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Design and Test of a Tangential-Axial Flow Picking Device for Peanut Combine Harvesting

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Abstract: This study presents a tangential-axial flow picking device for peanut combine harvesting. The device was designed with reference to the tangential-axial flow threshing mechanism of the grain combine harvesters. The main purpose of this study was to solve the problem of the high rate of loss and damage in the picking operation of the peanut combine harvesters in China. Through the theoretical analysis and design calculation of the key components of the peanut picking device, the structural and working parameters were determined. The orthogonal test was carried out by taking the feeding amount of the peanut plant, the picking clearance, the speed of the tangential cylinder, and the speed of the axial cylinder as the test factors. Additionally, the non-picking loss rate, entrainment loss rate, and damage rate of the peanut pods were used as the test indexes. The test results were analyzed by range analysis and analysis of variance, and the test parameters were optimized by fuzzy comprehensive evaluation method. The optimal parameter combination for the tangential-axial flow picking device was determined as follows. The feeding amount of the peanut plant was 2 kg/s, the picking clearance was 35 mm, the speed of the tangential cylinder was 360 r/min, the speed of the axial cylinder was 425 r/min. At this time, the non-picking loss rate was 0.52%, the entrainment loss rate was 0.54%, and the damage rate was 0.75%. The test results fully met the standard requirements of the peanut picking operation. This research provides a technical basis for the application of the tangential-axial flow picking device in peanut combine harvesters.

Keywords: peanut; combine harvesting; tangential-axial flow; picking device; fuzzy comprehensive evaluation

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1. Introduction

Peanuts (*Arachis hypogaea L.*) are one of the leading oil crops in the world today. The main peanut-growing countries include China, the United States, India, Australia, Senegal, Nigeria, Vietnam, Malawi, and so on. In 2020, China's peanut planting area was 4.73 million hectares and the total output was 17.99 million tons [1]. In recent years, with the development of the large-scale peanut planting in Huang-Huai-Hai region and Northeast of China, and the increasingly prominent problems such as labor shortage and difficulty in hiring workers in peanut harvest season, farmers engaged in peanut planting urgently need machinery that can realize peanut harvest with high quality and high efficiency [2]. The peanut combine harvester can complete a series of operations such as pick-up, picking, cleaning, and collecting at one time, which can effectively reduce the labor intensity and improve productivity. It has become an important direction in the research and development of peanut harvesting machinery in China at present and in the future [3].

The picking operation of the peanut pods is the key link of peanut combine harvester, which directly affects the operation quality and performance of the whole machinery. At present, the research and application of peanut combine harvesters worldwide mainly occur in the United States, and the structural types of the picking devices are mainly divided into multi-stage tangential flow and axial flow [4]. The picking device of the multi-stage tangential flow completes the picking operation through multiple tangential cylinders arranged horizontally, such as 3384 and 3386 traction type peanut combine harvesters of Kelley Manufacturing Company (KMC) and 9980 self-propelled peanut combine harvesters of AMADAS Industries. The picking device of the axial flow completes the picking operation through the axial cylinder arranged horizontally or longitudinally, such as the Twin Master Series traction type peanut combine harvester of Colombo North America. However, Chinese peanut varieties are mostly erect, while American peanut varieties are mostly climbing. Additionally, the peanut planting modes and soil types are different. Therefore, the direct introduction of the American peanut combine harvesters cannot meet the actual harvest requirements of the Chinese peanut. At present, through the introduction of the key technologies of the American peanut combine harvester and independent innovative design, some researchers and related enterprises have developed a variety of the peanut combine harvester suitable for Chinese peanut harvesting operations. The picking devices of these machines also mainly adopt the structural type of single axial flow [5,6] or multi-stage tangential flow [7,8], but these two devices still have the problem of high loss rate and damage rate in the practice of peanut picking.

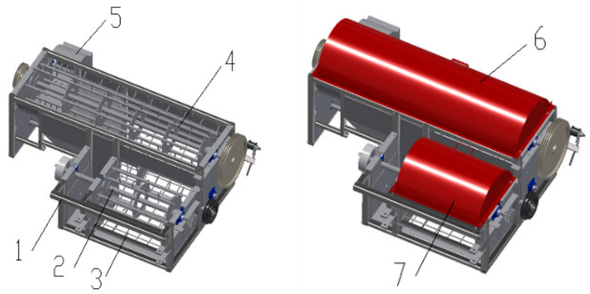
In order to solve the problem, based on the tangential-axial flow threshing technology of the grain combine harvester and according to Chinese peanut varieties, planting agronomy and harvest mode, a tangential-axial flow picking device for peanut combine harvester is designed, developed, and tested. It is hoped that this study can solve the problem of high loss rate and damage rate in the picking process of peanut combine harvesting in China and improve the quality of peanut combine harvesting.

2. Materials and Methods

2.1. Design of Overall Structure and Principle

2.1.1. Overall Structure

The picking device is designed to separate the peanut pods from the vines. It is an important part of the peanut combine harvester. At present, the picking devices used in Chinese peanut combine harvesters generally have the problems of high loss and damage, and some picking devices developed and applied overseas cannot adapt to Chinese peanut varieties and planting patterns. Therefore, it is necessary to develop a new type of high-quality and low-loss picking device according to the factors such as the cultivated varieties, planting mode, and harvest characteristics in the main peanut producing areas in China, so as to meet the needs of efficient peanut harvest. At present, the working width of the peanut combine harvester used in China is mostly 2500 mm, which is also adopted in this study. According to the layout and size of the key devices such as pick-up, cleaning, and collecting of the existing peanut combine harvesters, the length of the picking device is 2350 mm, the width is 1810 mm, and the height is 1030 mm. Meanwhile, on the basis of the picking operation requirements and referring to the structural type and layout of the tangential-axial flow threshing device of the grain combine harvesters [9–12], the tangential-axial flow picking device of the peanut combine harvester is designed, as shown in Figure 1. It mainly consists of a frame, tangential cylinder, axial cylinder, concave screen, screw auger, outer shell, vine discharging assembly, etc. Among them, the two cylinders are placed transversely, the tangential cylinder is in the front and the axial cylinder is in the back. Additionally, their axes are parallel and aligned at one end. The outer shell of the picking device comprises a tangential cylinder and an axial cylinder. The inner surface of the axial cylinder outer shell is distributed with a spiral deflector suitable for the rotation direction of the picking cylinder. The screw auger is located below the axial cylinder, and the vine discharging assembly is located on the end side of the axial cylinder.

