Adaptabilities of different harvesters to peanut plants after cutting stalks

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Abstract: At present, there are no harvesters specifically adapted to process peanuts after cutting stalks. In particular, methods for harvesting peanuts after cutting stalks have not been reported thus far. Therefore, to utilize peanut stalks as feed when harvesting plastic-film-grown peanuts, and to improve industry benefits, a three-stage harvesting method is proposed herein. In view of the three-stage harvesting method, the peanut stalks are cut before digging, with the remaining peanut plants being shorter, thereby increasing the peanut pod-stalk ratio. To investigate the adaptabilities of existing harvesters in harvesting peanuts after cutting stalks, three types of peanut harvesters—the self-propelled pick-up combine harvester, trailed pick-up combine harvester, and peanut picker were used to conduct a comparative test on harvesting intact peanut plants and plants after cutting stalks. The loss, breakage and impurity rates were used as evaluation indicators. The loss rates of these three harvesters were 14.64%, 16.44% and 1.33%; the breakage rates were 21.28%, 21.92% and 20.00%, and impurity rates were 4.60%, 8.76% and 9.06%. Analysis of variance showed that cutting stalks had a significant impact on the work qualities of the three harvesters ($p < 0.05$). With regard to the loss rate, results revealed that: the two peanut combine harvesters could not be adapted to harvest peanut plants after cutting stalks. The three harvesters had good adaptability to harvest peanut plants after cutting stalks, considering the breakage rate; however, based on the impurity rate, the three harvesters could not be adapted to harvest peanut plants after cutting stalks. The losses of the two combine harvesters consisted mainly of dropped and missed picking, with the sum of the losses accounting for 99.87% and 97.99% of the total losses of the two harvesters, respectively; this suggests that the drum pickup of the combine harvesters could not adapt to harvesting the peanut after cutting stalks. The breakage rates of the three harvesters were considerably reduced, suggesting that the pod picking devices of the three harvesters were suitable for harvesting the peanut after cutting stalks; the impurity rates of the three harvesters were considerably increased, indicating that the pod picking and cleaning devices of the three harvesters were not suitable for harvesting peanut after cutting stalks. To improve the adaptabilities of the harvesters, it is suggested that the speed of pickup elastic tooth, lateral spacing between adjacent elastic teeth, concave screen hole size of pod picking device, the structure and motion parameters of cleaning device should be optimized. The results of this study provide a reference for the development and improvement of peanut harvesters suitable for harvesting peanuts after the cutting of stalks.

Keywords: agricultural machinery, peanut, peanut harvesting after cutting stalks, peanut combine harvester, peanut picker, adaptability research

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1 Introduction

In 2018, peanut planting area was 4.62 million hm^2 in China, ranking second in the world, with an output of 17.33 million t, ranking first in the world, accounting for 16.2% and 37.7% of the world's total[1], respectively, and making China a major peanut-producing country[2,3]. Moreover, China plays an important role in the development of the global peanut industry[4]. Peanuts grown with plastic-film mulching are very common in China[5-7]. It is estimated that the area of peanut grown with plastic-film mulching in China—mainly in the Huanghuaihai, Northeast and Xinjiang regions—exceeds 2.33 million hm^2[8].

Based on the peanut stalk coefficient[9], the quantity of peanut stalk with plastic-film mulching is estimated to be approximately 8.75 million tons in China. Peanut stalks are often used as feed for livestock and poultry because of their rich nutrition[10,11]. Peanut harvesting process in the main producing areas occurs in two-stage, i.e., digging (the first stage) and the combining or threshing (the second stage)[12,13]. After harvesting, peanut stalks are mixed with a large volume of plastic-film, which affects feed utilization. To improve its industry benefits, Chen et al.[14] proposed a three-stage harvesting process suitable for planting peanuts with plastic mulching: the first stage involves cutting stalks, the second stage digging, and the third stage combining or threshing. It could not only harvest the peanut pods but also ensure that the peanut stalks would not be mixed with the plastic film. Peanut harvesting after stalk cutting is an important process in three-stage harvesting, the quality of this process directly affects the prospects of this new harvesting method.

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Peanut harvesting process occurs in two-stage in the United States of America which employs the most advanced peanut harvesting technologies in the world. The harvesters used are self-propelled or trailed, and are well adapted to their peanut varieties and planting patterns[4]. Based on the characteristics of their domestic peanut varieties and the level of economic development, Chinese researchers have developed various kinds of harvesters for two-stage harvesting. For example, Cao et al.[15] developed a full-feeding shearing flow type of peanut combine harvester, and optimized the design of the shearing flow picking device. Wang et al.[16] designed, optimized, and tested a semi-feed peanut picking device. Chen et al.[17] developed an axial-flow peanut picking device with screw bending-teeth, and conducted an optimization design and experiment of the peanut picking device. Guan[18] developed a multi-drum combined peanut picking test device and conducted picking tests. Wang et al.[19] developed a backpack-type peanut harvester for peanut picking-up and pod picking. Wang et al.[20,21] designed a picking-up and conveying device for a full feeding peanut combine harvester. Yuan et al.[22] developed a peanut picking mechanism for a self-propelled peanut combine harvester. Xu et al.[23] designed a spike-tooth type of peanut picking device with longitudinal axial flow. Shang et al.[24] developed a peanut combine harvester with a full feeding axial flow pod picking device. After continuous research and development, a variety of harvesters suitable for two-stage harvesting have been developed and widely used in China[25]. For example, peanut pickers have long been the most commonly used devices in the main production areas—including Huanghuaihai, Northeast China and Xinjiang—with self-propelled combine harvesters and trailed combine harvesters being rapidly applied and expected to become increasingly popular. However, at present, all harvesters at home and abroad have been developed to harvest completely intact peanut plants. There are no reports on the research of equipment specifically designed for harvesting peanuts after cutting stalks.

