DESIGN AND EXPERIMENT OF A THREE-RIDGE SIX-ROW PEANUT COMBINE HARVESTER BASED ON DEEP INTEGRATION OF AGRICULTURAL MACHINERY AND AGRONOMY

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基于深度农机农艺融合的三垄六行花生联合收获机的设计与试验

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ABSTRACT

In order to improve the efficiency of peanut harvesting in China, realize the deep integration of agricultural machinery and agronomy in peanut production and promote the development of peanut industry. According to the research on peanut planting agronomy and plant biological characteristics, this paper focuses on the analysis of the clamping and collecting scheme of the three-ridge six-row peanut combine harvester, and designs the structure of the clamping and collecting device to solve the situation that the peanut clamping and collecting process is prone to congestion under large feeding volume. By analysing the forces on the peanut plant, the structure of the core fruit picking device has been designed, and the factors and parameters affecting the effectiveness of the peanut picking operation have been optimised through experimental research using the peanut leakage and crushing rates as indicators. The whole machine structure of the three-ridge six-row peanut combine harvester was designed to ensure that the peanut combine harvester can complete the processes of harvesting, digging, clamping and conveying, soil removal, collecting, fruit picking, cleaning and fruit collection at one time. Finally, through field tests on the three-ridge six-row peanut combine harvester, it was verified that the peanut leakage rate was 1.92% and the crushing rate was 0.84% at different forward speeds, and all of them were congested, which met the national peanut harvesting standards.

摘要

为提高我国花生收获效率，实现花生生产农机农艺的深度融合，促进花生产业的发展。根据花生种植农艺及植株生物特性的研究，本文重点解析了三垄六行花生联合收获机的夹持归集方案，设计了夹持归集装置的结构，解决了在大喂入量情况下花生夹持归集过程易拥堵的情况；通过对花生植株进行受力分析，解析了摘果核心装置结构，以花生的破碎率、漏摘率为指标，试验分析得出了影响花生摘果作业效果的因素及参数范围。对三垄六行花生联合收获机整机结构进行了设计，确保花生联合收获及可以一次性完成扶禾、挖掘、夹持输送、去土、归集、摘果、清选、集果等工序。最终通过对三垄六行花生联合收获机进行田间试验验证得出机具在不同的前进速度下，花生的漏摘率为 1. 92%，破碎率为 0. 84%，且均未出现拥堵的情况，符合国家花生收获的标准。

INTRODUCTION

Peanut is the world's major cash crop and oil-bearing crop, but also one of the main cash crops exported by China (*Shang et al., 2005*). China's peanut planting area is of nearly 4.75 million hectares, accounting for more than 20% of the world's total peanut planting area, ranking second in the world for many years (*Gao L. et al., 2017*). But regarding the current level of mechanized joint harvesting of peanuts in China, whether compared to foreign harvesting levels or harvesting levels of other domestic food crops and major cash crops, there is a big gap, seriously hampering the rapid and healthy sustainable development of China's peanut industry (*Wang S. et al., 2022*).

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In recent years the peanut planting pattern gradually standardized, became large-scale and industrialized, which to a certain extent prompted the development of peanut harvesting machinery to large, efficient direction (*Wang B.et al., 2018*). Europe and the United States and other countries for peanut machinery research than China much earlier, peanut cultivars and China's peanut varieties differ greatly, the United States peanut is mostly prostrate peanut, using a two-stage harvesting method, through the peanut digging placement machine digging out the peanut plants laid in the field, after drying, the use of picking joint harvester to complete picking, fruit picking, cleaning and collection operations (*USDA, 2021*). The typical peanut digging and laying harvesters in the United States include a series of peanut harvesters produced by KMC, 9997 and 2110 traction peanut combine harvesters produced by Amadas (*Amada 2021*). The two models can harvest 4 rows and 6 rows of peanuts at the same time. These machines can simultaneously complete the peanut excavation, transportation, soil removal, flip the plants and lay them for drying, peanut excavation and harvesting loss rate can be steadily controlled within 2%. Typical peanut picking combine harvester is divided into two types, respectively, traction type peanut picking combine harvester and self-propelled peanut picking combine harvester. The representatives of traction type are KMC3376-6 and KMC3374-4 traction type picking combine harvester produced by KMC; the representatives of self-propelled type are 9900SP and 9970SP self-propelled peanut picking combine harvester produced by Amadas (*Tian, 2017*). For vertical peanuts planted in other developed countries, the combined harvesting method of one-time excavation, clamping collection, soil removal, fruit picking, cleaning, fruit collection and other processes is mostly adopted. This method generally adopts chain clamping trajectory device, which has high reliability and good clamping stability (*Ferezin E. et al., 2018; Leszczynski N. et al., 2011*). At present, foreign peanut harvesting machinery is developing in the direction of large-scale, machine-electric-hydraulic integration, intelligence and high efficiency (*Hu et al., 2010*). China gradually began to combine the actual situation of the country's peanut planting research and development of more efficient and applicable peanut harvesting machinery, with representative harvesting machinery. Qingdao Agricultural University developed 4HQL-2 type whole-feed peanut combine harvester and 4LH-2 type semi-feed self-propelled peanut combine harvester, Dongtai Machinery produced 4HBL-2 type peanut combine harvester and 4HB-2A type peanut combine harvester (*Hu et al., 2010*). The current semi-feed peanut combine harvester has been commonly promoted and applied, but there is still a lot of room for improvement with respect to China's peanut combine harvester regarding the adaptability and harvesting efficiency (*Hu et al., 2010*).