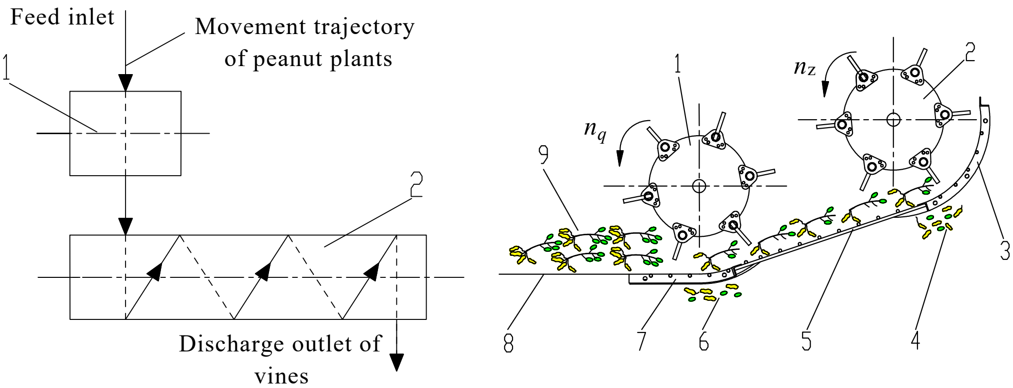


(**a**) (**b**)

Figure 1. Structure diagram of picking device: 1. Frame; 2. Tangential cylinder; 3. Concave screen; 4. Axial cylinder; 5. Vine discharging assembly; 6. Axial cylinder outer shell; 7. Tangential cylinder outer shell. (**a**) Without the outer shell. (**b**) With the outer shell.

2.1.2. Working Principle

The operation flow and principle of the designed peanut picking device are shown in Figure 2. During operation, the peanut plants are transported by the pick-up device across the conveying bridge into the tangential cylinder, and the initial picking operations such as grasping, beating, and kneading of peanut plants are completed under the joint action of the tangential cylinder and concave screen. The picked peanut pods fall into the cleaning device through the screen hole of the concave screen. The remaining peanut plants continue to move to the axial cylinder to complete the secondary picking operation under the joint action of the axial cylinder and the concave screen. At this time, the peanut pods picked from the front part of the axial cylinder directly fall into the cleaning device through the screen hole of the concave screen. Additionally, the rear parts fall into the screw auger, then they are transported to the cleaning device. The peanut vines enter the collecting box through the discharging assembly. At this point, the picking operation of the peanut plants has been completed.



(**a**) (**b**)

Figure 2. Operation flow and principle of picking device: 1. Tangential cylinder; 2. Axial cylinder; 3. Concave screen of axial cylinder; 4. Mixture of axial cylinder; 5. Concave screen of transition section; 6. Mixture of tangential cylinder; 7. Concave screen of tangential cylinder; 8. Feed inlet; 9. Peanut plants. (**a**) Operation flow. (**b**) Operation principle.

2.2. Structural Design of the Tangential Cylinder

The spike tooth cylinder has been widely used in the threshing of the grain combine harvesters because of its strong grasping and separating capacity [11–14]. Therefore, the tangential cylinder of this design also adopts the spike tooth structure. As shown in Figure 3, the designed tangential cylinder is mainly composed of the toothed rod, toothed rod connector, spike tooth, toothed rod mounting disc, and transmission shaft. The power of the tangential cylinder comes from the axial cylinder. During operation, the power is transmitted through the double row sprocket at one end, and then the tangential cylinder is driven to rotate through the transmission shaft. Meanwhile, power is transmitted forward to the pick-up device through the sprocket of the tangential cylinder. Additionally, power is also transmitted downward to the cleaning device through the pulley at the end of the tangential cylinder.

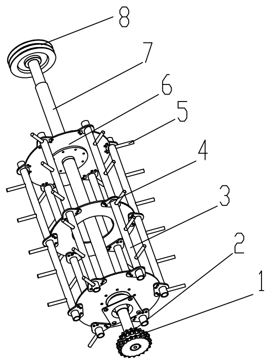


Figure 3. Structure diagram of tangential cylinder: 1. Double row sprocket; 2. Sprocket; 3. Toothed rod; 4. Toothed rod connector; 5. Spike tooth; 6. Toothed rod mounting disc; 7. Transmission shaft; 8. Pulley.

2.2.1. Determination of the Length

The main function of the tangential cylinder is to complete the initial picking operations such as grasping and beating of the peanut plants. Its effective working length is closely related to the carrying capacity of the peanut plants. According to the effective connection between the tangential cylinder and the conveying bridge (width 800 mm) of the front pick-up device, and to ensure that the peanut plants that have completed the initial picking enter the axial cylinder from the side as far away as possible, so as to prolong the picking time, the designed length of the tangential cylinder is 680 mm.

2.2.2. Determination of the Number of Toothed Rods and Spike Tooth Parameters

In order to ensure the balance when the cylinder rotates, the number of the toothed rods is usually an even number [13]. According to the previous research, the toothed rod of the tangential cylinder is designed as 6 rows, and the rods are evenly distributed according to the circumference. Considering the double action of grasping and picking, and the working length of the tangential cylinder is short, the rod spacing distribution of 3 rows of 6 teeth and 5 teeth are designed, respectively. The spike teeth on each rod are evenly arranged and the spike teeth on the adjacent two toothed rods are staggered. The transverse spacing between two adjacent spike teeth on the same toothed rod is 130 mm, and the tooth trace spacing between different toothed rods is 65 mm. The spike teeth are cylindrical, with a tooth height of 60 mm and a diameter of 12 mm.

2.2.3. Determination of the Diameter and Speed

The diameter of the tangential cylinder (including spike teeth) is mainly determined by the feeding amount of the peanut plants, the speed of the cylinder, and the size of the peanut plants. Generally, when the diameter of the cylinder is large, the smoothness and efficiency of the picking operation are higher, but a diameter that is too large will also increase the overall structural size of the picking device. On the contrary, if the diameter is too small, it is very easy to cause entanglement and blockage of peanut plants, and even damage to working parts. In addition, the diameter of the tangential cylinder meets the following equation:

$$D_q = D_{qg} + 2h_q \quad (1)$$

where D_q is the diameter of the tangential cylinder, mm; D_{qg} is the circumferential diameter of the toothed rods, which shall generally be greater than 300 mm [13]; h_q is the height of the spike teeth, mm.