In view of shortages of technology and equipment shortcomings for harvesting peanuts after cutting stalks, three typical harvesters types used in China were selected for a comparative test of peanut harvesting after cutting stalks and intact plants. By comparing the loss, breakage and impurity rate changes, different harvester problems could be identified and analyzed, providing a basis for developing and improving the harvesters suitable for harvesting peanuts after cutting stalks.

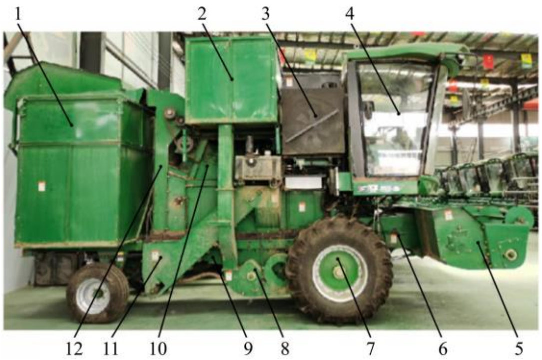
2 Materials and Methods

2.1 Test equipment

2.1.1 CF326 type self-propelled peanut combine harvester

The self-propelled peanut combine harvester (self-propelled peanut combine harvester, SPH, Figure 1) comprises a drum pickup, a conveying device, a pod picking device, a pod collecting device, a cleaning device, a trash lifting device, a wheeled chassis, a dynamic system, a pod tank, a stalk tank, a cab, etc., and can complete picking up, conveying, pod picking, cleaning, pod gathering, seedling gathering and other operations simultaneously.

During operation, the drum pickup picks up the peanut plants from the field and sends them to the conveying device, which then sends the peanut plants to the pod picking device, under the action of which the pods and stalks are separated. Longer stalks are discharged from the outlet of the pod picking device and chopped stalks are sent into the stalk tank. Picked pods, unpicked plants, short stalks, and soil impurities, among others, enter the cleaning device, and clean pods are sent into the pod tank by the pod collecting device. Short stalks are discharged from the end of the cleaning device, and after being chopped, they are blown into stalk tank. Soil and other impurities fall into the field, unpicked plants are discharged from the outlet of the cleaning device, and next, they are sent into the pod picking device by the trash lifting device to pick pods again, completing the entire harvesting process.

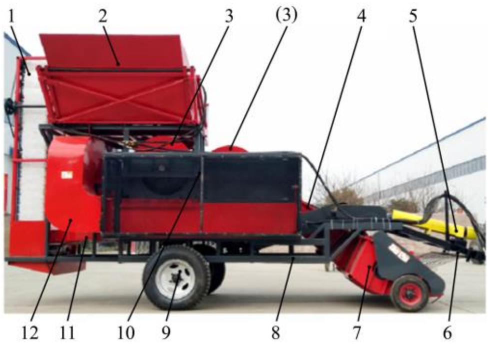


1. Stalk tank 2. Pod tank 3. Dynamic system 4. Cab 5. Drum pickup 6. Conveying device 7. Wheeled chassis 8. Pod collecting device 9. Cleaning device 10. Pod picking device 11. Trash lifting device 12. Stalk conveying and shredding device

Figure 1 CF326 type self-propelled peanut combine harvester

2.1.2 4HQJ-1650 type trailed peanut combine harvester

The trailed peanut combine harvester (trailed peanut combine harvester, TPH, Figure 2) comprises a traction frame, a drum pickup, a conveying device, a pod picking device, a cleaning device, a pod collecting device, a pod tank, a stalk tank, a transmission system, a frame, etc., and can complete operations such as picking up, pod picking, cleaning, pod collecting, and stalk collecting simultaneously.



1. Pod collecting device 2. Pod tank 3. Pod picking device 4. Conveying device 5. Transmission system 6. Traction frame 7. Drum pickup 8. Frame 9. Wheel 10. Stalk tank 11. Vibrating screen 12. Fan outlet

Figure 2 4HQJ-1650 type trailed peanut combine harvester

The harvester is trailed by a tractor, and power is provided by the tractor power take off (PTO). During processing, the drum pickup picks up the peanut plants from the field and sends them to the conveying device, which then sends the peanut plants to the pod picking device, under the action of which the pods and stalks are separated. Longer stalks are directly discharged into the stalk tank from the end of the pod picking device, while pods, short stalks, soil and other impurities fall onto the vibrating screen, and clean pods are sent into the pod tank by the pod collecting device. Because of the different suspension speeds, light and short stalks on the vibrating screen are sucked into the stalk tank by a negative pressure fan, the soil falling to the field. This completes the peanut harvesting process.