At present, China's peanut combine harvester has gradually developed from a single ridge double row harvesting to two ridge four rows, greatly improving the efficiency of peanut harvest. Taking into account the characteristics of peanut harvesting mostly in the rainy season, combined with the requirements of peanut harvesting standards, in order to further enhance the harvesting efficiency of peanuts, to achieve a rush harvest, the high-efficiency three-ridge six-row peanut combine harvesting machinery suitable for China's peanut plant agronomic requirements and characteristics was designed. The machine can complete the excavation, clamping collection, soil removal, fruit picking, cleaning, fruit collection and other processes at one time under the condition of large feeding capacity, and ensure that there is no congestion of clamping collection in the process, with low crushing and leakage rates.

MATERIALS AND METHODS

Agronomic Plant Biological Characterization Study of Peanut Planting

China's land area is large, the climate varies greatly, the soil moisture content and soil quality in different areas are different, so the peanut planting methods are also very different (*Wang S. et al., 2019)*. The current peanut planting can be broadly divided into flat planting, ridge planting and high ridge planting. The ridge method is conducive to plant ventilation and light, and also helps the peanut reasonable dense planting, improve the soil's drought resistance and moisture retention performance, to ensure high peanut yield and high quality. At present, most of the main peanut production areas in China use a ridge of two rows of mulching ridge peanut planting method. Figure 1 shows the actual production of one ridge and two rows of peanut ridge planting mode schematic diagram, ridge height H for 100 mm ~ 150 mm, row spacing S for 200 mm ~ 250 mm, ditch width M for 150 mm ~ 200 mm, ridge distance D for 700 mm ~ 800 mm, ridge top width L_1 for 500 mm ~ 550 mm, ridge bottom width L_2 for 600 mm ~ 650 mm.

There are many types of peanut varieties in China, and with the continuous maturation of breeding technology, peanut varieties are increasing (*Wang B. et al., 2022)*. Based on the morphological characteristics of peanut plants, peanuts can be divided into: erect type, semi-prostrate type and prostrate type. Currently, most of the peanuts promoted and planted in China are the upright type, and the peanuts planted in large areas in the main peanut production are Luhua series and Yuhua series. The four peanut plants that are most widely and commonly planted are Luhua 12, Jihua 18, Yuhua 40 and HuaYu 33 each with 50 plants for geometric measurements, and the dimensions are shown in Table 1.

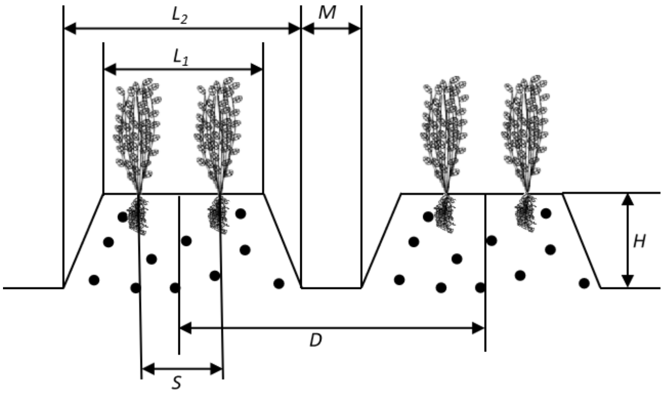


Fig. 1 - Planting pattern of one ridge and two rows peanut

Plant height: measuring the height of peanut plants in their natural state to provide a basis for studying the clamping position.

