajectories of the spring fingers in Figure 7b are more rapid and intense, which is conducive to improving the picking rate.

Field experiments

Field test is a necessary process in the research and development stage of agricultural machinery and equipment, which is used to test the working performance of products. The following will describe the field test from four aspects: test conditions, test method, evaluation indexes, and design of experiment.

Test conditions

Field experiments were conducted in a piece of farmland at Shouxian Town, Fengxian County, Xuzhou City, Jiangsu Province, China, from 25th to 29th September 2022, when hot peppers grew maturely. The water content of hot pepper was 50-60%. The variety of the hot pepper was Tianyu, the plant height was 0.55-0.82 m, the hot pepper diameter was 0.006-0.011 m, length was 0.03-0.07 m. The plant spacing was 0.25 m, the row spacing was 0.7 m.

The picking header developed in this study was mounted on a self-propelled pepper harvester with 4jz-1700. The overall dimensions of the prototype picking header were 1.5×1.7 m (length × width), and the lifting range of the picking unit was 0.2 to 0.5 m.

Test methods

Combined with the harvesting principle and structural characteristics of the prototype machine, the rotation speed and travel speed of the picking roller, and the moisture content rate of hot pepper were used as test factors in this study.

The test method is in accordance with the inspection standard of the promotion and appraisal outline of hot pepper harvester, the serial number of which is DG/T 114-2019. During each test, a typical test area with a length of 20 m and a width of 1.7 m was selected for a test, the naturally fallen hot and fallen branches and leaves in the selected test area were removed, and the working parameters of the harvester were adjusted before each test. Then, the machine was driven at a constant speed to pick hot pepper by the developed

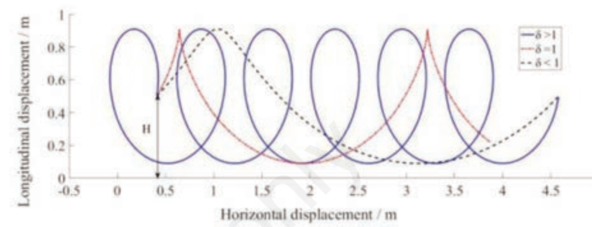

Figure 5. The motion trajectory of point M with the different values of δ.

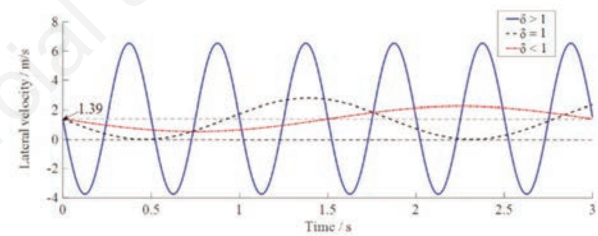

Figure 6. Velocities of point M in the horizontal direction at δ with different values.

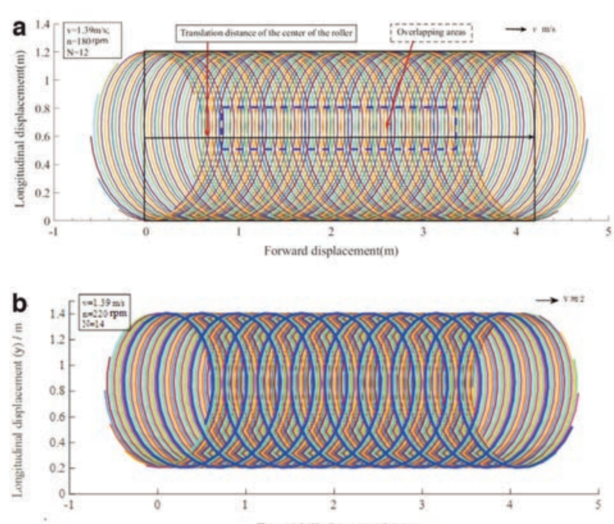

Figure 7. The motion trajectory of any point M on the spring-fingers. **a**) v=1.39 m/s, n=180 rpm, N=14; B) v=1.39 m/s, n=220 rpm, N=12.

picking header in the test area. The field test of the prototype pepper-picking machine is shown in Figure 8. After that, the following types of hot pepper, branches, and leaves were collected and weighed. The mass of unpicked hot pepper was m_1 kg, the mass of hot pepper dropping on the ground was m_2 kg, the mass of the mixture of hot pepper, branches and leaves harvested was m_3 kg, the mass of picked hot pepper sorted out from the mixture was m_4 kg, the mass of the breakage hot pepper sorted out from the picked hot pepper was m_5 kg.