2.1.3 5HZ-2000 type peanut picker

The peanut picker (peanut picker, PP, Figure 3) comprises a feeding device, a pod picking device, a cleaning device, a pod collecting device, a stalk tank, a frame, and a transmission system. It can perform pod picking, pod cleaning, pod collecting, and stalk collecting simultaneously.

The power of peanut picker is supplied by the tractor power take off (PTO). During processing, peanut plants are manually placed on the feeding device, and sent into the pod picking device by the feeding device. Under the action of the pod picking device, the separation of pods and stalks is completed, with longer stalks being discharged from the pod picking device into the stalk tank. Short stalks, soil and other impurities fall onto the vibrating screen, clean pods being transported by a belt scraper lifting mechanism (collecting device) and bagged manually. Owing to the different suspension speeds, light and short stalks on the vibrating screen are sucked into stalk tank by a negative pressure fan, the soil and other impurities pass through the vibrating screen holes and fall to the field. This completes the peanut picking process.

1. Feeding device 2. Pod picking device 3. Pod collecting device 4. Fan 5. Vibrating screen 6. Frame 7. Transmission system

Figure 3 5HZ-2000 type peanut picker

The major component structural types of the three test harvesters are listed in Table 1, and the major component structural and movement parameters are listed in Table 2.

Table 1 Major component structures of the three test harvesters

Harvester	Dynamic matching mode	Type of drum pickup	Type of conveying device	Type of picking device	Type of cleaning device	Type of pod collecting device
SPH	Self-propelled	Slide and drum	Chain harrow	Axial flow and nail tooth	Combined type of centrifugal fan plate vibrating screen	Combined type of screw conveyor and pneumatic conveying system
TPH	Trailed	Slide and drum	Chain harrow	The first stage: axial flow and nail tooth The second stage: shearing flow and nail tooth	Combined type of negative pressure mixed flow fan and long hole vibrating screen	Closed chain bucket elevator
PP	Stationary	/	Scraper	Axial flow and nail tooth	Combined type of negative pressure mixed flow fan and long hole vibrating screen	Belt scraper conveyor

Table 2 Structural parameters and motion parameters of major components of the three test harvesters

Harvester	Power	Working width/mm	Working speed /km·h^{-1}	Rows of pickup elastic tooth/n	Lateral spacing between adjacent elastic teeth/mm	Reel speed of pickup elastic tooth/r·min^{-1}	Dimension of threshing roller (diameter × length)/mm	Speed of tooth point of threshing roller/m·s^{-1}	Hole dimension of concave screen/mm
SPH	88.2 kW diesel engine	2700	2.0-6.0	6	155	127.5	710×2000	11.32	90×60
TPH	58.8-88.2 kW wheeled tractor	1650	0.6-1.8	6	105	45	The first roller: 540×630, The second roller: 633×1320	The first roller: 11.30, The second roller: 13.25	150×65
PP	22.1-36.8 kW wheeled tractor	/	/	/	/	/	600×2000	12.61	130×55

Note: 1. * indicates that the concave mesh screen shape is approximately rectangular. 2. All the motion parameters are measured at the rated speed of the engine or mating power.

2.2 Peanut plants for test

Henan Province has the largest peanut planting area in China, involving a considerable volume of plastic film mulching. The two-stage peanut harvesting process has generally been adopted in this region. The peanut variety used in this study was Yuanza 9102 cultivated by Henan Academy of Agricultural Sciences, which is widely planted in the main peanut-producing areas of China[26]. With reference to the GB/T 5262-2008 standard—'Measuring methods for agricultural machinery testing conditions-General rules'[27], the planting modes and growth conditions of peanut plants, such as row spacing, seed spacing, height, etc. were measured, the results of which shown in Table 3. A digger proceeded along the rows of plants, loosened the soil, cut the root, shook the soil from the peanuts, laying the plants back onto the field, after which the peanut plants could be manually collected and transferred to the test site.

The material to be tested was divided into two parts—that is, the peanut plants without cutting stalks, which were left to dry at the test site for 5 d, and the peanut plants were manually cut using a guillotine, before being left to dry at the test site for 5 d. To avoid cutting off the peanut carpopodium and creating losses when cutting stalks, it is necessary to ensure that the height H of the peanut plant stubble after cutting stalks is 120 mm (Figure 4). The stalk and pod moisture content of the intact plants and the plants with cut stalks and pod-stalk ratio were measured, the results of which are presented in Table 4.

Table 3 Planting modes and growth conditions of peanut plants

Wide row spacing/mm	Narrow row spacing/mm	Ridge height /mm	Seed spacing /mm	Height /mm	Yield /kg·hm^{-2}
475	225	122	134	567	4725

a. Cut stalks b. Cut position

Note: S_q is the cut plane; S_d is ground; H is the height of the peanut plant stubble, mm.

