Article

The Design and Optimization of a Peanut-Picking System for a Fresh-Peanut-Picking Crawler Combine Harvester

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Abstract: In view of the problem that peanut harvesting in hilly areas mainly involves fresh food, and that the peanut-picking purity rate is low and there is high breakage in the peanut-harvesting process, key components such as the picking system of a fresh-peanut-picking crawler combine harvester, the picking tooth, and the concave screen were designed, and ANSYS Workbench 2020 software was used to check the reliability of the picking roller under working conditions in hilly areas. In the process of equipment operation, the picking purity rate and breakage rate were the main evaluation indexes, and the Box–Behnken test method was used to study the speed of the peanut-picking roller, the feeding amount, and the picking gap as the test factors. The results showed that the picking purity rate is 98.95%, with an error margin of 0.98%, compared to the predicted value under the conditions of 342 r/min speed, 0.75 kg/s feeding amount, and 32 mm picking gap. The breakage rate is 4.23% and the error is 0.4% compared with the predicted value, indicating that the optimized model is reliable and predictive. This study provides a theoretical basis for the optimal design of the peanut-picking system of peanut-picking combine harvesters in hilly areas.

Keywords: agricultural machinery; peanut picking; harvester; response surface; parameter optimization

1. Introduction

Peanuts are one of the important economic crops in China and also a significant source of foreign exchange income. China is one of the world's major peanut producers, with a planting area second only to India. The peanut planting area in China is about 4.62 million hectares, accounting for 14.63% of the world's total, ranking second in the world in terms of area and first in terms of production [1–4]. Peanut cultivation in China is widespread. In 2022, the top five provinces in terms of peanut planting area were Henan, Shandong, Guangdong, Sichuan, and Hebei, with planting areas of 1.287 million hectares, 0.6098 million hectares, 0.347 million hectares, 0.295 million hectares, and 0.232 million hectares, respectively [5–8].

About one-third of China's peanut planting area is distributed in hilly regions such as Sichuan and Guangdong. The southern hilly regions are one of China's main peanut-producing areas. However, peanut planting and production in these regions still primarily rely on traditional manual methods. The comprehensive mechanization level of cultivation and harvesting is significantly lower than the national average for major crops. The main reasons are that peanut planting in hilly areas is mainly for fresh consumption, the

fields are small, the soil is heavy and sticky, and the agricultural practises are complex and diverse, making mechanized harvesting difficult to achieve [9–11]. To address the operating conditions in hilly regions, the Nanjing Research Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, designed a tracked fresh-peanut-picking combine harvester. This equipment has advantages such as small size and light weight, making it suitable for full-feed peanut picking and harvesting operations in hilly and mountainous areas. However, due to the high moisture content of fresh peanuts, which makes them prone to damage, and the small size of the working components, these factors result in a low picking purity rate and a high breakage rate for peanut-picking combine harvesters in the southern hilly regions of China. Consequently, the comprehensive mechanization rate for peanut planting areas in hilly regions is less than 20%, far below the over 60% level in the northern peanut planting regions of China [12–14]. To reduce the breakage rate of peanut pods during the harvesting process and improve harvesting performance, it is essential to optimize the design of peanut-picking devices in hilly regions.

At present, many scholars in China have carried out corresponding research on the picking institutions of peanut combine harvesters. Zhichao Hu et al. [15] designed a semi-feed peanut-picking test bench. Based on motion analysis during the peanut-picking process, they determined the ideal position and parameter relationships of peanut clusters in the peanut-picking section. They analyzed the factors influencing peanut-picking frequency and intensity, and their impact on operational performance. Hongbo Xu et al. [16] designed a multi-stage cutting-flow-type peanut-picking and -conveying machine. This device utilizes a structure combining seven-stage roller series and vibration conveyance to achieve coordinated peanut picking and conveying operations, addressing issues such as the short effective picking time and high breakage rate of peanuts. Dehuan Zhou et al. [17] designed a multi-stage series cutting-flow-type peanut-picking device. They proposed using a scheme with elastic-toothed nail-picking rollers, conducted peanut-picking performance tests, and optimized the structural parameters and operational parameters of the peanut-picking mechanism. Qingliu Fang et al. [18] employed the TRIZ method for the innovative design of a peanut-picking device, focusing on the picking purity rate, breakage rate, and stalk removal rate as research objectives. They conducted functional analysis, causal analysis, and other analyses across five aspects of the peanut-picking device. Zhongyu Chen et al. [19] used curved-tooth screw components in their peanut-picking device. They designed a peanut-picking roller, a concave screen, pneumatic cleaning and vibrating screen cleaning devices, and a transmission system. The design included the inclination angle, structure, arrangement, and quantity of the screws and curved tooth, and determined the overall length, diameter, and operating speed of the peanut-picking roller. Qinghua Wang et al. [20] used the response surface method to obtain that the optimal combination of operating parameters of the 4HLB-4 peanut combine was as follows: forward speed of 0.85 m/s, clamping height of 190 mm, speed of peanut-picking roller of 550 rpm, and vibration frequency of cleaning screen of 590 cpm. Under these conditions, the impurity rate reached 2.62% and the loss rate reached 2.05%, which effectively reduced the impurity rate and loss rate. The main difference between the crawler fresh-peanut-picking combine harvester and the 4HLB-4 peanut combine harvester in this paper is the peanut seedling feeding method and peanut-picking method. In summary, previous studies on the peanut-picking devices of peanut combined harvesters have primarily focused on large-scale machines used in northern peanut planting regions. There is relatively limited research on peanut-picking combine harvesters suitable for harvesting fresh peanuts in hilly terrain [21–24].

To address the characteristics of small peanut fields and high moisture content in hilly regions, the Nanjing Research Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, innovatively designed a fresh-peanut-picking crawler combine harvester, with its peanut-picking device as the core component. This paper optimizes the design of the fresh-peanut-picking crawler combine harvester. It verifies the operational safety of the peanut-picking device under hilly region conditions using ANSYS

Workbench finite element analysis software. A three-factor, three-level Box–Behnken experiment is conducted, and response surface analysis is used to determine the impact of interactive factors on evaluation metrics and derive the optimal combination of operational parameters. This study provides theoretical groundwork for optimizing the peanut-picking system of peanut-picking combine harvesters in hilly regions, significantly promoting the mechanized harvesting of peanuts in such areas.

2. Materials and Methods

2.1. The Overall Structure of the Fresh-Peanut-Picking Crawler Combine Harvester

The fresh-peanut-picking crawler combine harvester employs full-feed cross-axial-flow peanut picking and cleaning technology. It mainly includes the chassis walking system, picking platform, control console, peanut-picking device, inclined scraper conveyor, cleaning device, peanut collection device, and transmission and dynamical system. The overall machine structure is shown in Figure 1.
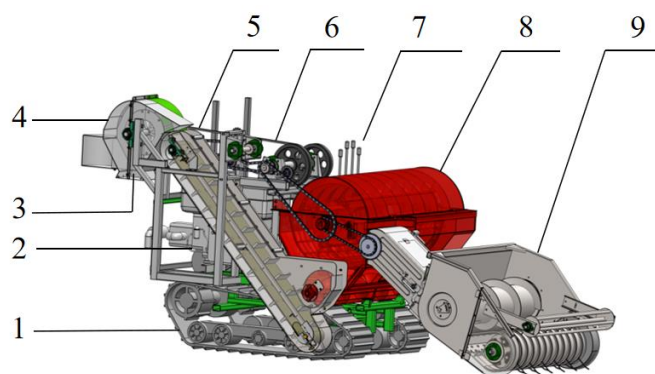

Figure 1. Fresh-peanut-picking crawler combine harvester: 1: chassis walking system; 2: dynamical system; 3: peanut collection device; 4: cleaning device; 5: inclined scraper conveyor; 6: transmission system; 7: control console; 8: peanut-picking device; 9: picking platform.