According to the growth height of the peanut plants, the characteristics of the peanut stems and leaves, the diameter series of the threshing cylinder of the grain combine harvesters is mostly 450–650 mm [11–14]. Through comprehensive analysis, the designed diameter of the tangential cylinder is 500 mm.

The speed of the tangential cylinder is mainly determined according to the linear speed at the end of the spike teeth when picking peanut pods and meets the following equation [14]:

$$n_q = 6 \times 10^4 \frac{v_q}{\pi D_q} \tag{2}$$

where n_q is the speed of the tangential cylinder, r/min; v_q is the linear speed at the end of the spike teeth, m/s.

On the basis of the relevant research results [7,8,15], the linear speed at the end of the spike teeth of the tangential cylinder has better picking performance when it is 8–12 m/s. Bringing the data into Equation (2), it can be calculated that the speed range of the tangential cylinder is 306–458 r/min. On the basis of the preliminary picking function of the tangential cylinder and considering the reasons such as reducing the damage caused by striking and ensuring the smooth backward transportation of peanut plants to the axial cylinder, the speed of the tangential cylinder should not be too high [12,15]. However, when the speed of the tangential cylinder is too low, the picking function cannot be well realized, and the productivity of picking operation is seriously reduced. According to the result of the pre-test, the speed of the tangential cylinder is designed to be 360–420 r/min.

2.3. Structural Design of the Axial Cylinder

In order to facilitate trial production and reduce processing cost, the axial cylinder also adopts a spike tooth structure. As shown in Figure 4, the designed axial cylinder is also composed of the toothed rod, toothed rod connector, spike tooth, toothed rod mounting disc, and transmission shaft. The power of the axial cylinder comes from the engine. During operation, the power is transmitted through the large pulley at one end, which drives the axial cylinder to rotate through the transmission shaft. At the same time, one power is transmitted to the tangential cylinder through the double row sprocket on the axial cylinder, the other is transmitted to the vine discharging assembly at the tail of the axial cylinder through the small pulley, and the third is transmitted to the screw auger through the sprocket of the axial cylinder.

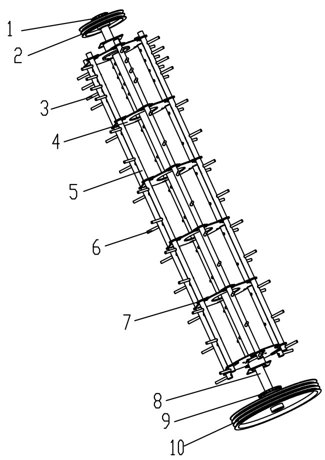


Figure 4. Structure diagram of axial cylinder: 1. Sprocket; 2. Small pulley; 3. Spike teeth of vine discharging; 4. Toothed rod mounting disc; 5. Toothed rod; 6. Spike tooth; 7. Toothed rod connector; 8. Transmission shaft; 9. Double row sprocket; 10. Large pulley.

2.3.1. Determination of the Length

The length of the axial cylinder determines the picking time and has an important influence on picking performance. Generally speaking, for a single peanut plant, the longer the picking time, the higher the picking rate. However, if the axial cylinder is too long this will also increase the picking power consumption and cleaning load (the broken number of vines increased). On the contrary, if the picking time is short, the non-picking rate will increase. During the picking operation, the peanut plant will make a spiral movement along the transmission shaft of the axial cylinder under the joint action of the spike teeth, the outer shell, and the concave screen. In general, the length of axial cylinder meets the following equation.

$$L_z = L_{zz} + L_{zp} \tag{3}$$

where L_z is the length of the axial cylinder, mm; L_{zz} is the length of the picking section of the axial cylinder, mm; L_{zp} is the length of the vine discharging section of the axial cylinder, mm.

Among them, the length of the picking section of the axial cylinder meets the following equation [15]:

$$L_{zz} = V_z t \tag{4}$$

where V_z is the axial movement speed of the peanut plant during picking, m/s; t is the picking time, s.

Some research results show that the optimum axial movement speed of peanut plant in axial cylinder picking operation is 483–600 m/s, and the picking time is 2–3 s [15,16]. Bringing these data into Equation (4), it can be obtained that the length of the picking section of the axial cylinder ranges from 966 to 1800 mm. Comprehensively considering the operating width of the peanut combine harvesters, the length of the tangential cylinder, and the characteristics of peanut plants after picking, it is finally determined that the length of the picking section is 1500 mm and the length of the vine discharging section is 400 mm, so, the length of the axial cylinder is 1900 mm.

2.3.2. Determination of the Number of Toothed Rods and Spike Tooth Parameters

In order to optimize the distribution density of the spike teeth of the picking cylinder, the number of the toothed rods is designed to be 6 and evenly distributed according to the circumference. Considering the long effective working length of the axial cylinder, in order to improve the picking efficiency and reduce the power consumption, the spike teeth on each toothed rod are designed to be evenly distributed and arranged according to the helix. Generally speaking, the number of helices is equal to the number of spike teeth passing through each tooth trace. The denser the spike teeth that are arranged spirally, the stronger the corresponding picking ability, but the too dense spike teeth will also cause peanut vine breakages and increase power consumption.

The number of the helixes is arranged according to the spike teeth of the threshing cylinder of the grain combine harvesters (mostly 2–5) [12–14]. During the preliminary tests, the spike teeth on the axial cylinder are finally designed to be arranged according to three helixes. According to the size of the peanut plants, the distance between adjacent spike teeth on the same toothed rod is designed to be 180 mm, and the distance from side teeth to the end face of the toothed rod is 30 mm. The distance between spike teeth of the vine discharging is 60 mm, and the distance from side teeth to the end face of the toothed rod is designed to be 72 mm. At the same time, in order to facilitate processing, the sizes of spike teeth of the picking and vine discharging of the axial cylinder are designed to be the same as that of the tangential cylinder.