Plant width: measuring the width of the plant in its natural state, to provide a basis for the design of the crop supporting device.

Root length, width and height: measuring the natural length of the root system of peanut plants to provide a basis for the study of the design of the fruit picking pair of rollers (*Hu et al., 2017)*.

Average number of pods: Measure the average number of pods of each peanut plant to provide a basis for the design of the structure and movement parameters of the peanut picking device.

Table 1

Geometric dimensions of peanut

Species	Average plant height/mm	Average plant width/mm	Average root length/mm	Average root width/mm	Average root height/mm	Average number of pods/mm
Luhua 12	463.45	199.7	129.97	85.44	130.14	43
Jihua 18	476.39	202.5	128.34	87.67	125.43	38
Yuhua 40	447.68	195.6	130.76	83.54	126.93	40
HuaYu 33	420.63	193.3	133.78	93.91	120.09	36

Structural design of the whole machine of three-ridge six-row peanut combine harvester

Combined with the peanut harvesting process, the overall structure of the machine is shown in Figure 2, which mainly consists of the grubbing device, digging device, clamping and conveying device, soil removal device, collecting device, fruit picking device, cleaning device, fruit collection device and other parts.

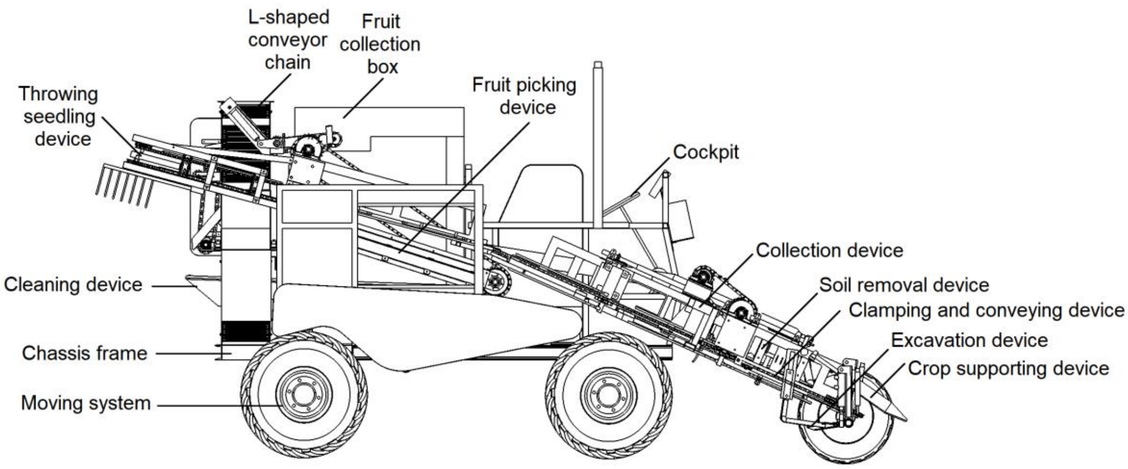
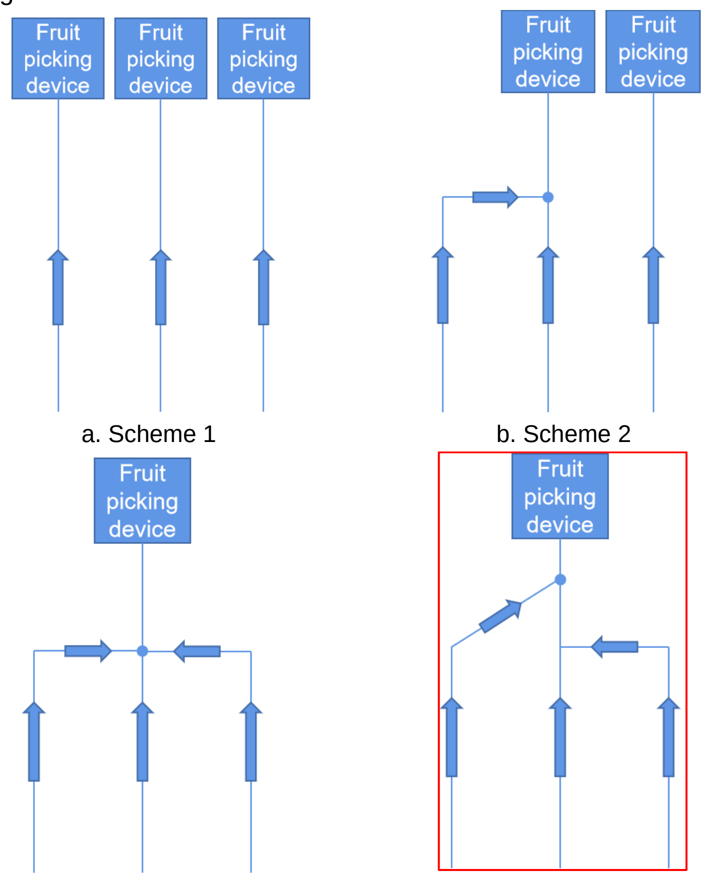