2.2. Working Principle

The machine can complete the pick-up, conveying, peanut picking, cleaning, grain collection, and other processes of digging and laying peanuts in the field at one time; the working principle is as follows: The machine is in normal driving mode in the field. The picking platform picks up the peanut seedlings that are spread in the field, and they are transported to the peanut-picking device through the chain scraper conveyor for peanut picking; most of the peanut residues are discharged through the bottom side of the peanut-picking device, and the peanut pods and some of the sundries are transported to the inclined scraper conveying device through the bottom auger, and then transported to the cleaning device for cleaning, and finally, the grain collection is bagged [25,26]. The main technical parameters are shown in Table 1.

Table 1. Main technical parameters of fresh-peanut-picking crawler combine harvester.

Parameters	Design Values
Type	Fully fed, self-propelled track
Machine dimensions Size (Length × width × height)/(mm × mm × mm)	$3500 \times 1500 \times 1600$
Total weight/(kg)	1300
Engine power/(kw)	20.2
Engine rated speed/(r/min)	2200
Most suitable row spacing/(mm)	700
Working width/(mm)	1040
Efficiency/(hm^2/h)	1–2.5

2.3. The Overall Structure of the Peanut-Picking System

The peanut-picking system is a single-roller full-feed transverse axial flow type, which is mainly composed of a peanut-picking roller, a concave plate screen, a lower conveying auger, and an upper cover plate. Its overall structure is shown in Figure 2.
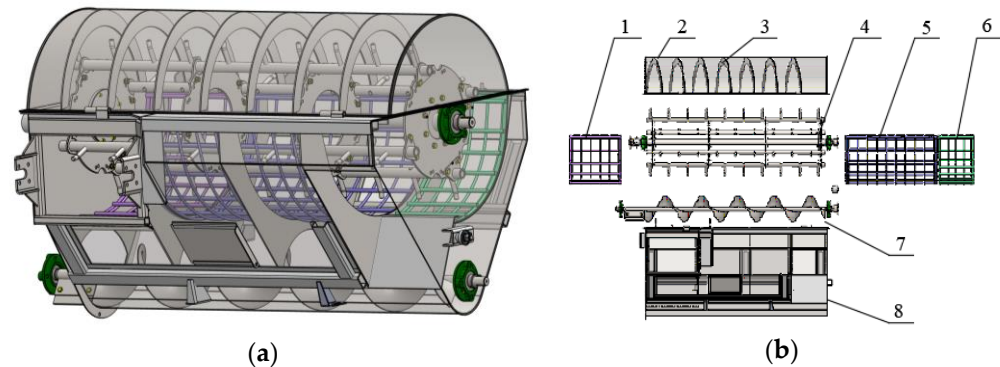

(**a**)　(**b**)

Figure 2. Peanut-picking system. (**a**) The overall structure of the peanut-picking system and (**b**) (1) the first-stage concave screen, (2) the upper shell, (3) the deflector, (4) the peanut-picking roller, (5) the secondary concave screen, (6) the three-stage concave screen, (7) the bottom auger, and (8) the lower shell of the peanut-picking chamber.

The reasonable collocation of each operating component in the picking system of the fresh-peanut-picking crawler combine harvester directly affects the picking effect. After the peanut seedlings are dried in the field, they are picked up by the peanut harvester picking table and transported to the feeding port in the upper part of the front of the picking mechanism, and then sent to the picking chamber. The position of the roller and the concave plate sieve was appropriately selected, so that the fed peanut vines were picked by the roller and the concave plate sieve, and a downward conveying auger was also added in this study. During the picking period, the downward auger can transport the picked pods to the debris discharge port, reduce the problem of blockage such as peanut vine residue in the picking room, and push the picked peanut pods from the bottom of the fruit picking room to the inclined scraper conveyor. Finally, the fan was used for negative pressure winnowing, so that the pods fell into the grain collection bag, which improved the smoothness and reliability of the peanut harvesting process.

2.4. Design of Key Components of the Peanut-Picking System

2.4.1. Peanut-Picking Roller

The structure of the peanut-picking roller is shown in Figure 3; the roller shaft passes through the middle hole of the disc, the shaft and the front and rear two flange discs are welded as a whole; the middle flange disc adopts a hollow design; the outside of the flange disc is successively distributed with rod-tooth-fixing seats, ensuring a positional relationship between the fixed rod tooth shaft and the flange disc; and the peanut-picking nail teeth are installed on the rod tooth shaft.
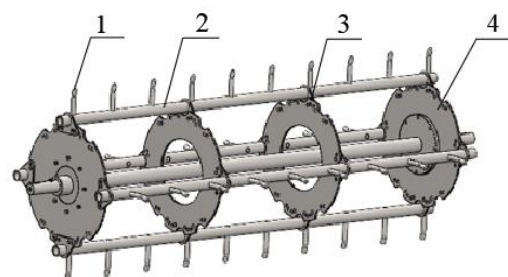

Figure 3. Peanut-picking roller. 1: Peanut-picking nail tooth. 2: Tooth bar. 3: Tooth holder. 4: Flange disc.

2.4.2. Length of the Peanut-Picking Roller

The length of the peanut-picking roller is directly related to the picking time and picking purity rate. Generally speaking, the longer the harvest period for a peanut, the higher the recovery rate. However, if the picking roller is too long, the power consumption of picking will increase, and the cleaning workload will increase (increasing the number of slim crushing). Conversely, if the harvest time is too short, the net harvest rate of the peanut will be reduced. When picking peanuts, with the cooperation of picking teeth, rollers, and concave screens, the plants make spiral movements along the drum drive shaft. In general, the length of the peanut-picking roller satisfies the following equation:

$$L = L_Z + L_P \tag{1}$$

where L is the length of the entire peanut-picking roller, mm; L_Z is the length of the peanut-picking roller to effectively pick the peanut, mm; L_P is the length of the effective peanut-picking roller except for the effective peanut-picking length of the peanut-picking roller, mm.

Among them, according to the equipment operating width of 1040 mm, the harvesting process is a double-ridge and four-row operation, so the length between the two peanut-picking teeth on the same tooth rod of the peanut-picking roller is 120 mm; then, the effective peanut-picking length L_Z is 1080 mm. Fully considering the complexity of the working conditions in hilly areas, the structure of the whole machine is reasonably arranged, and the length of the whole peanut-picking roller is designed to be 1200 mm, This is shown in Figure 4.
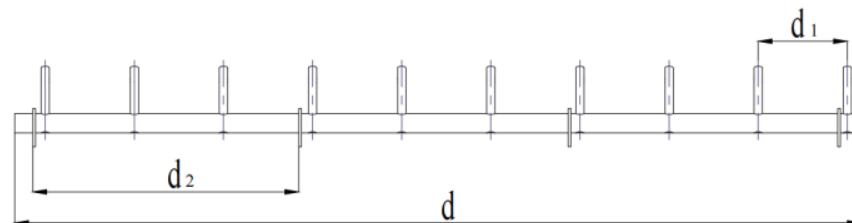

Figure 4. Length of the picking roller.

2.4.3. Diameter of the Peanut-Picking Roller

The smaller the diameter of the roller, the easier it is for smaller peanut seedling vines to cause congestion in the process of peanut picking, and it is easy to be entangled in the inside of the peanut-picking roller and the peanut-picking tooth, and the peanut-picking quality is poor. The larger the diameter of the peanut-picking roller and the larger the peanut-picking chamber, the smoother the movement of peanut seedling vine will be in the peanut-picking process, but with the larger the size of the mechanism, the machine is bulky, and the economic cost and manufacturing cost increase. In order to facilitate the smooth picking of peanut pods, it is important to ensure that the picking room is smooth and not blocked, so that the whole machine is lightweight. The diameter of the peanut-picking roller is

$$D = \frac{MS}{\pi} + 2H \tag{2}$$

where M is the number of rows of peanut-picking nail teeth; S is the unfolding spacing of each row of peanut-picking nail teeth, mm; H is the height of a nail tooth, mm.