Evaluation indexes

Granting to the agronomic demands of hot pepper harvest in actual production, picking rate, breakage rate, and loss rate were usually used as evaluation indexes of the picking effect. Since this study is only for the evaluation of the picking header and not for the evaluation of other relevant components, the picking rate and breakage rate are considered as the evaluation indexes.

These evaluation indexes were calculated according to the definitions of evaluation indexes as shown in Table 2. In Table 2, η_p stands for the picking rate, and η_b stands for the breakage rate.

Design of experiment

When the structural parameters of the picking header are determined, only the rotation speed of the roller and the forward travel speed of the whole machine can be adjusted, while the position parameters of the key components in the prototype are not adjustable. Therefore, the rotation speed of roller and travel speed of the machine were selected as the main factors to respond to the test results, and they were indicated by *A* and *B*, respectively. When the picking header is driven by an engine to work, the rotation speed range of the roller is 180-240 rpm, and the forward travel speed of the machine is 2.0-6.0 km/h. Central composite design (CCD) is the most commonly used experimental design method in response surface design, and it consists of cubic point tests, axial point tests, and central point tests, which includes five levels for each factor. Considering the design requirements of CCD and the working conditions of the picking header, a two-factor and three-level test design table was designed, as shown in Table 3. In Table 3, the rotation speed at 215 rpm and the travel speed at 4.0 km/h are the central point tests, which are represented by 0 respectively. The rotation speed at 230 (200) rpm and the travel speed at 5.0 (3.0) km/h are the cubic point tests, which are represented by 1 or -1, respectively. The rotation speed at 236.2 (193.8) rpm and the travel speed at 5.4 (2.6) km/h are the axial point tests, which are represented by 1.414 or -1.414, respectively.

Results

The number of test groups is 11. Each group was repeated three times and the average value was taken as the result of each group. The experiment results are presented in Table 4.

Figure 8. Field test of the prototype picking machine.

Table 2. Definitions of evaluation indexes.

Indexes	Definition
Picking rate	$\eta_p = m4/(m_1+m_2+m_4)\times 100\%$
Breakage rate	$\eta_b = m_5/m_4 \times 100\%$

Table 3. Factors and levels for field tests.

Code	*A* (rpm)	*B* (km/h)
-1	200	3.0
0	215	4.0
1	230	5.0
1.414	236.2	5.4
-1.414	193.8	2.6

Table 4. The experimental results of field tests.

No.	Test factors		Test indexes	
	A (rpm)	B (km/h)	Picking rate (%)	Breakage rate (%)
1	0	0	98.58	3.92
2	-1.414	0	95.26	2.45
3	1	1	99.52	4.75
4	0	0	98.65	3.95
5	0	0	98.68	3.92
6	0	-1.414	98.08	3.86
7	0	1.414	98.88	4.35
8	-1	1	96.78	3.13
9	1.414	0	98.88	4.7
10	1	-1	98.15	4.32
11	-1	-1	96.38	2.85

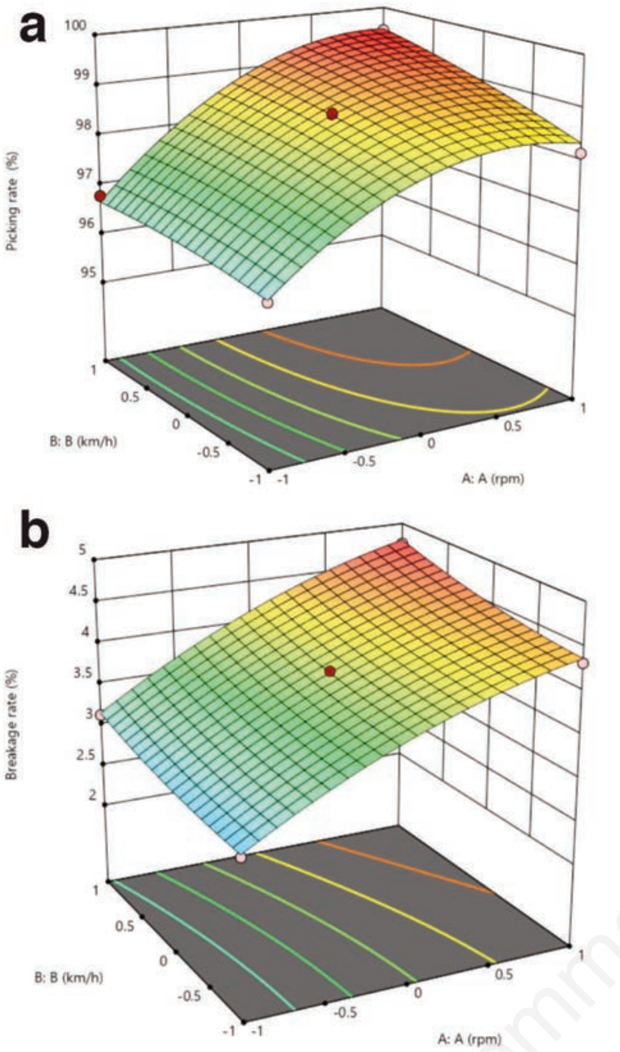

Figure 9. The impact of interaction between each two factors on the picking performance. a) The impact on the picking rate; b) the impact on the breakage rate.