Fig. 2 - Structure diagram of three-ridge six-row peanut combine harvester

When the three-ridge six-row peanut combine harvester is in operation, the peanut plants to be harvested are separated from the peanuts in other rows by a three-pair crop clamping device, and the holding device rotates in the direction of the peanut plants to be harvested, that is, rotating to the inside, and the peanut plants are raised and gathered in the middle position. At the same time, the digging shovel will break the main root of the peanut and loosen the soil under the action of the forward force of the machine. With the cooperation of the crop supporting device and the digging device, the peanut plant moves backward according to the inertia and enters the clamping chain in turn. In the process of clamping and conveying, the soil removal device will follow the peanut to carry out the left and right reciprocating beating action, and remove the soil and impurities on the root system of the peanut plant. After that, the three-row peanuts will be gathered in the middle and sent to the fruit picking section, the roots of peanut plants will enter the picking roller device under the clamping and conveying of the clamping chain. The picking roller drives the picking boards, and picks the pods on the peanut roots by rotating the brush. The peanuts fall to the cleaning parts under the action of gravity, and the heavier soil blocks and other impurities are sieved out through the reciprocating motion of the parts. At the same time, the lighter boards and membranes are blown out with the blower to complete the secondary impurity removal operation. After cleaning, the peanut pods will enter the fruit box driven by the L-shaped conveyor belt. The fruit box is equipped with a hydraulic device, which can tilt the box to facilitate subsequent bagging operations. After the picking operation is completed, the podded peanut plant is conveyed backward with the clamping conveyor chain, and finally thrown into the field through the guide rail and the seedling guide device with the clamping chain as the power.

Design of key devices for three-ridge six-row peanut combine harvester

The peanut clamping and collecting device is the key core component of the three-ridge six-row peanut combine harvester, which plays a vital role in the transmission efficiency of peanut plants (*Leszczynski N.,2011; Gao Z. et al., 2023; Yang et al., 2010)*. The current peanut harvesting ridge two-row clamping device is relatively mature, and the structure and motion parameters are able to complete the operation better; the structure of the collecting device should be able to realize the collection of six rows of peanuts into the same conveying chain without congestion. Combined with the analysis of the literature for the aggregation components, the final choice of the highly reliable clamping chain type conveying, the conveying route was designed as shown in Figure 3.



a. Scheme 1 b. Scheme 2 c. Scheme 3 d. Scheme 4

Fig. 3 - Design of peanut clamping conveying scheme

In scheme 1 and scheme 2, the clamping and conveying device sends peanuts into the picking device according to 1 and 2 ways respectively. The peanut picking efficiency is high and the picking effect is relatively good. However, the large peanut combine harvester is equipped with two or more sets of fruit picking devices, which makes the whole machine structure and transmission become quite complex, and it is not convenient for the simplification of the machine. Scheme 3 and scheme 4 only need to configure a set of fruit picking device, and the fruit picking effect and fruit picking efficiency are not as good as in the first two schemes. However, by adjusting the structure and motion parameters of the fruit picking device, the crushing rate and leakage rate of peanut fruit picking can be effectively reduced, and the effect of peanut fruit picking can be improved. Among them, in scheme 3 peanuts are collected at the same position, which is easy to cause congestion of peanut vines during transportation, while scheme 4 can effectively alleviate congestion, so scheme 4 clamping collection path is finally determined.