According to the overall space configuration of the fresh-peanut-picking crawler combine harvester, under the premise of ensuring the simplicity and light weight of each component, the diameter of the peanut-picking roller of this machine is 500 mm.

2.4.4. Peanut-Picking Roller Speed

The speed of the peanut-picking roller affects the picking performance of the peanut-picking combine harvester, and increasing the speed of the peanut-picking roller will increase the net picking rate of peanut pods, but will increase the damage rate of peanut pods to a certain extent. Through the experimental analysis, the best picking performance is found when the linear speed of the peanut-picking roller is 8–10 m/s. Then, the speed of the peanut-picking roller is

$$n = \frac{60v}{\pi D} \tag{3}$$

where n is the speed of the peanut-picking roller, r/min; v is the linear speed of the peanut roller, 8–10 m/s; D is the diameter of the peanut-picking roller, 500 mm.

Substituting the above formula, the speed of the peanut-picking roller can be obtained as 306~382 r/min.

2.4.5. Peanut-Picking Tooth

The common peanut-picking elements of peanut-picking combine harvesters include nail teeth, elastic teeth, bow teeth, etc., and the form of peanut-picking elements has an important impact on the peanut-picking effect [27,28]. In this paper, an axial flow peanut-picking roller is used alongside the nail tooth peanut-picking element to impact the peanut seedling vine entering the roller and the grate comb action to pick peanuts. The bending angle of the nail tooth is set to 15°; the diameter of the peanut-picking nail tooth is set to 8 mm, wherein the distance between the height of the nail tooth and the bottom of the tooth holder is 120 mm, and the distance between the bottom of the nail tooth and the tooth holder is 100 mm; the structure is shown in Figure 5.
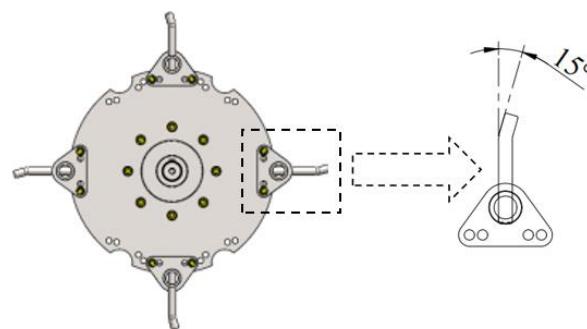

Figure 5. Peanut-picking tooth—partial enlargement.

After the peanut plant is picked up by the picking table, the peanut plant is transported from the feeding entrance into the peanut-picking roller for peanut plant separation, and in the whole process, the peanut plant is discharged from the feeding mouth after entering the axial spiral to the impurity discharge port due to the effect of the peanut-picking tooth, and during this period, the separation of peanut pod and peanut seedling is realized. The movement force of peanut plants in the peanut-picking roller is analyzed to verify the rationality of the structure of the peanut-picking device.

During the process of peanut picking using an axial-flow picking roller, the holding force (F) of the picking roller is exerted on the peanut plant, the centrifugal force (Fc) is exerted when the roller rotates, and there is the gravitational force (G) of the plant itself. There is also a concave sieve support for the plant (Fn) and frictional force (f), and an inertial force in the opposite direction of acceleration to its own (ma). As can be seen from the accompanying figure, inside the drum, the X-axis and Y-axis of the peanut seedling are fixed, because the backward inclination of the peanut picking is α, so the grip force (F) and the X-axis of the picking are at α angles, and β is the position angle of the plant in the roller, that is, the angle between the vertical axis and the roller. This is shown in Figure 6.
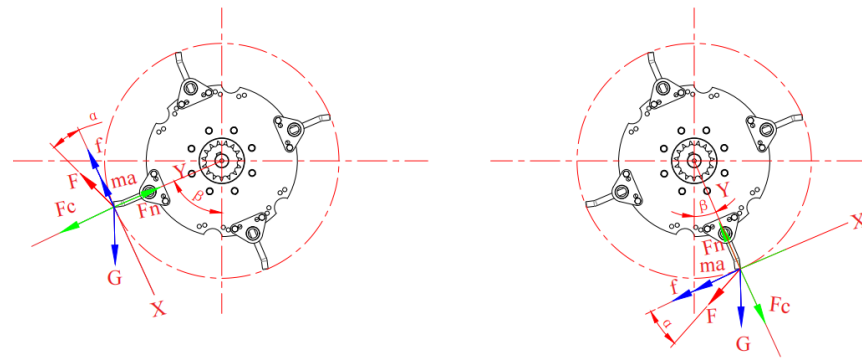
Figure 6. Analysis of the force of peanut plants in the picking roller.

The balance equation for the forces on the X-axis and Y-axis of the peanut plant at the point of contact with the peanut-picking tooth is established as follows:

$$\begin{aligned}
\sum X = 0, \ G \cdot \sin\beta - ma - f - F \cdot \cos\alpha = 0 \\
\sum Y = 0, \ F_n - F_c - F \cdot \sin\alpha - G \cdot \cos\beta = 0
\end{aligned} \tag{4}$$

The balance equation for the forces on the X-axis and Y-axis of the peanut plant leaving the peanut-picking roller from the debris discharge port yields

$$\begin{aligned}
\sum X = 0, \ -G \cdot \sin\beta - ma - f - F \cdot \cos\alpha = 0 \\
\sum Y = 0, \ F_n - F_c - F \cdot \sin\alpha - G \cdot \cos\beta = 0
\end{aligned} \tag{5}$$

According to $F_c = m\frac{v^2}{R}$, $G = mg$, the collation obtains

$$\begin{aligned}
a = g\sin\beta - \frac{F_n R - mV^2 - mgR\cos\alpha\sin\beta}{\tan\alpha Rm} - \frac{f}{m} \\
a = -g\sin\beta - \frac{F_n R - mV^2 - mgR\cos\alpha\sin\beta}{\tan\alpha Rm} - \frac{f}{m}
\end{aligned} \tag{6}$$

where F is the grasping force of the peanut-picking element, N; F_C is centrifugal force, N; G is the peanut plant's own gravity, N; F_N is the supporting force, N; f is the friction force, N.

From the mechanical equation, it can be seen that when the peanut plant enters the picking roller, its acceleration is greater than that when it leaves the picking roller; when moving in the picking roller, β continues to change due to the rotation speed of the picking roller, resulting in a continuous change in the force on the plant.

2.4.6. Number of Tooth Rows for Peanut Picking

In order to meet the dynamic balance requirements of peanut picking, the number of rows of peanut-picking teeth is generally even, and the more rows, the smaller the spacing between the rows of peanut-picking teeth, which leads to the weakening of the grasping ability of the peanut-picking teeth on the peanut seedlings, and the number of rows is too small, resulting in a reduction in the smoothness of peanut picking. The formula for calculating the number of teeth is as follows:

$$M = \frac{C \times p}{h} \tag{7}$$

where M is the number of nail teeth of the peanut-picking roller; C is the circumference of the peanut-picking roller, and the diameter of the peanut-picking roller is known to be 500 mm; then, C = π · D = 1570 mm; p is the number of rows of teeth of peanut plants at the same time; if we take 1.5–2 h as the peanut plant height, the plant height of peanut plants is 300~400 mm.