Based on the CCD and these test results, the experimental data was analyzed by using Design-Expert software (Srikanth *et al.*, 2020). During the analysis of the experimental data of the response surface design, the picking rate and breakage rate were taken as the response indicators, and the two factors of the rotation speed and travel speed were taken as the main influence factors. The analysis of variance (ANOVA) of the quadratic model for the experimental data is shown in Table 5. As can be seen from Table 5, P-values of the picking rate model and breakage rate model are both less than 0.01; and the P-values of lack of fit in picking rate model and breakage rate model are 0.0698, 0.0649, both greater than 0.05, indicating that the two fitted models are feasible. In addition, the determination coefficients R^2 of the two regression models are 0.9866 and 0.9950, respectively, indicating that both regression models can explain more than 98% of the evaluation indicators.

In the ANOVA of the model, the P-value is a key judgment indicator. If the P-value is less than 0.01, it indicates that the influence of this factor on the response is extremely significant. If the P-value is less than 0.05, it indicates that the influence of this factor on the response is significant; if the P-value is greater than 0.05, it indicates that the influence of this factor on the response is not significant (Yu *et al.*, 2023). According to this judgment condition, it can be drawn the following two conclusions. In the regression model of picking rate, A and A^2 are the extremely significant factors, B is a significant factor, and the rest AB and B^2 are not significant factors. In the damage rate regression model, A, B, and A^2 are extremely significant factors, B^2 is a significant factor, and the remaining AB is an insignificant factor. In addition, the degree of influence of each test factor on the picking rate and damage rate of hot pepper can be determined according to the response values affected in Table 5. The order of influence on the picking rate of hot pepper is: $A>B$, and the order of influence on the damage rate of hot pepper is also: $A>B$.

The effect of interaction between each two factors on the picking rate and breakage rate was analyzed by using Design Expert software, and the analysis results are shown in Figures 9a and 9b.

The experimental data were analyzed by optimization operation in Design Expert, and the optimization results of the three factors were obtained as shown in Figure 10. The optimization results are as follows: rotation speed is 215.00 rpm, travel speed is 3.59 km/h, the picking rate is 98.47%, and the breakage rate is 3.87%.

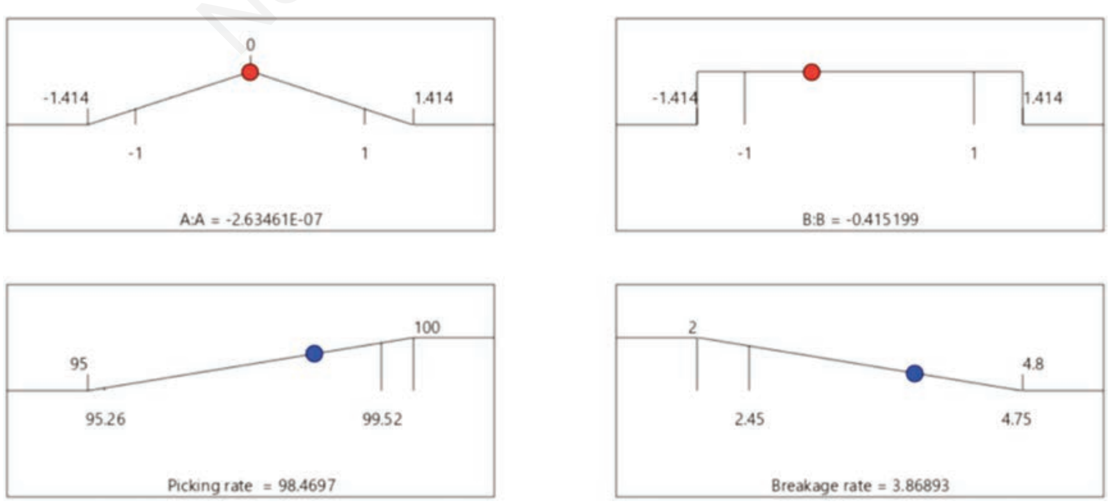

Figure 10. The optimization results for two test factors and two response values.