The structure of the clamping and collecting device is shown in Figure 4. The device mainly completes the processes of crop supporting, digging, clamping and conveying, and tapping the root system to remove soil, etc. (*Chen et al., 2020; Zhai et al., 2020)*. It is composed of three parallel and identical structures, and after completing the series of processes, it is collected and conveyed to the fruit picking operation. The overall layout of the structure is reasonable. In order to increase the adjustment range of the chain and avoid congestion in the process of conveying, the double floating adjustment method is adopted. At the same time, in order to adapt to the different agronomy of peanut planting in different regions of China, the design of automatic adjustment device of ridge width is more applicable to the ridge distance of peanut planting in different regions.

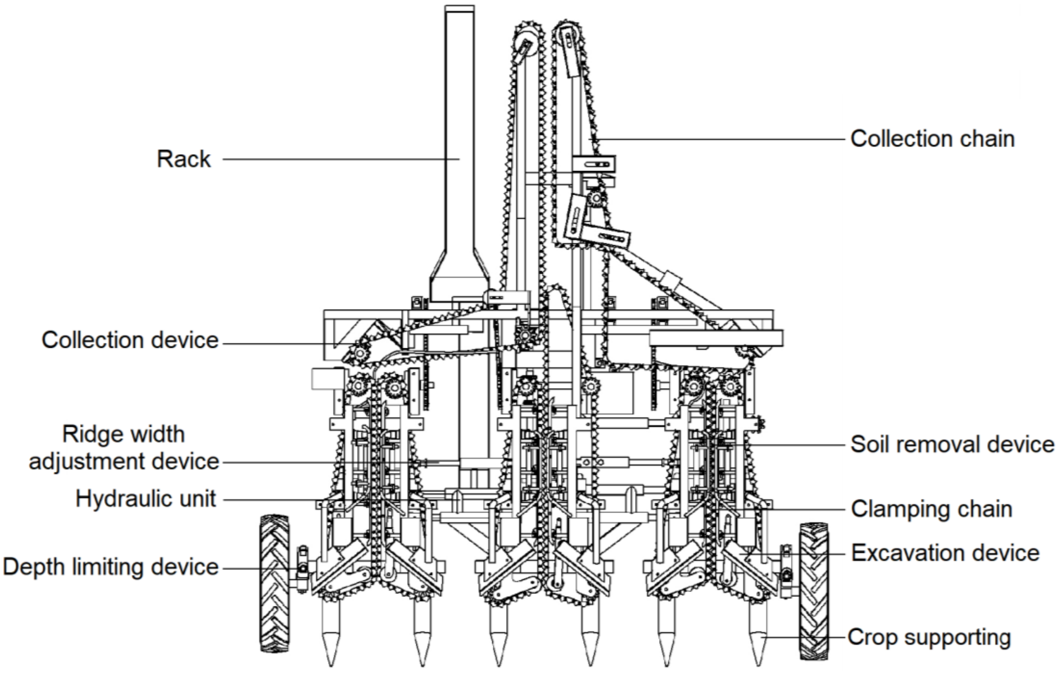


Fig. 4 - Structure diagram of clamping and collecting device

At present, there are two kinds of picking methods for peanut combine harvester: half feeding picking method and full feeding picking method. (*Wang et al., 2022)*. Semi-feeding means that the peanut plant seedlings and vines are transported in the direction opposite to the machine's operating speed under the clamping action of the chain, and the plant roots enter the fruit picking device. The pulling force of the chain on the vine of the plant and the brushing force of the pod picking device (pod picking board) on the roots pull the peanut pods down from the root system to complete the harvest, which is applicable to the harvesting of dried peanuts and freshed peanuts.

The full feeding method is to feed the peanut plant into the fruit picking drum and separate the plant from the pods through fruit shaking and fruit stroking, mostly used for dried peanuts harvesting, when harvesting fresh peanuts, this method has a greater impact on the peanut crushing rate and lower harvesting efficiency. Therefore, the final selection of semi-fed pod picking method, picking device as shown in the Figure 5.