Figure 4 Cut peanut plant stalks

Table 4 Moisture content and pod-stalk ratio after drying of the peanut plants

Material	Pod moisture content/%	Stalk moisture content/%	Pod-stalk ratio
Intact plants	19.76	11.14	1.2
Plants after cutting stalks	18.86	10.66	2.6

2.3 Test method

2.3.1 Two kinds of combine harvester tests

Based on the peanut row spacing and seed spacing measured in the field, according to the same density, the intact plants and the plants after cutting stalks were manually laid on the test site, over a length of 30 m with a blank area of 10 m at both ends. To reserve sufficient travel for the harvester to enter a stable working state, the width of plant laying area was equal to the working width of the two harvesters. The forward speed of the self-propelled combine harvester was then set to 4.0 km/h (the measured average speed was 3.8 km/h), and the trailed combine harvester was set to 1.2 km/h (the measured average speed was 1.1 km/h) based on the operating instructions of the harvesters for their operational forward speed. The tests of intact plants and plants after cutting stalks were conducted in turn, with reference to the NY/T 502-2016 standard 'Operating quality for peanut harvesters'[28]. Five tests were conducted for each harvester for different materials. All the pods in the pod tank and stalks in the stalk tank were collected after each test, while pods on the ground and plants that were missed picking during each test were collected manually.

2.3.2 Peanut picker test

Based on the operating instructions for the volume of feed, the intact plants and the plants after cutting stalks were divided into several small piles with a mass of 3.3 kg, after which the manual feeding speed was set, that is, one pile was fed every 5 s. Each test lasted 10 min. With reference to the NY/T 993-2006 standard 'Operating quality for peanut pickers'[29], five tests were conducted for different materials, and all the pods in the pod tank and stalks in the stalk tank were collected and retained after each test.

The tests were conducted from September 14th to 27th, 2018, at the test site of Henan Nongyouwang Agricultural Equipment Technology Co., Ltd., Suiping County, Zhumadian City, Henan Province. The field test environment is shown in Figure 5.

a. Self-propelled peanut combine harvester b. Trailed peanut combine harvester c. Peanut picker

Figure 5 Prototype field test environment

2.4 Data process

2.4.1 Loss rate

The NY/T 502-2016 standard 'Operating quality for peanut harvesters'[28] stipulates that the total loss rate of peanut combine harvester is required to be ≤5.0%, including the pod drop and unpicked rate. Because peanut combine harvesters were not equipped with stalk tank when the standard was formulated, they exhausted the stalks and impurities directly back to the field, and the total loss rate could be obtained directly by measuring the pod drop and unpicked rates. However, current peanut combine harvesters are equipped with stalk tanks for collecting the peanut stalks. Some pods can be mixed with stalks and subsequently be exhausted to the stalk tank, making it unreasonable to calculate the loss rate by considering only the pod drop and unpicked rates. Therefore, the calculation and sampling methods of the total loss rate of the two combine harvesters differ from the standard regulations.

Based on the operating principles and operational process of the two combine harvesters, the total loss rate should include the missed picking, pod drop, entrainment, and unpicked rates. Moreover, because the self-propelled combine harvester is equipped with a stalk shredding device, the materials entering the stalk tank are shredded, making it is impossible to determine whether the peanut pods (including broken pods) in the stalk tank are unpicked, entrained, or both. At the same time, the tests found that the number of pods (including broken pods) in the stalk tank of the self-propelled combine harvester was less than 0.5% of the total loss rate. Additionally, the self-propelled combine harvester is equipped with an auger-belt scraper trash lifting device, which can send the unpicked plants to the pod picking device for re-picking. Therefore, it can be approximate as zero when calculating the unpicked rate of the self-propelled combine harvester.

The testing methods for the missed picking, pod drop, entrainment, unpicked—note that the unpicked rate of the self-propelled combine harvester is 0—and the total loss rates of the two combine harvesters are as follows:

Method of testing the missed picking rate: Manually pick up all the peanut plants that have not been picked up in the test area, pick off the peanut pods, weigh their mass, and calculate the missed picking rate based on Equation (1).

Method of testing the pod drop rate: Manually pick up all the pods that have been separated from the peanut plant in the test area, weigh their mass, and calculate the pod drop rate based on Equation (2).

Method of testing the entrainment rate: All pods separated from the peanut plant in the stalk tank in the test area are selected, weighed, and the entrainment rate calculated based on Equation (3).

Method of testing the unpicked rate: Manually pick up all unpicked pods from plants in the stalk tank in the test area, weigh their mass, and calculate the unpicked rate based on Equation (4).

The formula for calculating the total loss rate of the combine harvesters can be expressed as in Equation (5).

$$L_j = \frac{m_1}{m_1 + m_2 + m_3 + m_4 + m_5} \times 100\% \tag{1}$$

$$D_l = \frac{m_2}{m_1 + m_2 + m_3 + m_4 + m_5} \times 100\% \tag{2}$$

$$J_d = \frac{m_3}{m_1 + m_2 + m_3 + m_4 + m_5} \times 100\% \tag{3}$$

$$W_z = \frac{m_4}{m_1 + m_2 + m_3 + m_4 + m_5} \times 100\% \tag{4}$$

$$S_z = W_j + D_l + J_d + W_z \tag{5}$$

where, m_1 is the mass of unpicked pods from peanut plants, g; m_2 is the mass of pods separated from peanut plants on the ground, g; m_3 is the mass of picked pods in the stalk tank, g; m_4 is the mass of unpicked pods in the stalk tank, g; m_5 is the mass of the pods in the pod tank, g; L_j is the missed picking rate, %; D_l is the pod drop rate ,%; J_d is the entrainment rate, %; W_z is the unpicked rate, %; and S_z is the total loss rate of the combine harvester, %.