Discussion

A picking header was designed for hot peppers planted in a small plot or pepper fields in hilly and mountainous areas. Compared to the previous picking header, the advantage of the prototype of the new picking header is that the space size of that is small. It is easy to operate in a small piece of hot pepper field.

After the design and development of the prototype of the hot pepper picking header, field experiments were carried out in a piece of hot pepper field. During the field experiments, the rotation speed of the spring-finger type roller and the forward travel speed of the whole machine were selected as the main influencing factors. In addition, the interaction of the two factors was also considered as variable to study the effect on picking effectiveness. The CCD was selected as the design method and 11 groups of tests were carried out in a hot pepper field.

The test results showed that the highest picking rate and the lowest breakage rate were achieved when the roller rotation speed at 215.00 rpm and the travel speed at 3.59 km/h. If the rotation speed of the roller is too low, the spring finger provides too little pull force and impact force to pick hot pepper. If the rotation speed of the roller is too high, the contact time between the spring finger and hot pepper is short, and the hot pepper is broken by excessive impact force or hit on the upper cover plate and then dropped on the ground. Therefore, the rotation speed of the roller with excessively high or low rotation speed is not conducive to increasing the picking rate. At the same time, if the travel speed of the picking machine is too high, it will cause problems such as blockage of branches and high impurity content. If the travel speed of the picking machine is low, the picking efficiency will be reduced and some hot peppers will fall off resulting in a high loss rate.

Besides the above two factors, many other factors affect the performance of the hot pepper picking mechanism, such as the diameter of the drum, the height of the drum from the ground, and the clearance between fingers. The difference in the growth height of pepper plants and the number of pepper fruits in the farmland affects the results of the experiment, so the uncertain distribution of hot pepper may lead to test errors. The influence of these factors on the picking performance and the optimization of their parameters will be the next research content. If the distribution of cultivated hot pepper is as consistent as possible, the mechanical picking effect will be greatly improved.

Conclusions

In this study, the three-dimensional model of key components of the spring finger roller type picking header was developed in SolidWorks. In the design process, the design requirements of lightweight and reliability were comprehensively considered for the structural design of the picking head. The experimental results showed that the structural strength of the picking header was able to meet the use requirements.

In the field test, this picking header showed good picking effectiveness in picking rate and breakage rate, which was better than other picking headers. The picking rate and breakage rate of the picking header could reach 98.46%, and 3.86% respectively by adjusting the working parameters. Another notable advantage of this picking header was that the working width of which was consistent with the hot pepper planting mode in the region. In addition, the space size of the header is not huge, so it is convenient to operate. The picking header has been tested in fields with stable operation and good reliability. Therefore, this study provides a technical foundation for the realization of mechanized hot pepper harvesting. Although the prototype achieved better picking effectiveness, the spring finger roller type picking header still has some problems, and it needs further optimization before promoting its application. It is necessary to improve the structure of the picking header to replace the spring finger type roller and adjust its position and height easily, and the influence of spring fingers spacing and its interaction with spring finger rotation speed on picking effectiveness should also be studied.

The next research plan is to optimize and improve the prototype machine based on the optimal parameter combination of machine structure parameters, travel speed, and the rotating speed of the drum. In addition, the effects of working parameters on the picking effectiveness and energy consumption will be studied by orthogonal experiments. Moreover, the picking machine also needs to automatically control its travel speed and the rotating speed of the drum to realize unmanned operation.

Table 5. Analysis of variance of quadratic model for the experimental data.

Source	Picking rate					Breakage rate				
	Sum of squares	Degrees freedom	F-value	P-value	Significant	Sum of squares	Degrees freedom	F-value	P-value	Significant
Model	16.62	5	148.63	<0.0001	**	5.49	5	400.25	<0.0001	**
A	11.59	1	518.42	<0.0001	**	4.92	1	1793.78	<0.0001	**
B-	1.05	1	47.06	0.0010	*	0.2460	1	89.75	0.0002	**
AB	0.2352	1	10.52	0.0229	no	0.0056	1	2.05	0.2114	no
A^2	3.6160	1	161.73	<0.0001	**	0.2189	1	79.85	0.0003	**
B^2	0.0512	1	2.29	0.1907	no	0.0262	1	9.56	0.0271	*
Residual	0.1118	5	-	-	-	0.0137	5	-	-	-
Lack of fit	0.1065	3	13.48	0.0698	no	0.0131	3	14.56	0.0649	-
Pure error	0.0053	2	-	-	-	0.0006	2	-	-	-
Cor total	16.7275	10	-	-	-	5.50	10	-	-	-

Asterisks are used to indicate discriminant significance in this table. indicates a significance level of 0.05, *indicate a significance level of 0.01, and ***indicate a significance level of 0.001.

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