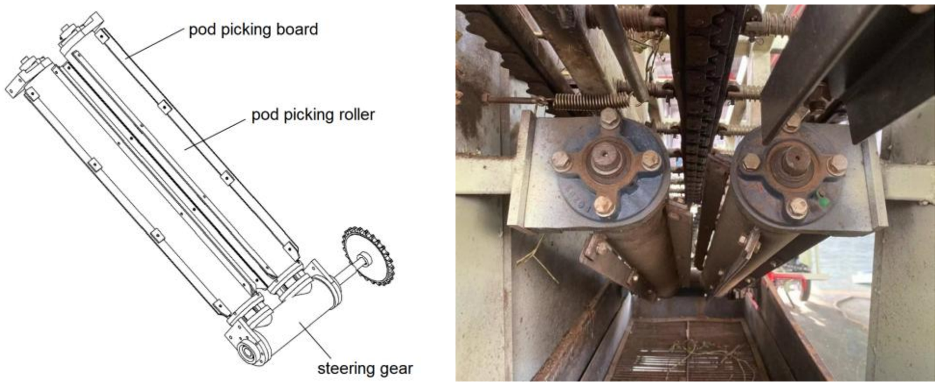


Fig. 5 - Fruit picking pair of rollers structure diagram

Analysis of peanut plant stresses during fruit picking

During the whole pod picking process, the peanut plant is not only subjected to the tension of the clamping and conveying chain, but also the root system and peanut pods are also subjected to the centrifugal force and impact force generated during the brushing of the boards on the roller. The force of the peanut plant when beated by one side of the picking board is analysed, as shown in Figure 6.

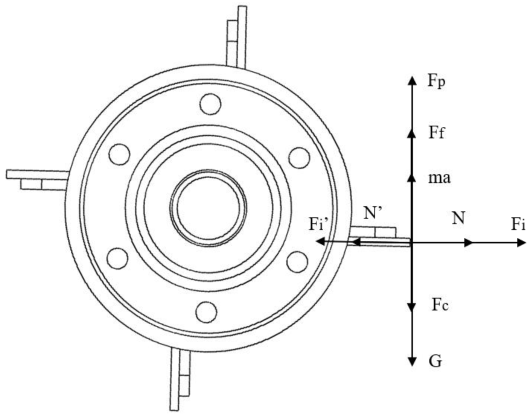


Fig. 6 - Stress of peanut plants during fruit picking

The forces applied to the peanut plant during the fruit picking process yielded.

$$\begin{cases} F_i + N = F_i{}' + \mathrm{N}' \\ F_p + F_f + ma = F_c + G \end{cases} \tag{1}$$

where: Fi—Centrifugal force of peanut pods slapped by picking boards, N;

$F_i{}'$—Centrifugal force of peanut pods slapped by picking boards on the other side, N;

F_p—Pull of peanut plant by clamping chain, N;

F_f—Peanut pod picking leaf friction, N;

ma—The inertial force of peanut pods, N;

F_c—Impact force of peanut pods when slapped by picking boards, N;

G—Peanut plant gravity, N.

The centrifugal force on the peanut pods is $F_c = mw^2R$, w is the rotational speed of the fruit picking pair of rollers. R is the radius of rotation of the fruit picking pair of rollers. Organizing the equation yields,

$$F_p = F_c + mg - \mu N - ma \tag{2}$$

As can be seen from the formula, the speed of the fruit picking pair of rollers directly affects the size of the impact force on peanuts, and is proportional; at the same time, as the speed continues to increase, the clamping conveyor chain will increase the pull force on the plant, excessive rotation speed will cause peanut plants to be pulled off, the speed of the pod picking rollers needs to be further determined by experimentation.

At present, most peanut picking institutions in China mainly pick peanuts after drying, mainly because after drying the fibres in the shell become hard, at this time they can withstand a stronger impact force, not easy to cause peanuts crushing, making it easier to improve the peanut harvesting rate. However, due to the fragility of freshed peanut shell fibers, the peanut pods can withstand less impact force when the peanuts are picked. If the speed of the fruit picking blade is too fast or the brushing force is large in the brushing process, it will lead to crushing peanut pods; while when the speed of the fruit picking blade is too slow or the brushing force is small, it will make the peanuts not be completely picked, and then this will lead to an increase in the peanut leakage rate. Therefore, the impact test on peanut pods and analysis of test data were performed to provide a theoretical basis for the design of the structure and parameters of the subsequent peanut picking device.