The NY/T 993-2006 standard 'Operating quality for peanut pickers'[29] stipulates that: when a peanut picker is used for dry peanut picking, the total loss rate is required to be ≤1.0%; the total loss rate equals the cleaning loss rate; the entrainment loss and unpicked loss rates are not calculated in the total loss rate. However, it was found that some peanut pods and unpicked plants were present in the stalk tank when peanut pickers were used to pick dry peanut plants, and the pods discharged by the cleaning device were immature or too small. Immature or small pods should not be included in the total loss rate; in other words, the cleaning loss rate of the test peanut picker is 0. Consequently, the method for calculating the total loss rate of peanut picker differs from that of the standard.

The total loss rate of the peanut picker comprises the entrainment and unpicked loss rates. The calculation methods are as follows:

Method of testing the entrainment loss rate: Pick out all the peanut pods separated from the peanut plants in the stalk tank after each test, weigh their mass, and calculate the entrainment loss rate based on Equation (6).

Method of testing the unpicked loss rate: After each test, pick up all pods that were not picked from the peanut plants in the stalk tank, weigh their mass, and calculate the unpicked loss rate based on Equation (7).

The formula for calculating the total loss rate of the picker can be expressed by Equation (8).

$$J_{zd} = \frac{m_6}{m_6 + m_7 + m_8} \times 100\% \tag{6}$$

$$W_{zz} = \frac{m_7}{m_6 + m_7 + m_8} \times 100\% \tag{7}$$

$$S_{zz} = J_{zd} + W_{zz} \tag{8}$$

where, m_6 is the mass of peanut pods separated from peanut plants in the stalk tank, g; m_7 is the mass of peanut pods that were not picked from peanut plants in the stalk tank of the picker, g; m_8 is the mass of peanut pods collected at the outlet of the picker, g; J_{zd} is the entrainment rate of the picker, %; W_{zz} is the unpicked rate of the picker, %; and S_{zz} is the total loss rate of the picker, %.

2.4.2 Breakage rate

The NY/T 502-2016 standard 'Operating quality for peanut harvesters'[28] stipulates that the breakage rate of a peanut combine harvester is required to be ≤5.0%. The NY/T 993-2006 standard 'Operating quality for peanut pickers'[29] stipulates that: when a peanut picker is used for picking dry peanut plant, the breakage rate is required to be ≤4.0%.

The formula for the breakage rate of a combine harvester and peanut picker can be expressed as follows:

$$P_s = \frac{m_9}{m_9 + m_{10}} \times 100\% \tag{9}$$

where, m_9 is the mass of broken pods in the sample taken from the pod tank of the test harvester, g; m_{10} is the mass of the undamaged pods in the sample taken from pod tank of the test harvester, g; and P_s is the breakage rate, %.

2.4.3 Impurity rate

The NY/T 502-2016 standard 'Operating quality for peanut harvesters'[28] stipulates that the impurity rate of a peanut combine harvester is required to be ≤8.0%. The NY/T 993-2006 standard 'Operating quality for peanut pickers'[29] stipulates that: when peanut picker is used for picking dry peanut plant, the impurity rate is required to be ≤2.0%.

The formula for the impurity rate of a combine harvester and the peanut picker can be expressed as follows:

$$Z = \frac{m_{11}}{m_9 + m_{10} + m_{11}} \times 100\% \tag{10}$$

where, m_{11} is the mass of impurities in the sample taken from the pod tank or pod collecting device of the test equipment, g; and Z is the impurity rate, %.

2.4.4 Statistical analysis

Excel 2013 was used for data statistics, calculations and drawings. SPSS 19.0 was used for analysis of variance, and the significance level was set at $p<0.05$.

3 Results analysis and discussion

3.1 Loss rate

Loss in the mechanized harvesting process is inevitable, and loss rate is an important indicator for evaluating the performance and adaptability of harvesters.

As shown in Figure 6, when harvesting intact peanut plants, the average total loss rate of the self-propelled combine harvester, trailed combine harvester, and peanut picker are 6.22%, 5.68%, and 1.94%, respectively. When harvesting peanut plants after cutting stalks, the average total loss rate of the self-propelled combine harvester is 14.64%, an increase of 135.37%; the average total loss rate of the trailed combine harvester is 16.44%, an increase of 189.44%; the average total loss rate of the peanut picker is 1.33%, a reduction of 31.44%. The total loss rates of the three harvesters are greater than the standard requirements for harvesting intact plants or peanut plants after cutting stalks. The analysis of variance shows a significant difference in the total loss rate of the three harvesters when harvesting intact plants and peanut plants after cutting stalks ($p<0.05$), indicating that cutting stalks have a significant impact on their total loss rate.