Considering the picking intensity of fresh wet peanuts from peanut plants in hilly areas, the number of peanut-picking teeth is designed as 4 rows.

2.4.7. Peanut Miscellaneous Conveying Auger

The auger is located under the peanut-picking roller, and its main function is to drive the spiral blades through spindle rotation to push the fallen peanut pods and sundries to the conveyor for cleaning. The auger is mainly composed of a spindle, a spiral blade, and a scraper, wherein the diameter of the spindle is 25 mm, the outer diameter of the spiral blade is 180 mm, the length of the scraper is 140 mm, and the total length of the bottom auger is 1350 mm, and the structure is shown in Figure 7.
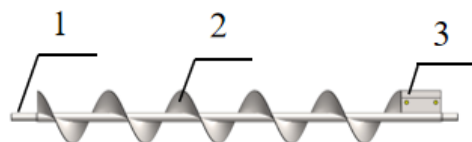

Figure 7. Peanut miscellaneous conveying auger. 1: Spindle. 2: Spiral blade. 3: Scraper.

As a transverse pushing device for peanut pods and some residual materials, the conveying efficiency of the bottom auger determines the smoothness of the peanut-picking process, and its conveying efficiency is as follows:

$$Q = \frac{\pi}{24}\left[(D - 2\lambda)^2 - d^2\right]\varphi\gamma snC \times 10^{-10} \tag{8}$$

where Q is the material conveying efficiency; s is the blade spacing of the spiral blades of the bottom auger, 250 mm; n is the rotational speed of the bottom auger, 800 rpm; C is the tilt angle coefficient; φ is the filling coefficient when pushing the material, 0.4; D is the outer diameter of the spiral blade, 180 mm; d is the inner diameter of the spiral blade, 20 mm; γ is the mass of the material per unit volume, 750 kg/m^3; λ is the gap between the spiral blades and the housing, 10 mm.

The lateral thrust efficiency of the bottom auger is calculated to be 6.4 kg/s.

2.4.8. Concave Plate Screen

(1)   Concave plate screen structure

The concave plate screen plays the role of blocking and combing the fed peanut seedlings in the process of peanut picking, and the peanut pods that are brushed off leak out through the grid of the concave plate screen, and the concave plate screen plays the role of peanut picking and the separation of peanuts and miscellaneous parts. The concave screen is mainly composed of side plates, round steel screens, and gusset plates, and the whole concave screen part is divided into a first-stage concave plate screen, a secondary concave plate screen, and a third-stage concave plate screen. This is shown in Figure 8.

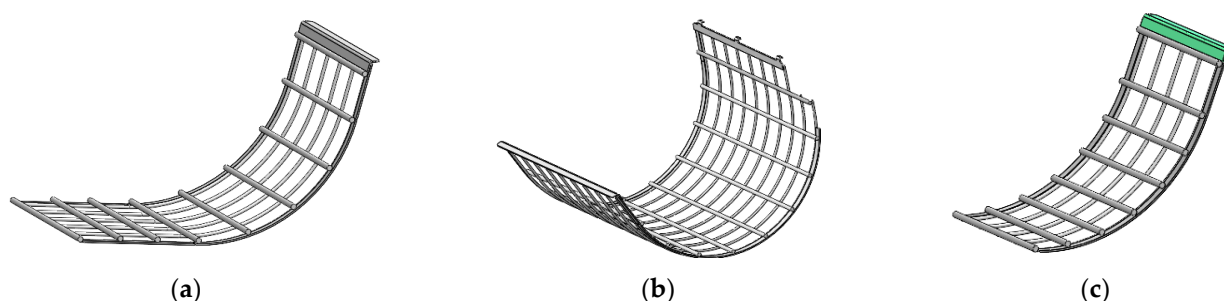**Figure 8.** Concave plate screen: (**a**) first-stage concave plate screen, (**b**) secondary concave plate screen, and (**c**) third-stage concave plate screen.

The first stage of the concave screen is installed in the peanut-seedling side of the peanut-picking system through the feeding inlet. In order to ensure that the peanut pods can smoothly pass through the peanut screen grid, the size of the sieve must be greater than

the size of the peanut pods. Through investigation and testing of peanut varieties in hilly and mountainous areas, the shape of the first stage of the concave screen grid is rectangular; the size is 65 × 70 mm, and the length is 350 mm. The secondary concave screen is installed in the middle part of the peanut-picking system in the process of peanut picking, where the peanut seedling vine stays for the longest time, so the design structure of the secondary concave plate screen is different from that of the first- and third-stage concave plate screens. In order to ensure that peanut seedlings are picked from the vine thoroughly, and for the peanut pods to have a good passing ability, the length of the secondary concave plate screen is 632 mm, and the size of the sieve grid is 65 × 70 mm. The third-stage concave screen is located in the discharge area of peanut seedling residues in the peanut-picking system, so that the peanut seedling vine residues can be discharged smoothly, and the third-stage concave screen is specially designed to have a shortened length. The length of the integral third-stage concave screen is 246 mm, and the screen grid size is designed to be 53 × 70 mm.

(2)   Peanut-picking gap and wrapping angle

The gap between peanut-picking intervals significantly impacts the efficiency of the picking process. Smaller gaps can increase the picking purity rate, but they also raise the breakage rate. Conversely, when the gap is larger, it becomes easier for peanuts to be picked incompletely or to break. Therefore, it is necessary to find a feasible picking interval that balances both the purity rate and the breakage rate.

The larger the wrapping angle, the more peanuts are picked, but the increase in the wrapping angle must increase the centre distance of the adjacent roller at the same time, so as to reduce the smoothness of the handover make it easy for the seedling vine to wrap around the roller. The wrapping angle of the first-stage concave plate screen is set to 77°; the second-stage concave plate screen is set to 140°, and the third-stage concave plate screen wrapping angle is set to 65°. The parameters of the concave plate screens at all stages are shown in Table 2.

Table 2. Concave screen parameters.

Concave Screen Category	Length (mm)	Sieve Grid Size (mm)	Wrap Corners (°)
first-stage concave plate screen	350	65 × 70	77
secondary concave plate screen	632	65 × 70	140
third-stage concave plate screen	246	53 × 70	65

2.5. Analysis of the Operational Reliability of the Picking Roller

The strength and stiffness of the peanut-picking roller determine the performance and efficiency of peanut picking, and only the peanut-picking roller with qualified strength and stiffness can meet the normal working performance of the peanut-picking combine harvester. The ANSYS Workbench finite element analysis software is used to perform static analysis and modal analysis on the peanut-picking roller, and the total deformation, stress, strain, and modal data of the peanut-picking roller were obtained.

2.5.1. Static Analysis

The characteristic parameters of the picking rollers were modelled using Solid works 2022 software, stored as IGS files, and imported into the ANSYS platform. Supports were applied to each end of the picking roller and the speed of the rollers was set to 6 rad/s. The material model in Table 3 was built in the ANSYS Workbench material library, and the material of the picking roller was set as 45 steel with a Poisson's ratio of 0.3 and density of 7850 kg/m^{-3}.

Once the harvesting unit material was created, we meshed it using the Modal module in ANSYS Workbench. Tetrahedral mesh was mainly used; the mesh element size was set to 4 mm, and there were 505,034 nodes and 168,646 elements after meshing.

Table 3. Mechanical properties of 45 steel.

Material	Poisson's Ratio	Elastic Modulus (M Pa)	Hardness (HB)	Density (kg/m^{-3})	Yield Strength (M Pa)
45 Steel	0.3	200	197	7850	355

2.5.2. Modal Analysis

Rotating peanut-picking rollers are prone to vibration, which can cause fatigue damage to the peanut-picking components, affect the service life, and even cause accidents. The peanut-picking crawler combine harvester uses a 20.2 kW single-cylinder engine, which vibrates with the peanut-picking roller during operation. Therefore, ANSYS Workbench is used to perform a modal analysis of the peanut-picking roller to check its safety, and its excitation frequency and maximum deformation were analyzed.