2.3.3. Determination of the Diameter and Speed

The diameter of the axial cylinder also has an important influence on picking performance. When other conditions are certain, the cylinder diameter is large, and the smoothness and efficiency of picking operation are also high. However, a diameter too large will increase the overall structural size and picking damage rate of the device. When the diameter of the cylinder is too small, it is easy to entangle and block the peanut vines. Similar to the tangential cylinder, the diameter of the axial cylinder meets the following equation:

$$D_z = D_{zg} + 2h_z \quad (5)$$

where D_z is the diameter of the axial cylinder, mm; D_{zg} is the circumferential diameter of the toothed rods, which shall generally be greater than 300 mm [13]; h_z is the height of the spike teeth, mm.

According to the diameter of the existing peanut axial cylinder and considering the convenience of processing and installation, the diameter of the axial cylinder and the tangential cylinder are designed to be the same, that is, the diameter of the axial cylinder is 500 mm.

The speed of the axial cylinder is mainly determined by the linear speed at the end of the spike teeth when picking peanut pods and meets the following equation [14].

$$n_z = 6 \times 10^4 \frac{v_z}{\pi D_z} \quad (6)$$

where n_z is the speed of the axial cylinder, r/min; v_z is the linear speed at the end of the spike teeth, m/s.

According to the relevant research results [6,17–19], the axial cylinder has better picking performance when the linear speed at the end of spike teeth is 9–14 m/s. Bringing the data into Equation (6), it can be calculated that the speed range of the axial cylinder is 344–535 r/min. The preliminary pre-test research shows that when the speed of the axial cylinder is less than 400 r/min, the picking productivity is low, and the blockage problem will occur under the condition of large feeding amount. However, when the speed of the axial cylinder exceeds 475 r/min, the damage rate and entrainment loss rate of the peanut pods are more than 2%. Therefore, after comprehensive consideration, it is finally determined that the appropriate range of the axial cylinder speed is 400–475 r/min.

2.4. Structural Design of the Guide Plate

In order to ensure the picking performance and control the axial moving speed of the peanut plants during operation, seven spiral guide plates are designed on the inner surface of the axial cylinder outer shell. As shown in Figure 5, in order to smoothly guide the peanut plants after tangential picking to the axial cylinder and avoid uneven feeding and blockage, the spacing between two adjacent guide plates is designed to be 260 mm and the front and rear overlap is about 110 mm. At the same time, in order to ensure that the peanut vines after picking can be smoothly exported to the discharging assembly and avoid blocking, the last guide plate is designed to extend into the discharging port.

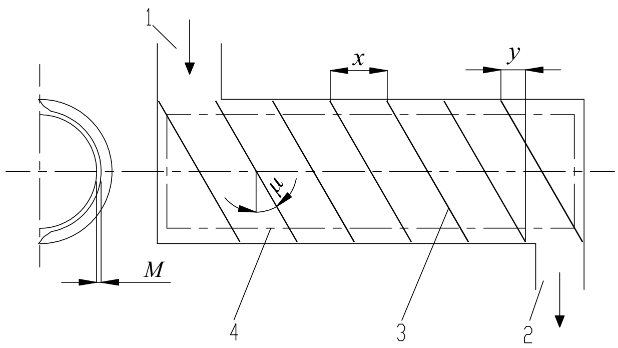


Figure 5. Structural diagram of guide plate: 1. Feed inlet; 2. Discharging port; 3. Guide plate; 4. Axial cylinder. Note: x is the spacing between two adjacent guide plates, mm; y is the front and rear overlap of the guide plate, mm; μ is the spiral rise angle of the guide plate, (°); M is the clearance between the guide plate and the spike teeth of the axial cylinder, mm.

The spiral rise angle and the clearance between the guide plate and the axial cylinder have a great influence on the picking performance. Generally, the spiral rise angle of the guide plate is 20–50°. If it is too large, the guide plate cannot realize the role of the axial push, and retention and accumulation of the peanut plants is easily caused. According to peanut plant characteristics and related studies [6,16], the spiral rise angle of the guide plate is designed to be 35°. When the clearance between the guide plate and the axial cylinder is too large, the axial fluidity of peanut plants becomes poor, which reduces the productivity and may even be blocked. If the clearance is too small, the damage of peanut pods will increase, and the power consumption is large. Especially when the peanut plant is wet, it is more likely to cause blockage. Referring to the size of peanut pods and related studies [16], the clearance between the guide plate and the spike teeth of the axial cylinder is designed to be 15 mm and can be adjusted through the installation position of the axial cylinder shell to meet the needs of different varieties of peanut picking.

2.5. Structural Design of the Concave Screen

In addition to cooperating with the cylinder for picking, the concave screen should have strong separation capacity. At present, the commonly used concave screen is divided into grid format and punching according to its structure [13]. The perforated screen is easy to process, but the screen porosity (the ratio of screen area to the total area of concave screen) is only 25–30%, and the separation rate is less than 50%. However, the porosity and separation rate of the grid format screen can reach 40–70% and 75–90%, respectively. Moreover, compared with the perforated screen, the grid format screen has stronger brushing off ability, so it is selected in this design.

As shown in Figure 6, in order to facilitate the processing of the concave screen and the smooth and orderly migration of the peanut plants, the grid format screen adopts a combined structure. It mainly includes tangential flow, transition and axial flow sections. The separation screen hole is formed by crisscross screen strips.

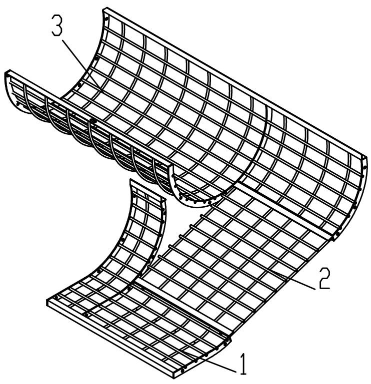


Figure 6. Structural diagram of concave screen: 1. Tangential section; 2. Transition section; 3. Axial section.

Meanwhile, in order to ensure the picking performance of peanut plants in the tangential section and the smoothness of transportation to the axial section, the concave screen wrapping angle should not be too large [13], which is taken as 95°. Due to the irregular shape of the peanut pods and poor fluidity, in order to improve the separation rate, the concave screen in the axial section adopts a larger wrapping angle, which is taken as 200°. At the same time, according to the size of the picking section of the tangential and axial cylinder, the width of the tangential section of the concave screen is designed to be 750 mm, the width of the transition section is 600 mm, and the width of the axial section is 1600 mm. The screen bar is made of round steel with a diameter of 10 mm. The transverse screen bar is located above the longitudinal screen bar, so as to improve the impact effect of the cylinder on the peanut plant and give full play to the picking and separating functions.