Test Method and Result Analysis

The test material was peanut pods at harvest time, and Luhua 12, Jihua 18, Yuhua 40 and HuaYu 33, which are the most widely planted in China, were selected as the main research subjects. Taking the peanut sowing time as the starting point, the peanut harvesting period is about 148 days. The test samples of each variety consist of 10 plants, and the moisture content is measured. Based on this, the impact force range that peanut pods can bear is measured.

After determining the test samples, a test bench was used to conduct impact tests on 40 peanut plants. The peanut plants were fixed on the clamping conveyor chain according to the actual clamping height at the time of harvesting, and the impact plate was driven to rotate and brush the peanut root system by adjusting the engine speed. The peanut pods were impacted by the impact plate and fell downward in the form of a parabola, ensuring that each peanut pod is hit only once. Combine the engine speed, calculate the speed of pod picking board according to the speed ratio, and count the crushing rate of 4 kinds of peanuts under different impact speed.

The maximum rotational speed that peanuts can bear on the day of harvest was measured by experiment. According to the broken situation of peanuts at different rotational speeds, the quantitative relationship between peanut crushing rate and the speed of picking roller was obtained. The test results are shown in Table 2.

Table 2

Crushing rate of peanut at different rotational speeds

Peanut varieties	Water content/%	Peanut crushing rate at different speeds/%				
		450 r/min	500 r/min	550 r/min	600 r/min	650 r/min
Luhua 12	54.47	0.03	0.84	1.47	1.84	2.32
Jihua 18	58.35	0.05	0.92	1.66	2.02	2.65
Yuhua 40	52.41	0.01	0.81	1.25	1.96	2.21
Huayu 33	55.82	0.03	0.76	1.38	1.89	2.58

From the above table, it can be derived that at peanut speed of 450 r/min, peanut pods began to crush, and as the speed continues to increase the rate of breaking peanut pods also increased, when the speed reached 650 r/min, four kinds of peanuts crushing rates are more than China's peanut picking industry standard (NY/T-993-2006), so it was determined that the impact speed of peanut pods can withstand a range of 450 r/min ~ 650 r/min, the distance between the two fruit picking rollers is 190mm.

The maximum impact speed that the peanut pods can withstand can be calculated by the formula:

$$v = \frac{2\pi D}{60} \cdot n \tag{3}$$

That is, the maximum impact velocity range of peanuts under suspension is 8.95 m/s~12.93 m/s.

RESULTS

By means of the actual harvesting of the whole machine in the field, the structure and parameters of the optimized clamping and gathering and fruit picking devices were used to adapt to different planting patterns and feeding volumes of different ridge widths, and important indexes such as leakage rate, crushing rate and productivity were measured during the operation of the whole three-ridge six-row peanut combine harvester.

Test material

The average height of the root system was 130.14 mm, width 85.44 mm and length 129.97 mm. The weight of 100 fruits was about 212.76 g. The soil moisture content of the trial field was 10.7% during the harvest period, and the planting pattern was one ridge and two rows.

Test Method

The test equipment is a three-ridge six-row peanut combine harvester equipped with a designed and optimized clamping and collection scheme and a picking device structure and motion parameters, electronic scale.

Eighteen plots were randomly selected in the test field, each 50 m long, with a three-ridge width (2.1 m) as the standard for the test. The leakage rate, crushing rate and harvesting efficiency of the peanut combine harvester at different speeds were measured, and the average value of each test group was taken and recorded accordingly.

After the test, the leakage of pods on the peanut plant, the crushing rate of peanut pods in the fruit collection box and the productivity of the peanut harvester as a whole were measured. The congestion in the clamping and collecting part of the peanut combine harvester was observed during each group of tests.

Fig. 7 - Field test verification

Analysis of results

The feeding amount of peanuts is controlled by controlling the forward speed of the machine. From table 6.1, it can be seen that with the continuous increase of the forward speed of the machine, the missing picking rate and crushing rate of peanuts also increase. The specific experimental data are shown in figures 8 and 9. In the whole test process, there was no congestion at the clamping collection, which proved that the optimized clamping collection speed was reasonable. The maximum forward speed of three-ridge six-row peanut combine harvester is 0.7 m / s, which is consistent with the results of preliminary field experiment.