2.6. Test Methods and Indicators

2.6.1. Test Methods

In the process of peanut picking, various factors will have a certain impact on the picking purity rate and breakage rate of peanuts, such as pod size, plant characteristics, the structure of the fruit harvesting device, etc. The rotation speed of the roller is the key factor that determines the picking effect of the picking roller and the degree of post-harvest damage. Too little dosing will cause poor picking results, and too much dosing will cause fruit aggregation, which will affect the work of the picking rollers. The picking interval has an important impact on the picking effect; if the picking interval is too short, it will easily cause incomplete picking, and large intervals have the advantage of improving the picking power and crushing rate. Therefore, the factors that have a significant impact on the picking force and breakage rate, such as the rotation speed of the fruit picking roller, the feeding amount, and the picking distance, were selected to carry out the picking-effect experiment. After a single-factor experiment, it was determined that the speed of the fruit picking roller was 325–375 r/min, the feeding amount was 0.6–1.2 kg/s, and the picking gap was 20–40 mm.

The peanut-picking performance test was conducted in Longqiu Village, Kelu Town, Leizhou City, Guangdong Province, in mid-June 2024, with a longitude of 110° (N), a latitude of 21° (E), an average temperature of 32 °C at the time of the test, a sandy loam soil type, a bulk density of 1.38 g/cm^3, and a soil moisture content of 9.5%, and a peanut variety widely planted in this area is Yueyou 43, with a plant height of 540 mm, a planting ridge spacing of 600 mm, and a moisture content of flower-growing seedlings of 24.4%. The operating conditions of the peanut-picking combine harvester are that the plants are evenly laid in strips, and the soil carrying rate is not more than 20%. According to the actual growth of peanuts and the requirements of this test, three plots were laid for testing; the length of each plot was 30 m, where the front and back 5 m were the transition areas and the middle 10 m is the test area. We tested the quality of peanut pods picked in the test area, the quality of the unpicked pods on the peanut plant, and the quality of the ground peanut pods, and each group of experiments was repeated 3 times.

2.6.2. Test Indicators

The picking purity rate and breakage rate are important indicators to evaluate the performance of peanut picking, and the test is carried out with reference to the harvesting standard of peanut-picking combine harvesters in NY/T502-2016 "Ministry of Agriculture of the People's Republic of China Industry Standard Peanut Harvester Operation Quality" [29].

The picking purity rate refers to the ratio of the total number of peanuts picked after harvest, and the formula is

$$Y_1 = \frac{m - m_1}{m} \tag{9}$$

where Y_1 is the picking purity rate; m1 is the mass of unpicked peanut pods, kg; m is the total mass of peanut pods, kg.

The breakage rate refers to the ratio of the number of broken peanut pods to the total number of peanuts during the harvesting process, and the formula is

$$Y_2 = \frac{m_2}{m} \tag{10}$$

where Y_2 is the breakage rate; m_2 is the mass of broken peanut pods, kg; m is the total mass of peanut pods, kg.

The test scheme is a three-factor and three-level Box–Behnken test, and a response surface test is carried out on the three test factors of the peanut-picking roller speed (X_1), the feeding amount (X_2), and the peanut-picking gap (X_3), and the test factors and levels are shown in Table 4.

Table 4. Test factors and levels.

Levels	Picking Roller Speed X_1 (r/min)	Feeding Amount X_2 (kg/s)	Picking Gap X_3 (mm)
−1	325	0.6	20
0	350	0.9	30
1	375	1.2	40

3. Results

3.1. Analysis of Static Simulation Results

The total deformation contours, strain contours, and stress contours of the peanut-picking roller were obtained by solving the calculations by the ANSYS solver, as shown in Figure 9, and the simulation results are shown in Table 5.
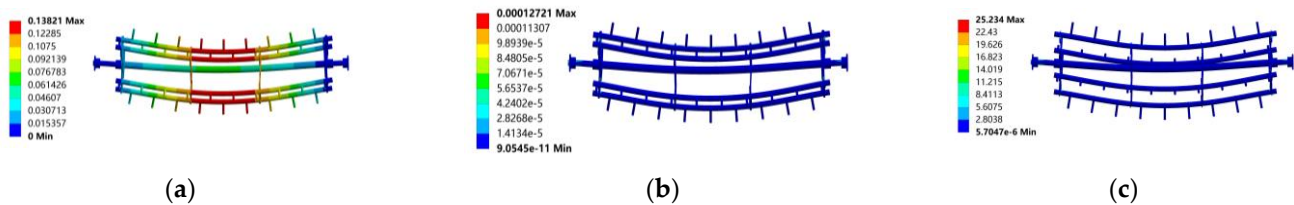

Figure 9. Contour diagram of (**a**) total deformation, (**b**) strain, and (**c**) stress of peanut−picking roller.

Table 5. The total deformation, strain, and stress values of the picking roller.

Picking Rollers	Total Deformation (mm)	Strain ($\times 10^{-4}$ mm)	Stress (M Pa)
maximum	0.138	1.2721	25.234
minimum	0.000	9.0545×10^{-7}	5.7047×10^{-6}

Compared with other parts, the middle part of the peanut-picking roller has large deformation, reaching 0.138 mm. Although it is within the allowable deformation range of peanut-picking rollers, for the safety of long-term operation in hilly and mountainous areas, the thickness of the flange disc is increased in the middle part of the peanut-picking roller to improve its supporting strength. The maximum strain of the peanut-picking roller is 1.2721×10^{-4} mm, which is small and in line with the safety of the operation. The maximum stress of the peanut-picking roller is 25.234 MPa, which meets the requirements as long as it does not exceed the allowable range according to the strength theory.