In order to ensure the separation capacity of the concave screen and considering the convenience of processing, the grid sizes of three sections of concave screen are designed to be the same. As shown in Figure 7, the transverse dimension of concave screen grid is 120 mm and the longitudinal dimension is 90 mm.

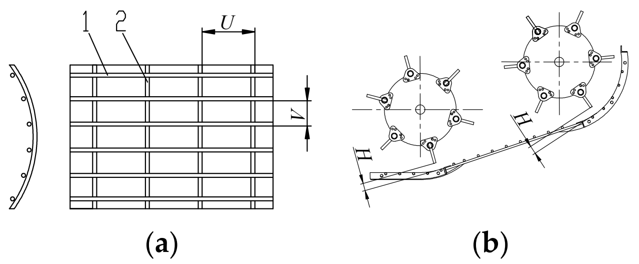


Figure 7. Parameters of the concave screen: 1. Transverse screen bar; 2. Longitudinal screen bar. (**a**) Grid size. (**b**) Picking clearance. Note: U is the transverse dimension of concave screen grid, mm; V is the longitudinal dimension of concave screen grid, mm; H is the picking clearance, mm.

The picking clearance is the gap between the concave screen and cylinder, which is the key parameter affecting the quality of the picking operation. Generally, if the picking clearance is small the peanut plant can be grasped well, which significantly improves the picking ability of the first half of the concave screen. However, a gap that is too small will increase the number of broken vines and easily cause damage to peanut pods. On the contrary, if the gap is too large, the ability of the cylinder to grasp the peanut plant and the separation ability of the front section of the concave screen are weakened, which seriously affects the picking quality. According to the size of the peanut pods and related studies [7,15], and considering meeting the needs of the peanut picking of different varieties and moisture content, as shown in Figure 7b, the designed picking clearance range is 25–40 mm, which can be adjusted by the installation position of the concave screen.

2.6. Analysis of Feeding Amount of Peanut Plants

The feeding amount of the combine harvester should be equal to the product of the forward speed and the peanut plant weight per meter within the width of the harvesting operation. That is, the feeding amount is related to the forward speed and operating width of the combine harvester and the weight of the peanut plants per hectare. It meets the following equation [13]:

$$Q = \frac{BMV_0}{667\beta} \tag{7}$$

where Q is the feeding amount of the combine harvester, kg/s; B is the operating width of the combine harvester, mm; M is the peanut pod quality per hectare, kg; β is the ratio of the peanut pod mass to total plant mass, %.

According to the previous tests and relevant literature [5,6,20,21], the forward speed of the peanut combine harvester is 0.8–1.5 m/s. According to field measurements and relevant literature [15], the yield of the peanut pods in China is 3000–4500 kg per hectare, and the ratio of the peanut pod quality to total plant quality is about 45%. The operating width of the peanut combine harvester is 2500 mm. Substituting data into Equation (7), the feeding amount ranges from 1.33 to 3.75 kg/s. The previous single factor test results showed that when the feeding amount was less than 1.5 kg/s, the operation productivity was low and could not meet the production requirements of the peanut combine harvester. When the feeding amount exceeds 3.0 kg/s, the fluidity of the peanut plant is blocked and sometimes blocked during picking. Therefore, in order to ensure the normal operation of the picking device, the feeding amount of the peanut plant is finally determined as 1.5–3.0 kg/s.

Based on the above analysis and related studies [5–8,15–19], the main factors affecting the operating performance of the picking device are the feeding amount of the peanut plant, the speed of the picking cylinder, and picking clearance. In order to further study the influence of these factors on the picking quality, and obtain the optimal operation parameters, it is necessary to carry out relevant performance tests.

2.7. Test Conditions and Instruments

In September 2020, the test was carried out in Sanqiao Town, Henan Province, China. The planting scale of peanut in the test field is about 15 hectares. The terrain of the test field is flat, the soil type is sandy loam with some viscosity, and the crop planted in the previous season is wheat. The peanut variety is Wanhua 2. The planting mode is ridge cultivation, and the ridge distance is 85 cm. During the experiment, the peanut plants were dug up by a digging harvester and sun-dried for 5 days. At this time, the moisture content of the peanut vines was 15.60%, and the moisture content of the peanut pods was 17.82%, which meets the requirement that the moisture content is less than 20% during peanut combine harvesting [22].

The designed and trial produced picking device was configured on the self-developed peanut combine harvesting prototype, and a movable peanut field harvest test bench was constructed to carry out experimental research. The field test process and test bench are shown in Figure 8. The test bench was mainly composed of the pick-up device, picking device, cleaning device, collecting device, and cab. It can complete the operations of the picking, conveying, picking, cleaning, and collection at one time. Other main instruments include a tachometer (Model: FLUKE931, manufacturer: Fluke testing instruments (shanghai) Co., Ltd., Shanghai, China, measurement accuracy: +0.02%) and electronic balance (Model: HTP312, manufacturer: Shanghai Huachao Electric Appliance Technology Co., Ltd., Shanghai, China, measurement accuracy: 0.1 g).