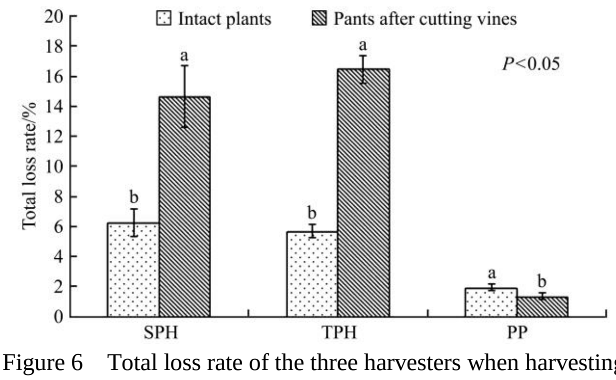
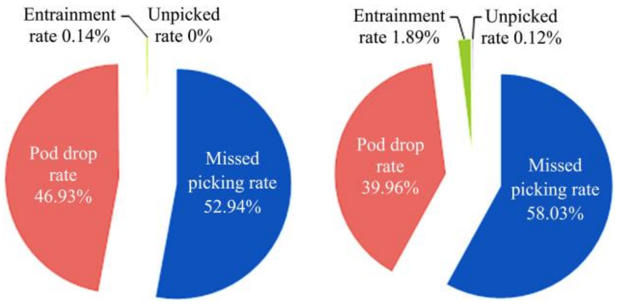


Figure 6 Total loss rate of the three harvesters when harvesting intact plants and plants after cutting stalks

As mentioned previously, the total loss rate of the combine harvester consists of the missed picking, pod drop, entrainment, and unpicked rates. The loss rates of the two combine harvesters when harvesting peanut plants after cutting stalks are shown in Figure 7.



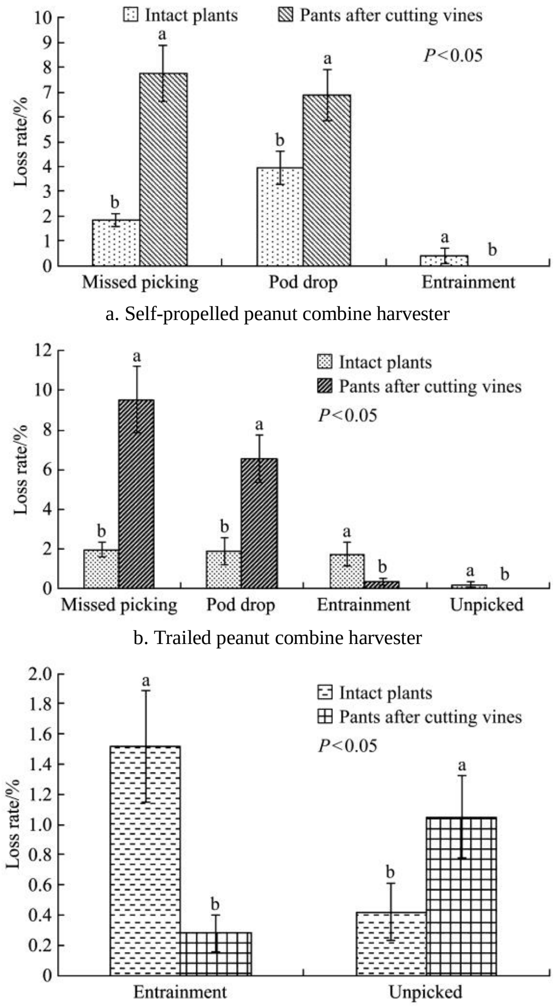
a. Self-propelled peanut combine harvester b. Trailed peanut combine harvester

Figure 7 Different loss rate proportions of the two peanut combine harvesters

As shown in Figures 7a and 7b, when the self-propelled combine harvester and the trailed combine harvester harvested the peanut plants after cutting stalks, the total loss rate mainly comprises the pod drop and missed picking rates. The pod drop and missed picking rates of the self-propelled combine harvester accounted for 46.93% and 52.94% of the total loss rate respectively, while the pod drop and missed picking rates of the trailed combine harvester accounted for 39.96% and 58.03% of the total loss rate, respectively. The pod drop and missed picking rates are caused mainly by the drum pickup of the two combine harvesters, indicating that it is not suitable for harvesting peanut plants after cutting the stalks.

The changes in loss rates when the three harvesters process intact plants and plants after cutting stalks are shown in Figure 8. As can be seen in Figure 8a, the missed picking rate of the self-propelled combine harvester increases from 1.84% to 7.75%. The main reason may be that the lateral spacing between the adjacent elastic teeth of the drum pickup is too large, and the peanut plants are so short after cutting the stalks that the elastic teeth cannot pick them up. The pod drop rate increases from 3.95% to 6.87%. The main reason may be that cutting stalks results in a larger pod-stalk ratio, which means more pods enter the drum pickup relatively, and the chances of elastic teeth hitting the pods directly increases; consequently, more pods are dropped. The entrainment rate decreases from 0.4% to 0.02%. The main reason may be that cutting stalks results in a larger pod-stalk ratio, which means fewer stalks enter the pod picking device relatively, and the size of hole dimension of concave screen being relatively large, the pods are more likely to fall through the concave screen under the action of centrifugal force, and are not easy to be "wrapped" into the stalk tank by the stalks. The analysis of variance shows a significant difference in the loss rates of the self-propelled combine harvester when harvesting intact plants and plants after cutting stalks (p<0.05), and also shows that cutting stalks has a significant impact on the loss rates of the self-propelled combine harvester.