3.2. Analysis of Modal Simulation Results

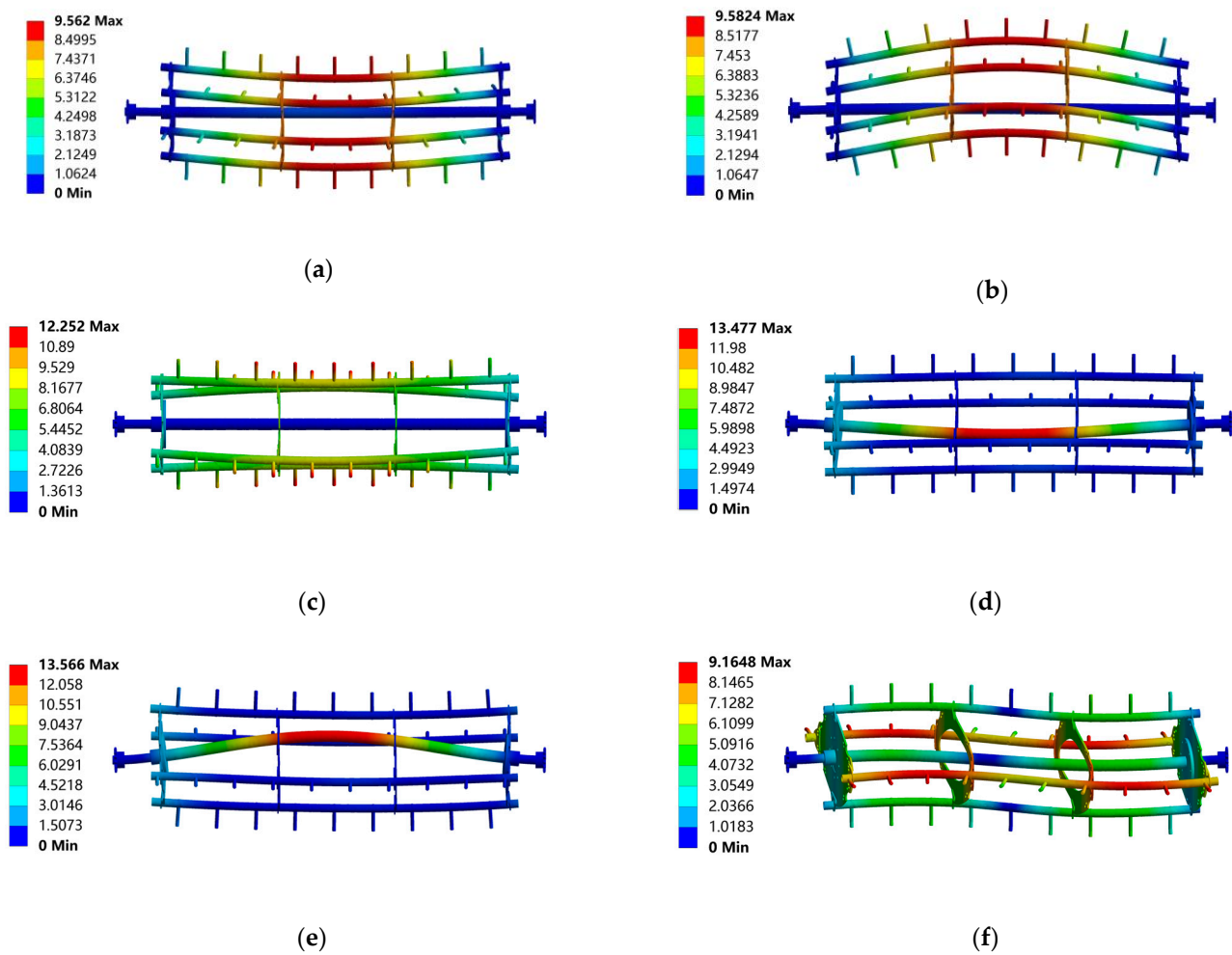The numerical simulation results are shown in Figure 10 and Table 6.

Figure 10. The modal analysis of the first six orders for picking rollers: (**a**) Model 1, (**b**) Model 2, (**c**) Model 3, (**d**) Model 4, (**e**) Model 5, and (**f**) Model 6.

Table 6. First six orders of frequency and maximum deformation of picking rollers.

Picking Roller	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Excitation frequency (Hz)	50.89	51.98	70.04	81.67	82.80	129.24
Maximum deformation (mm)	9.52	9.58	12.25	13.48	13.57	9.16

As can be seen from the graph, the first six stages of the fruit harvesting equipment have a range of 50.89 Hz to 129.24 Hz. That is, when the frequency of the external disturbance is close to the previous six modes, there will be a risk of resonance. The second bending vibration has a great influence on the force of the fruit picking machine; the vibration of the fruit picking machine is a linear combination of various modes, and the lower mode has a greater impact on the vibration of the equipment. The vibration characteristics of the fruit harvesting mechanism depend on its low-order modes. Regarding the overall vibration of the fruit harvesting mechanism, the main mode of the first order is the Z-axis bending vibration of the fruit picking mechanism, which causes the whole fruit to bend and deform, and the middle part is the largest. The main modes of the second order are similar to those of the first order, but their deformation changes significantly. The third-order primary mode is a bending–torsional composite vibration along the Z-axis and the horizontal axis. The main modes of order 4 and order 5 are similar; both have bending vibrations of 81.67 Hz and 82.80 Hz along the Z-axis. The sixth-order mode is characterized

by 129.24 Hz, which is dominated by the bending of the X-axis and the distortion of the Z-axis.

When there is a relationship between the excitation frequency and the natural frequency of the peanut-picking roller, the roller does not resonate [30–32].

$$0.75W_0 < W < 1.3W_0 \tag{11}$$

where W_0 is the natural frequency, Hz; W is the excitation frequency, Hz.

The power source selected for this peanut-picking roller is a diesel engine with low excitation frequency, so the main vibration of the whole fuselage is 20–40 Hz, or low-frequency vibration. As can be seen in the above figure, the frequency range of the vibration of the peanut-picking roller is 50.89~129.24 Hz, which is not in the same range as the frequency of the fuselage, so the excitation of the diesel engine will not resonate with the peanut-picking roller, indicating that the design of this structure is more reasonable.

3.3. Test Results

The Box–Behnken test is designed with a three-factor three-level test, including 17 sets of tests, and the test protocol is generated using Design Expert 13 software; the results are shown in Table 7.

Table 7. Test schemes and results.

No.	X_1 (r/min)	X_2 (kg/s)	X_3 (mm)	Y_1 (%)	Y_2 (%)
1	375	0.6	30	98.91	7.98
2	350	0.6	20	98.52	5.96
3	350	0.9	30	98.63	5.45
4	325	0.9	40	95.24	5.88
5	375	0.9	40	97.64	7.82
6	350	1.2	40	96.34	6.65
7	325	0.6	30	95.81	5.45
8	375	0.9	20	98.93	9.43
9	325	0.9	20	95.75	5.28
10	350	0.9	30	98.68	5.28
11	350	0.6	40	96.36	4.72
12	375	1.2	30	95.98	10.14
13	350	0.9	30	98.47	5.02
14	350	0.9	30	98.09	5.32
15	350	1.2	20	95.39	7.86
16	350	0.9	30	98.85	4.95
17	325	1.2	30	93.64	6.54

3.4. Analysis of Test Results

3.4.1. Regression Model Building

The data in Table 7 were analyzed by Design-Expert software, and the quadratic regression models of Y_1 (picking purity rate) and Y_2 (breakage rate) were obtained, respectively:

$$\begin{aligned}
Y_1 &= 98.54 + 1.38X_1 - 1.03X_2 - 0.3763X_3 - 0.1900X_1X_2 \\
&\quad - 0.1950X_1X_3 + 0.775X_2X_3 - 1.11X_1^2 - 1.35X_2^2 - 0.5432X_3^2 \\
Y_2 &= 5.20 + 1.53X_1 + 0.8850X_2 - 0.4325X_3 + 0.2675X_1X_2 \\
&\quad - 0.5525X_1X_3 + 0.0075X_2X_3 + 1.56X_1^2 + 0.7593X_2^2 + 0.3343X_3^2
\end{aligned} \tag{12}$$

where Y_1 is the picking purity rate, %; Y_2 is the breakage rate, %; X_1 is the speed of the peanut-picking roller, r/min; X_2 is the feeding amount, kg/s; X_3 the peanut-picking gap, mm.

3.4.2. Regression Equation Analysis

As shown in Table 8, the analysis of variance of the picking purity rate and the breakage rate shows that when $p < 0.01$, the influencing factors have a highly significant impact on the regression equation, and when $p < 0.05$, the influencing factors have a significant impact on the regression equation. Among the main factors affecting the picking purity rate, X_1 (the speed of peanut-picking roller) and X_2 (the feeding amount) were extremely significant, and X_3 (the peanut-picking gap) was significantly affected. Among the interaction factors, the effect of X_2X_3 is extremely significant. Among the secondary terms, X_1^2 and X_2^2 had a very significant effect, and X_3^2 had a significant effect. Among the main factors affecting the breakage rate, X1 (the speed of the peanut-picking roller), X_2 (the amount of feeding), and X_3 (the peanut-picking gap) were all significantly affected. Among the interaction factors, X_1X_3 had a very significant effect. Among the secondary terms, X_1^2 and X_2^2 had a very significant effect, and X_3^2 had a significant effect. According to the coefficient of the regression equation, the effects on the picking purity rate from large to small were X_1 (the speed of the peanut-picking roller), X_2 (the feeding amount), and X_3 (the peanut-picking gap). The effects on the breakage rate from large to small are X_1 (the speed of the peanut-picking roller), X_2 (feeding amount), and X_3 (peanut-picking gap).