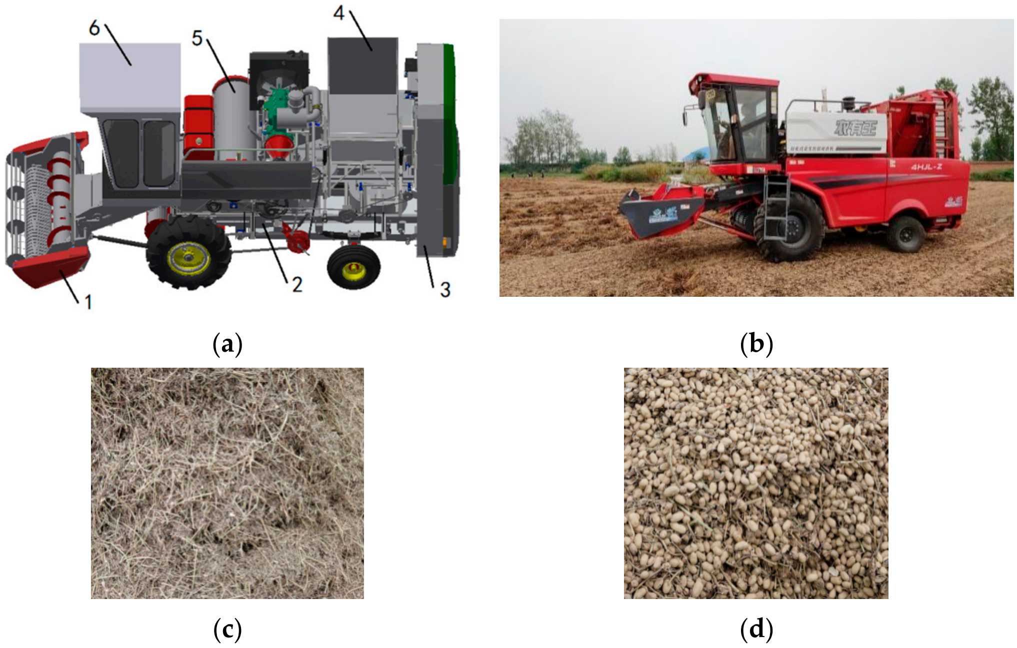


Figure 8. Movable test bench and test process: 1. Pick-up device; 2. Cleaning device; 3. Collecting device of pods; 4. Pods box; 5. Picking device; 6. Cab. (**a**) Movable test bench. (**b**) Field test process. (**c**) Materials in the vines box during the test. (**d**) Materials in the pods box during the test.

2.8. Test Factors, Indexes, and Methods

According to the previous analysis, the orthogonal test with four factors and four levels was carried out. The feeding amount of the peanut plant, the picking clearance, the speed of the tangential cylinder, and the speed of the axial cylinder were taken as the test factors. The non-picking loss rate, entrainment loss rate, and damage rate of the peanut pods were the test indexes. The peanut picking performance was studied under different combinations of the feeding amount of 1.5–3.0 kg/s, the picking clearance of 25–40 mm, the speed of the tangential cylinder of 360–420 r/min, and the speed of the axial cylinder of 400–475 r/min. During the test, the forward speed of the movable test bench was changed to meet the requirements of different feeding amounts. The speed adjustment of the tangential cylinder and axial cylinder was realized by replacing the drive pulley or sprocket with different diameters. The adjustment of different picking clearance was realized through the installation position of the concave screen.

Based on the relevant contents of agricultural industry standard for the operating quality for peanut harvesters, NY/T 502—2016 [22], it was defined that the non-picking loss rate is the percentage of the weight of non-picking after the picking device operation among the total weight of pods. The entrainment loss rate is the percentage of the weight of the removed pods discharged with the vines after the picking device operation among the total weight of pods. The damage rate is the percentage of the weight of the kernel and shell damaged pods after the picking device operation among the total weight of pods.

During the test, the length of each test measuring area was 10 m. Each group of tests was repeated 3 times, and the average value was taken as the final test result. After each test, intact pods and damaged pods were distinguished from the pods box of the movable test bench. Then the non-picking pods and pods taken away by the vines were determined. Finally, the non-picking loss rate, entrainment loss rate, and damage rate of peanut pods were calculated according to Equations (8)–(10).

$$y_\mathrm{p} = \frac{m_\mathrm{p}}{m_\mathrm{p} + m_\mathrm{j} + m} \times 100\% \tag{8}$$

$$y_\mathrm{j} = \frac{m_\mathrm{j}}{m_\mathrm{p} + m_\mathrm{j} + m} \times 100\% \tag{9}$$

$$y_\mathrm{s} = \frac{m_\mathrm{s}}{m} \times 100\% \tag{10}$$

where y_p is the non-picking loss rate, %; y_j is the entrainment loss rate, %; y_s is the damage rate, %; m_p is the weight of the non-picking pods, g; m_j is the weight of the pods taken away by the vines, g; m_s is the weight of the damaged pods, g; m is the weight of the intact pods and damaged pods, g.

The arrangement of each factor is shown in Table 1. An $L_{16}(4^5)$ orthogonal table was established, in which *A*, *B*, *C*, and *D* are the coding values of each factor level.

Table 1. Test factors and codes.

Levels	Factors			
	Feeding Amount of Peanut Plant/(kg/s)	**Picking Clearance/(mm)**	**Speed of Tangential Cylinder/(r/min)**	**Speed of Axial Cylinder/(r/min)**
1	1.5	25	360	400
2	2.0	30	380	425
3	2.5	35	400	450
4	3.0	40	420	475

Through the range analysis, analysis of variance, and fuzzy comprehensive evaluation [23], the primary and secondary relationships of the effects of the feeding amount, picking clearance, cylinder speed on the non-picking loss rate, entrainment loss rate, and damage rate were explored, and the optimal parameter combination was determined.

However, through range analysis and analysis of variance, the influence order and optimal parameter combination of various factors on the test indexes were obtained, but the influence law and optimal combination were only for a single test index. In order to find an effective balance among the three test indexes, the orthogonal test results were analyzed by fuzzy comprehensive evaluation method, so as to obtain the optimal parameter combination meeting the three test indexes at the same time.

Firstly, the non-picking loss rate, the entrainment loss rate, and the damage rate were determined as the evaluation index set. The 16 groups of test result data of orthogonal test were the evaluation object set. Secondly, the membership function was established and the weight distribution set was determined. Finally, the fuzzy comprehensive evaluation value was calculated and analyzed [23]. When the values of the non-picking loss rate, the entrainment loss rate, and the damage rate are smaller, the effect is better. Therefore, the membership function is established as follows.

$$\boldsymbol{R} = \begin{bmatrix} r_{11}\ r_{12}\ \ldots\ r_{1n} \\ r_{21}\ r_{22}\ \ldots\ r_{2n} \\ r_{31}\ r_{32}\ \ldots\ r_{3n} \end{bmatrix} (n = 16) \tag{11}$$

Among them,

$$r_{1n} = \frac{y_{p1n\max} - y_{p1n}}{y_{p1n\max} - y_{p1n\min}} (n = 1, 2, \ldots, 16) \tag{12}$$

$$r_{2n} = \frac{y_{j2n\max} - y_{j2n}}{y_{j2n\max} - y_{j2n\min}} (n = 1, 2, \ldots, 16) \tag{13}$$

$$r_{3n} = \frac{y_{s3n\max} - y_{s3n}}{y_{s3n\max} - y_{s3n\min}} (n = 1, 2, \ldots, 16) \tag{14}$$

where $\boldsymbol{R}$ is the membership function.