As shown in Figure 8b, the missed picking rate of the trailed combine harvester increases from 1.95% to 9.54%, the pod drop rate of the trailed combine harvester increases from 1.84% to 6.57%, and the entrainment rate of the trailed combine harvester decreases from 1.72% to 0.31%. The reasons for the loss rate changes are the same as those for the self-propelled combine harvester. The unpicked rate decreases from 0.17% to 0.02%, the main reasons being that cutting stalks results in a larger pod-stalk ratio, which means fewer stalks enter the pod picking device relatively, and the pods lack the 'protection' of the stalks, making it easier for the pods to be knocked off. The analysis of variance shows a significant difference in the loss rates of the trailed combine harvester when harvesting intact plants and plants after cutting stalks (p<0.05), indicating that cutting stalks has a significant impact on its loss rates.



a. Self-propelled peanut combine harvester

b. Trailed peanut combine harvester

c. Peanut picker

Figure 8 Variation of the harvester loss rates when harvesting intact plants and plants after cutting stalks

As shown in Figure 8c, the entrainment rate of the peanut picker decreases from 1.52% to 0.28%. The reasons are the same as those for the lower entrainment rates of the two combine harvesters. The unpicked rate of the peanut picker increases from 0.42% to 1.05%.The reasons for the unpicked rate changes may be that after cutting stalks, the length of the peanut plants shortens, and the distance between the tooth traces of the picking nails and the gap between tooth tip and concave screen is relatively large, making it difficult to break up the plants and pick up pods, which resulting in an increase in the unpicked rate. The analysis of variance shows a significant difference in the loss rates of the peanut picker when harvesting intact plants and plants after cutting stalks (p<0.05), and also shows that cutting stalks has a significant impact on the loss rates of the peanut picker.

3.2 Breakage rate

The breakage rate refers to the percentage of the mass of damaged peanut kernels, damaged peanut shells and cracked peanut pods in the total mass of pods after harvesting. An excessive breakage rate is not conducive to the safe storage of pods and reduces their commodity[30,31]. Picking up, conveying, picking, collecting and other processing links may cause breakages, but pod picking is the most important factor in terms of breakages when adopting full-feeding and pod picking modes. Consequently, this test focused on analyzing the impact of pod picking on the breakage rate.

As shown in Figure 9, when harvesting intact plants and plants after cutting stalks, the breakage rates of the self-propelled combine harvester are 24.11% and 21.28%, those of the trailed combine harvester are 37.20% and 21.92%, and those of the picker are 33.69% and 20.00%, respectively. The analysis of variance shows a significant difference in the breakage rate of the three harvesters when harvesting intact plants and plants after cutting stalks (p<0.05), indicating that cutting stalks have a significant impact on their breakage rates.

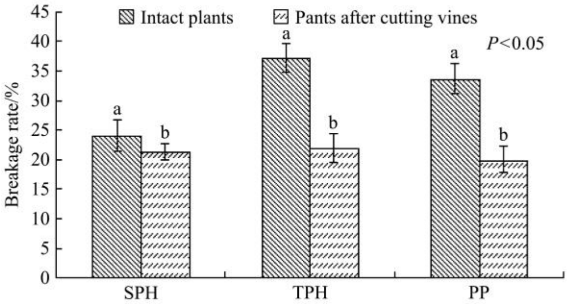


Figure 9 Breakage rate of the three harvesters when harvesting intact plants and plants after cutting stalks

The breakage rates of the three harvesters decrease when plants are harvested after cutting the stalks. The reasons may be: cutting stalks results in a larger pod-stalk ratio, which means fewer stalks enter the picking device relatively, and pods separated from plants fall more easily from the concave screen under the action of centrifugal force due to the lack of a stalk barrier, which reduces the probability of repeatedly hitting the pods, reducing the pod breakage rate; at the same time, due to fewer stalks and the large gap between the tooth tip and concave screen, the rubbing effect of plants between the nail teeth and concave screen is weakened, the result of which is reduced breakage rates.

3.3 Impurity rate

The impurity rate reflects the volume of impurities in peanut pods, including soil, stems, leaves, weeds, etc.[32,33]. The impurities in the three harvesters were mainly peanut stalks, and there was almost no soil. The main reason may be that the plants were shaken by digger before picking up, and next the plants were collected, sorted and laid out manually resulting in the removal of soil; additionally, in adopting the full-feeding picking mode, soil would be easily broken by the picking device and discharged by the cleaning device.

As shown in Figure 10, when harvesting intact plants and plants after cutting stalks, the impurity rates of the self-propelled combine harvester are 4.17% and 4.60%, those of the trailed combine harvester are 7.70% and 8.76%, and those of the picker are 7.29% and 9.06%, respectively. The analysis of variance shows a significant difference in the impurity rates of the three harvesters when harvesting intact plants and plants after cutting stalks (p<0.05), indicating that cutting stalks have a significant impact on their impurity rates.