Table 8. Variance analysis of regression equation.

Source	Rate of picking purity, Y_1			
	Sum of squares	Degree of freedom	F value	Significant level p
Model	43.04	9	39.27	<0.0001 **
X_1	15.18	1	124.66	<0.0001 **
X_2	8.51	1	69.87	<0.0001 **
X_3	1.13	1	9.3	0.0186 *
X_1X_2	0.1444	1	1.19	0.3122
X_1X_3	0.1521	1	1.25	0.3006
X_2X_3	2.42	1	19.86	0.0029 **
X_1^2	5.19	1	42.66	0.0003 **
X_2^2	7.65	1	62.85	<0.0001 **
X_3^2	1.24	1	10.2	0.0152 *
Residual	0.8524	7		
Lack of fit	0.5213	3	2.1	0.2431
Pure error	0.3311	4		
Total	43.89	16		
Source	Rate of breakage, Y_2			
	Sum of squares	Degree of freedom	F value	Significant level p
Model	42.14	9	68.34	<0.0001 **
X_1	18.67	1	272.46	<0.0001 **
X_2	6.27	1	91.46	<0.0001 **
X_3	1.5	1	21.84	0.0023 **
X_1X_2	0.2862	1	4.18	0.0802
X_1X_3	1.22	1	17.82	0.0039 **
X_2X_3	0.0002	1	0.0033	0.9559
X_1^2	10.3	1	150.38	<0.0001 **
X_2^2	2.43	1	35.43	0.0006 **
X_3^2	0.4704	1	6.87	0.0344 *
Residual	0.4796	7		
Lack of fit	0.3015	3	2.26	0.224
Pure error	0.1781	4		
Total	42.62	16		

Note: $p < 0.01$ (highly significant, **); $p < 0.05$ (significant, *).

3.5. Analysis of the Influence of Interaction Factors on Picking Performance

3.5.1. Analysis of the Influence of Interaction Factors on Picking Purity Rate

As shown in Figure 11, the response surface of interaction factors to the picking purity rate is generated by Design-Expert software, and the effects of the speed of the peanut-picking roller, the feeding amount, and the picking gap were analyzed.
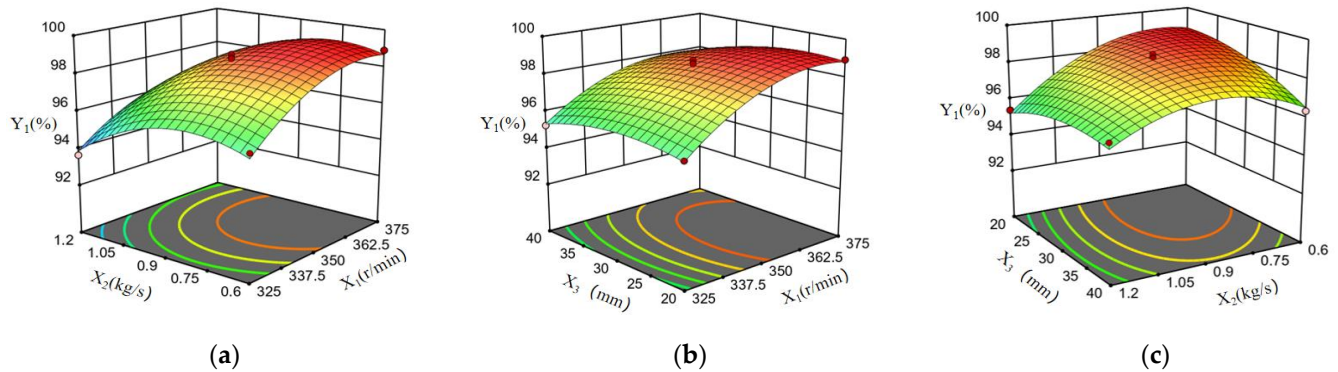

Figure 11. The influence of interaction factors on picking purity rate. (**a**) The effect of peanut-picking roller speed and feeding amount on picking purity rate. (**b**) The effect of peanut-picking roller speed and peanut-picking gap on picking purity rate. (**c**) The effects of feeding amount and peanut-picking gap on picking purity rate.

In order to explore the effects of peanut-picking roller speed and feeding amount on picking purity, the picking purity was 98.85% when the peanut-picking roller speed was 350 r/min, the feeding amount was 0.9 kg/s, and the peanut-picking gap was 30 mm. With the increase in the peanut picking roller speed and feeding amount, the picking purity first increased and then decreased. When the speed of the picking roller is too low, the picking intensity is insufficient, and the pods may not be picked effectively, resulting in a decrease in picking purity. The feed amount is too small, and the roll utilization rate is low, which affects the cleaning efficiency. When the dosing amount is too large, the load in the peanut-picking room increases, and the picking roller may not be able to process all the fed peanut seedlings in time, resulting in some pods not being picked, reducing the picking purity. An excessive feed amount can also cause the roller to clog and affect the normal operation of the equipment. To explore the effects of the peanut-picking roller speed and peanut-picking gap on the picking purity rate, when the speed of the peanut-picking roller is 375 r/min, the peanut-picking gap is 20 mm, and the fixed feeding amount is 0.9 kg/s, the picking purity rate is 98.93%. When the speed of the peanut-picking roller is constant, if the peanut-picking gap is too large, the pods may not be effectively grasped, resulting in a decrease in the picking purity rate. A small interval between peanut picking, although it can ensure that the peanut is picked, may cause peanut damage and also affect the picking purity rate. Therefore, the picking gap is adjusted according to the size and hardness of the pods to guarantee a high picking purity rate. In order to explore the effect of the feeding amount and peanut-picking gap on picking purity, when the feeding amount was 0.6 kg/s, the peanut-picking gap was 20 mm, and the picking purity was 98.52% when the picking roller was 350 r/min. A larger feed rate requires a larger pick-up gap to avoid pod build-up and damage.

3.5.2. Analysis of the Influence of Interaction Factors on the Breakage Rate

As shown in Figure 12, the response surface of interaction factors to the breakage rate is generated by Design-Expert software, and the effects of the speed of the peanut-picking roller, the feeding amount, and the picking gap were analyzed.
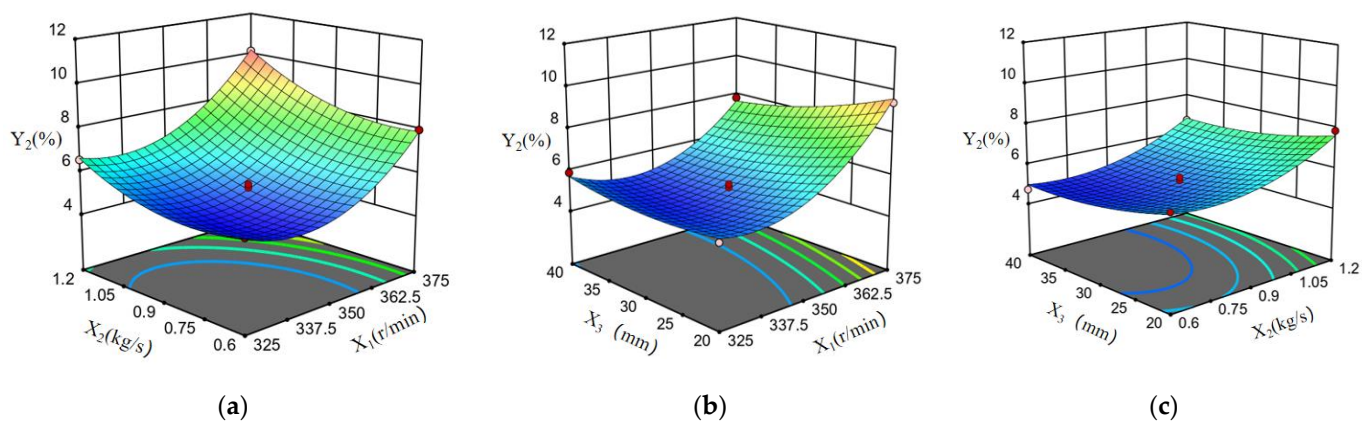
Figure 12. The influence of interaction factors on breakage rate. (**a**) The effect of peanut-picking roller speed and feeding amount on breakage rate. (**b**) The effect of peanut-picking roller speed and peanut-picking gap on breakage rate. (**c**) The effects of feeding amount and peanut-picking gap on breakage rate.