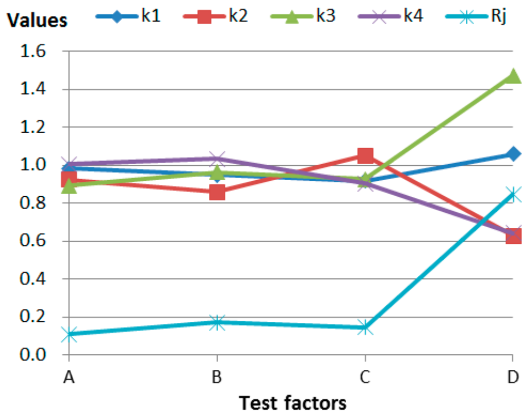
The primary goal of the picking device of the peanut combine harvester is to pick the peanut pods and avoid entrainment loss as much as possible. The non-picking loss and entrainment loss during picking are the direct sources of loss and should be strictly controlled. At the same time, according to the inspection and analysis after the test, most of the damage caused by picking operation is local damage of the shell, and only a few have pod fracture and kernel crushing. Therefore, through comprehensive consideration, it is determined that the non-picking loss rate and entrainment loss rate are the same proportions, and slightly higher than the damage rate. That is, the corresponding weight allocation set $\boldsymbol{P}$ = [0.4, 0.4, 0.2]. Then, the fuzzy comprehensive evaluation value is $\boldsymbol{M} = \boldsymbol{RP}$.

3. Results and Discussion

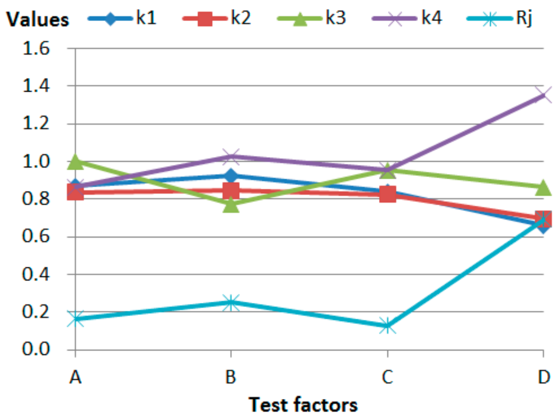
The test results are shown in Table 2. The range analysis and analysis of variance of the test results are shown in Figure 9 and Table 3.

Table 2. Test design and results.

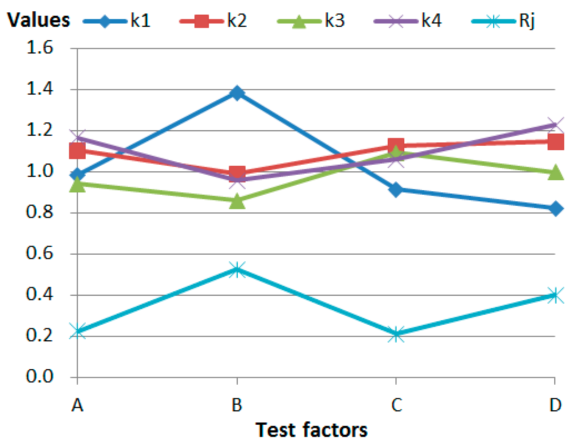
Test No.	*A*	*B*	*C*	*D*	y_p/%	y_j/%	y_s/%
1	1	1	1	1	1.09	0.61	0.98
2	1	2	2	2	0.66	0.58	1.14
3	1	3	3	3	1.46	0.79	0.74
4	1	4	4	4	0.72	1.50	1.07
5	2	1	2	3	1.56	0.75	1.46
6	2	2	1	4	0.46	1.20	1.04
7	2	3	4	1	0.99	0.57	0.74
8	2	4	3	2	0.69	0.83	1.17
9	3	1	3	4	0.55	1.58	1.54
10	3	2	4	3	1.31	0.98	0.86
11	3	3	1	2	0.56	0.61	0.71
12	3	4	2	1	1.15	0.84	0.65
13	4	1	4	2	0.60	0.76	1.56
14	4	2	3	1	1.01	0.62	0.92
15	4	3	2	4	0.84	1.13	1.25
16	4	4	1	3	1.57	0.94	0.93



(**a**)



(**b**)



(**c**)

Figure 9. Range analysis of test results; (**a**) y_p; (**b**) y_j; (**c**) y_s.

Table 3. Analysis of variance.

Indexes	Variance Source	Sum of Squares	Free Degree	*F*-Value	*p*-Value	Significance
y_p	*A*	0.032	3	3.453	0.1680	
	B	0.060	3	6.493	0.0794	*
	C	0.056	3	6.008	0.0875	*
	D	1.945	3	209.717	0.0006	***
	Error	0.009	3			

Table 3. *Cont.*

Indexes	Variance Source	Sum of Squares	Free Degree	*F*-Value	*p*-Value	Significance
y_j	*A*	0.066	3	14.012	0.0286	**
	B	0.141	3	29.959	0.0098	***
	C	0.059	3	12.560	0.0332	**
	D	1.222	3	258.897	0.0004	***
	Error	0.005	3			
y_j	*A*	0.130	3	7.308	0.0683	*
	B	0.644	3	36.062	0.0075	***
	C	0.103	3	5.756	0.0923	*
	D	0.377	3	21.095	0.0161	**
	Error	0.018	3			

Note: The critical value of significant judgment $F_{0.01}(3,3) = 29.46$, $F_{0.05}(3,3) = 9.28$, $F_{0.1}(3,3) = 5.39$. * indicates that the factors have some influence on the test index ($0.05 < p \leq 0.1$), ** indicates that the factors have a significant influence on the test index ($0.01 < p \leq 0.05$), *** indicates that the factors have a very significant influence on the test index ($p \leq 0.01$).

From the results of range analysis and analysis of variance, it can be seen that the influence order of various factors on non-picking loss rate is $D > B > C > A$, and the better parameter combination is $A_3B_2C_4D_2$; the order of influencing factors on entrainment loss rate is $D > B > A > C$, and the better parameter combination is $A_2B_3C_2D_1$; the influence order of each factor on the damage rate is $B > D > A > C$, and the better parameter combination is $A_3B_3C_1D_1$.

At the same time, the membership and fuzzy comprehensive evaluation values of the non-picking loss rate, the entrainment loss rate, and the damage rate are obtained, as shown in Table 4.

Table 4. Membership degree of test index and fuzzy comprehensive evaluation value.