Table 3

Harvesting effects of three-ridge six-row peanut combine at different speeds

Machine advance speed/m•s^{-1}	Average missed pick rate/%	Average crushing rate/%	Productivity/hm^2•h^{-1}	Congestion
0.3	0.00	0.00	0.23	Not available
0.4	0.02	0.01	0.30	Not available
0.5	0.67	0.34	0.38	Not available
0.6	1.53	0.90	0.45	Not available
0.7	2.79	1.63	0.53	Not available
0.8	4.88	2.21	0.61	Not available

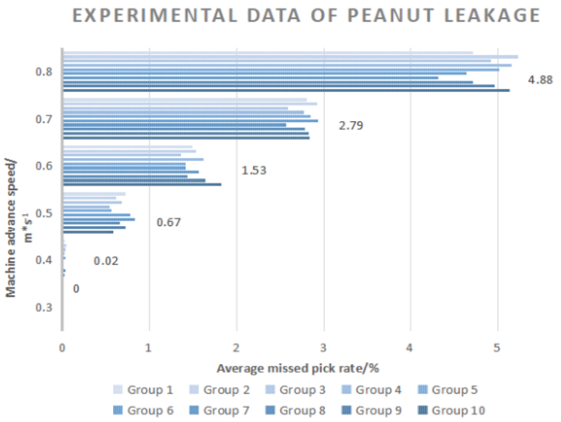


Fig. 8 - Experimental data of peanut leakage

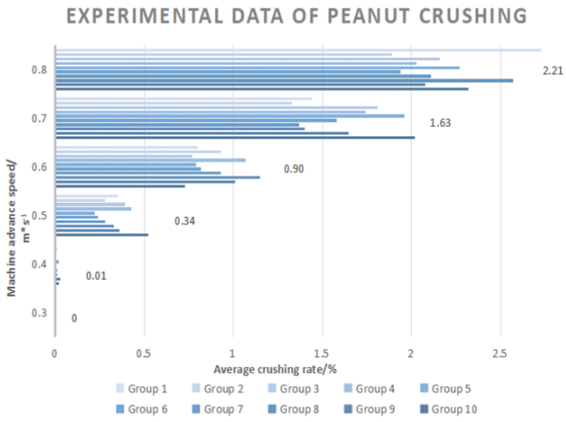


Fig. 9 - Experimental data of peanut crushing

Under the condition of ensuring the harvesting efficiency of peanut combine harvester, 10 sets of validation tests were conducted after setting the forward speed of the machine at 0.6 m/s. The final experimental results are shown in Table 4.

Table 4

Test results of three-ridge six-row peanut combine harvester

Projects	Test results	Technical Requirements
Missed pick rate	1.92%	5%
Crushing rate	0.84%	2%
Congestion	Not available	/
Productivity	0.45 hm^2/h	/

The field test results found that the performance of the three-ridge six-row peanut combine harvester harvesting has been able to meet the technical requirements. Moreover, there was no peanut plant congestion in all 10 trials, which proved that the combine harvester could ensure normal and efficient operation under the condition of large feeding volume. The field test proved that the machine is better than the national standard in various indicators while ensuring harvesting efficiency.

CONCLUSIONS

The article studied the agronomic and biological characteristics of peanut planting and determined the peanut planting pattern of one-ridge two-row of mulch ridge culture crop. 50 plants of each of the 4 peanut varieties most widely and commonly grown in China were selected and their plant height and width, root length, width and height, and average number of pods were measured to provide theoretical support for the design of structural and movement parameters of the peanut picking device.

Through comparison and experimental verification, the structure design scheme of clamping and collecting device of the three-ridge six-row peanut combine harvester was determined. Through mechanical analysis and experimental research, the motion parameters of the picking device were determined.

The overall design of the three-ridge six-row peanut combine harvester was completed, and the field test was carried out. The feeding amount of peanuts was controlled by controlling the forward speed of the machine, and the average leakage rate, crushing rate, productivity and congestion of the harvester were obtained. The operation effect of the whole machine was the best at 0.6 m/s, and 10 sets of verification tests were carried out. There was no congestion of peanut plants, and the combine harvester could ensure normal and efficient operation.

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