In the interaction process of the two influencing factors, when the speed of the peanut-picking roller is 350 r/min, the feeding amount is 0.6 kg/s, and the picking gap is 40 mm; the pod breakage rate is the lowest, which is 4.72%. In Figure 12a, with the increase in the peanut-picking roller speed and feeding amount, the pod breakage rate increased, and the pod breakage rate reached 10.14% when the speed of the peanut-picking roller was 375 r/min and the feeding amount was 1.2 kg/s. When the rotation speed is too high, the impact force of the roller on the pod increases, which can easily cause mechanical damage to the peanut, thereby increasing the breakage rate. When the feeding amount is too large, the peanuts accumulate in the picking room, which increases the extrusion and collision between the pods, which can easily lead to pod damage. In Figure 12b, the effects of peanut-picking roller speed and peanut-picking gap on the pod breakage rate were shown; when the peanut-picking roller speed is 350 r/min, the peanut-picking gap is 30 mm, and the fixed feeding amount is 0.9 kg/s, the pod breakage rate is 4.95%. The larger the speed of the peanut-picking roller, the smaller the peanut-picking gap, and the pod breakage rate shows an increasing trend. The combination of high speed and a large gap could easily lead to missed picking, and the combination of low speed and a small gap could lead to pod damage. Therefore, it is necessary to select the appropriate combination of speed and clearance according to the characteristics of the pod and the working conditions of the equipment. In Figure 12c, the effects of feeding amount and peanut-picking gap on the pod breakage rate are shown, and the pod breakage rate is 5.02% when the feeding amount is 0.9 kg/s, the peanut-picking gap is 30 mm, and the fixed peanut-picking roller speed is 350 r/min. With the increase in the feeding amount, the gap between picking and the breakage rate of pods increased, and the combination of a large feeding amount and a small gap could easily lead to pod extrusion and mechanical damage, while the combination of a small feeding amount and a large gap could lead to missing peanuts during picking. Therefore, it is necessary to reasonably adjust the feeding amount and peanut-picking gap according to the actual situation.

3.6. Determination of Optimal Operating Parameters

According to the optimization of the peanut-picking performance parameters of the crawler flower-harvesting combine, the picking purity should reach the highest rate and the breakage rate should reach the lowest value. According to the actual working conditions of

the peanut combine harvester and the analysis results of the above correlation regression equations, the optimization constraints are selected as the following formula:

$$\min Y(X) = \begin{cases} Y_1(X_1 X_2 X_3) \\ Y_2(X_1 X_2 X_3) \end{cases}$$

$$\begin{cases} -1 \leq X_1, X_2, X_3 \leq 1 \\ 95\% \leq Y_1 \leq 100\% \\ 0 \leq Y_2 \leq 5\% \end{cases} \tag{13}$$

When the speed of the peanut-picking roller is 341.93 r/min, the feeding amount is 0.75 kg/s, and the peanut-picking gap is 32.12 mm, the picking purity rate is 97.97%, and the breakage rate is 4.63%.

3.7. Field Test Validation

In order to verify the accuracy of the optimization theoretical model, a verification test is carried out on the basis of the test conditions. The speed of the peanut-picking roller is selected to be 342 r/min, the feeding amount is 0.75 kg/s, and the peanut-picking gap is 32 mm, and three verification tests were carried out according to the test scheme in Section 2.6. The results were averaged, and the field test is shown in Figure 13.

Figure 13. Field test of fresh-peanut-picking crawler combine harvester.

As shown in Table 9, the field test showed that the picking purity rate of the pods is 98.95%, and the error is 0.98% compared with the predicted value under the conditions of 342 r/min rotation speed, 0.75 kg/s feeding amount, and 32 mm peanut-picking gap. The pod breakage rate is 4.23%, with an error of 0.4% compared with the predicted value. The results show that the optimized model is reliable and can predict the peanut-picking purity rate and breakage rate under different equipment parameters.

Table 9. The optimization and verification solutions.

Items	X_1 (r/min)	X_2 (kg/s)	X_3 (mm)	Y_1 (%)	Y_2 (%)
Optimization solution	341.93	0.75	32.12	97.97	4.63
Verification solution	342	0.75	32	98.95	4.23

4. Discussion

The fresh-peanut-picking crawler combine harvester has the characteristics of adapting to small fields in hilly areas and harvesting fresh peanuts. The whole machine adopts a lightweight design to reduce the assembly. When carrying out peanut harvesting, the

equipment driving speed, which represents the feeding amount, has an impact on the picking rate and crushing rate of peanut pods. This is because when the equipment driving speed is higher, the number of peanut seedlings that enter the fruit picking room increases, which will cause blockage and seedling accumulation, which is not conducive to the fruit picking operation and subsequent seedling discharge, and the appropriate driving speed should be selected according to the specific field conditions and peanut varieties. In general, a moderate travel speed can reduce the crushing rate while maintaining a high picking rate, thus improving the overall harvesting efficiency. This equipment takes peanut varieties in hilly areas as the harvesting object, and because the chassis adopts a crawler type, it has strong adaptability to the terrain in the hilly areas of southern China and is more targeted. For the follow-up optimization direction, the first area of focus is the design of fruit picking teeth, because fresh peanut seedlings have stronger toughness, so there are higher requirements for the design form and material of fruit picking teeth. The second is the efficiency of peanut harvesting; due to the terrain limitations, the model is lightweight and simplified, and the subsequent optimization design of the fruit picking roller improves the efficiency of peanut harvesting.

5. Conclusions

(1) According to the topography and peanut planting mode in hilly areas, a peanut-picking device for peanut harvesting in hilly areas is designed, and its working process and key components were designed and analyzed. ANSYS Workbench software is used to check the reliability of the designed peanut-picking device, and its maximum stress is 25.234 M Pa, and the frequency range of vibration is 50.89~129.24 Hz, which met the operation requirements.

(2) The test results showed that when the speed of the peanut-picking roller is 341.93 r/min, the feeding amount is 0.75 kg/s, and the picking gap is 32.12 mm, the picking purity rate and breakage rate are 97.97% and 4.63%, respectively. The field test showed that the picking purity rate is 98.95%, and the error is 0.98% compared with the predicted value when the speed of the picking roller is 342 r/min, the feeding amount is 0.75 kg/s, and the picking gap is 32 mm. The pod breakage rate was 4.23%, and the error was 0.91% compared with the predicted value, indicating that the optimized model was reliable and predictive.

(3) The fresh-peanut-picking crawler combine harvester is suitable for peanut planting in hilly areas, with a wide range of adaptability and strong pertinence. Fresh peanut seedlings have strong toughness, and the form and material of peanut-picking teeth are more demanding. Due to terrain limitations, it is necessary to make the equipment lightweight and simplified and then optimize the design of peanut-picking rollers to improve the efficiency of peanut picking.

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