Test No.	Membership Degree of Non-Picking Loss Rate (r_{1n})	Membership Degree of Entrainment Loss Rate (r_{2n})	Membership Degree of Damage Rate (r_{3n})	Fuzzy Comprehensive Evaluation Values (M_n)
1	0.432	0.960	0.637	0.684
2	0.820	0.990	0.462	0.816
3	0.099	0.782	0.901	0.533
4	0.766	0.079	0.538	0.446
5	0.009	0.822	0.110	0.354
6	1.000	0.376	0.571	0.665
7	0.523	1.000	0.901	0.789
8	0.793	0.743	0.429	0.700
9	0.919	0.000	0.022	0.372
10	0.234	0.594	0.769	0.485
11	0.910	0.960	0.934	0.935
12	0.378	0.733	1.000	0.644
13	0.874	0.812	0.000	0.674
14	0.505	0.950	0.703	0.723
15	0.658	0.446	0.341	0.510
16	0.000	0.634	0.692	0.392

The results of range analysis of fuzzy comprehensive evaluation values are shown in Table 5.

Table 5. Analysis of the range of fuzzy comprehensive evaluation values.

Indexes		Factors			
		A	*B*	*C*	*D*
M_n	k_1	0.620	0.521	0.669	0.710
	k_2	0.627	0.672	0.581	0.781
	k_3	0.609	0.692	0.582	0.441
	k_4	0.575	0.546	0.599	0.498
	R_j	0.052	0.171	0.088	0.340

According to the results in Table 5, the order of factors affecting the comprehensive effects of the non-picking loss rate, the entrainment loss rate, and the damage rate is $D > B > C > A$. That is, the order of factors is the speed of the axial cylinder, the picking clearance, the speed of the tangential cylinder, and the feeding amount of the peanut plant. The optimal parameter combination for comprehensive analysis is $A_2B_3C_1D_2$. The corresponding feeding amount of the peanut plant is 2.0 kg/s, the picking clearance is 35 mm, the speed of the tangential cylinder is 360 r/min, and the speed of the axial cylinder is 425 r/min.

In order to further verify the performance of the designed picking device, three repeated verification tests were carried out under the above obtained optimal working parameters. The measured non-picking loss rate was 0.52%, the entrainment loss rate was 0.54%, and the damage rate was 0.75%. On the basis of the membership degree of the test index and the assigned weight, the calculated fuzzy comprehensive evaluation value is higher than that of the 11th group of the orthogonal test. That is, the test results under this working parameter combination are better than the test results of the 11th group in the orthogonal test (the non-picking loss rate of 0.56%, entrainment loss rate of 0.61%, damage rate of 0.71%). It indicates that this working parameter combination is believable.

The combine harvester has been an important focus of peanut harvesting equipment research and development in China in recent years [3,4,24,25]. At present, the picking devices suitable for peanut combine harvesters are mainly single axial flow and multistage tangential flow [5–8]. The single axial flow picking device has the problem of low picking rate. The multi-stage tangential flow picking device has the problem of large structure, and it also causes great damage to peanut pods. Compared with the single axial-flow or multi-stage axial-flow devices, the tangential-axial flow picking device designed in this study has a more compact structure and has been widely used in grain combine harvesters such as rice [9,10,26], maize [11,27], soybean [12], buckwheat [28], and herbaceous oil crops [29]. Therefore, it is feasible to apply this technology to the picking operation of peanut combine harvesting in this study.

The relevant experimental results show that the designed picking device has good performance. The results under the optimal parameter combination show that the non-picking loss rate is 0.52%, the entrainment loss rate is 0.54%, and the damage rate is 0.75%. The test results of the performance indexes of the peanut picking device designed in this study and the existing devices are shown in Table 6.

As can be seen from Table 6, the test result is far lower than the operating performance index of the existing single axial flow and multi-stage tangential flow picking devices. The main reason is that the designed tangential-axial flow picking device adopts a two-step operation mode [12]. The first completes the primary picking operation of the peanut plants through the tangential cylinder, and then completes the secondary picking operation through the axial cylinder, which can effectively reduce the non-picking loss rate, the entrainment loss rate, and damage rate of the peanut pods.

Table 6. Comparison of test results of performance indexes.

Structure Type of Peanut Picking Device	Sources	Performance Indexes		
		Non-Picking Loss Rate (%)	Entrainment Loss Rate (%)	Damage Rate (%)
Tangential-axial flow	This study	0.52	0.54	0.75
Multi-stage tangential flow	Ref. [7]	1.56	1.23	3.85
	Ref. [8]	3.20	1.68	4.91
	Ref. [30]	2.13	/	1.75
Single axial flow	Ref. [18]	0.94	/	0.93
	Ref. [19]	1.84	/	1.41

4. Conclusions

In view of the problems of high loss and damage in the operation of the picking device of Chinese peanut combine harvesters, a tangential-axial flow picking device was designed, developed, and tested in this study. The study was carried out by applying the tangential-axial flow threshing technology of a grain combine harvester to peanut picking, according to the factors and conditions such as cultivated varieties, planting mode, and harvest characteristics in the main peanut producing areas of China.

Through the range analysis and analysis of variance, it was determined that the factors affecting the non-picking loss rate were the speed of the axial cylinder, the picking clearance, the speed of the tangential cylinder, and the feeding amount of the peanut plant. The factors affecting the entrainment loss rate were the speed of the axial cylinder, the picking clearance, the feeding amount of the peanut plant, and the speed of the tangential cylinder. The factors affecting the damage rate were the picking clearance, the speed of the axial cylinder, the feeding amount of the peanut plant, and the speed of the tangential cylinder. Through the fuzzy comprehensive evaluation method, the optimal parameter combination was obtained as follows. The feeding amount of the peanut plant of 2.0 kg/s, the speed of the tangential cylinder of 360 r/min, the speed of the axial cylinder of 425 r/min, and the picking clearance of 35 mm. At this time, the non-picking loss rate of peanut pods was 0.52%, the entrainment loss rate was 0.54%, and the damage rate was 0.75%. It was proved that the tangential-axial flow picking device designed in this study can be used for the operation requirements of peanut combined harvest and has good picking performance.

At present, only one variety of peanut was tested in this study. The research team will continue to carry out experiments on different varieties of peanuts in the experimental field, to further verify the operational performance and adaptability of the designed picking device.

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