Harvesting the plants after cutting stalks, and owing to the larger pod-stalk ratio, the number of stalks entering the harvester is relatively smaller than that when harvesting intact stalks, supposedly reducing the impurity rates of the harvesters. However, the impurity rates of the three harvesters did not decrease but increased. The main reasons may be as follows: the concave screens of the three harvesters were designed for harvesting intact plants; the peanut plants after cutting stalks are likely to fall from the concave screen holes to the vibrating screen due to the large concave screen holes, and then enter the pod tank, resulting in an increased impurity rate. Although the impurity rates of three harvesters all increased, because the self-propelled combine harvester was equipped with an auger-belt scraper trash lifting device, the plants that were not picked and fell onto the vibrating screen could be sent to the picking device to be picked again, so its impurity rate was the lowest.

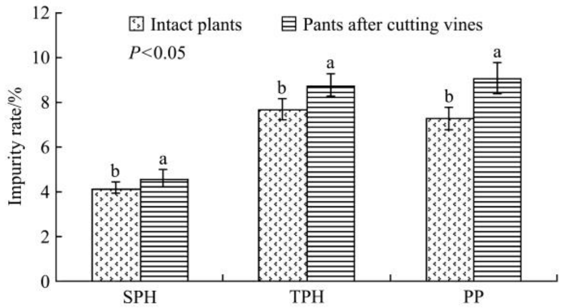


Figure 10 Impurity rate of the three harvesters when harvesting intact plants and plants after cutting stalks

3.4 Discussion

The peanut planting mode in China can be mainly divided into bare land and plastic-film mulching cultivation, based on whether or not film mulching is used. Depending on the sowing season, peanuts in China include spring and summer peanuts[34]. To improve the multiple cropping index and early sowing, spring peanuts are often grown with plastic-film mulching in Huanghuaihai (the first major peanut producing area in China). Due to low spring temperature, perennial drought and rainless conditions, spring peanuts (single crop per year) are widely planted with film mulching in northeast China and Xinjiang. The main producing areas are the principal livestock and poultry breeding areas in China [35], which consume a large volume of raw feed materials annually. Consequently, peanut pods are harvested, as their stalks, which are used for livestock and poultry feed in the above-mentioned areas. At present, the peanut with plastic-film mulching harvesting process occurs in two stages in the above-mentioned areas, and peanut stalks mixed with plastic film after harvesting cannot be used as feed. The three-stage harvesting process can help to avoid the mixing of stalks and plastic film (compared with the two-stage process), it can also prevent the mixing of other impurities (such as soil) and improve feed quality. Therefore, the three-stage harvesting process has good application prospects in the aforementioned areas.

However, there is currently no research on combining or threshing technologies specifically used for harvesting the peanuts with plastic-film mulching. In response to production needs, three types of harvesters were selected to study their adaptabilities when harvesting peanuts after cutting stalks.

The test results showed that cutting stalks had a significant impact on the work quality of the three harvesters (p<0.05). Compared with harvesting intact peanut plants, the loss rates of the self-propelled combine and trailed combine harvester increased by 135.37% and 189.44% respectively, and the loss rate of picker decreased by 31.44%; the breakage rates of the three harvesters decreased by 11.74%, 41.08% and 40.64% respectively; the impurity rates of the three harvesters increased by 10.31%, 13.77% and 24.28% respectively. Considering the loss rates, the picker was more suitable for harvesting peanut after cutting stalks; considering the breakage rates, all three harvesters were suitable for harvesting peanut after cutting stalks; considering the impurity rates, the three harvesters were not suitable for harvesting peanut after cutting stalks, the self-propelled combine harvester equipped with an auger-belt scraper trash lifting device (with enable repeated picking) had a better impurity rate index. All work quality aspects of the three harvesters, especially during production, often require small loss rates; consequently, the picker could be used in three-stage harvesting of film mulching peanuts in the Huanghuaihai, Northeast and Xinjiang regions.

From a mechanized peanut harvesting development perspective, combine harvesting with higher operating efficiency and reduced labor is a good trend[4]. However, the two types of combine harvesters examined here exhibited high loss and impurity rates. Therefore, it would be necessary to reduce the loss and impurity rates and improve the components of the two combine harvesters to enhance their adaptabilities to peanut harvesting after cutting stalks. Based on the study results, the following improvements are proposed for discussion: optimize the design of the drum pickup, which can increase the pick-up rate by reducing the lateral spacing between adjacent elastic teeth, and reduce the rotation speed of elastic teeth to reduce pod drop rate; decrease the size of the concave screen hole of the picking device to reduce the impurity rate, although its influence on the breakage rate should be comprehensively considered; equip the secondary picking device to reduce unpicked plants entering the pod tank; optimize the structure of the cleaning device to enhance the cleaning up of small impurities. Optimization of key devices does not only affect one work quality of a harvester, but should also systematically consider its impact on other work qualities.

4 Conclusions

(1) When harvesting peanut plants after cutting stalks, the total loss, breakage and impurity rates of the self-propelled combine harvester were 14.64%, 21.28%, and 4.60%, respectively; compared with harvesting intact peanut plants, the total loss and impurity rates increased by 135.37% and 10.31%, and the breakage rate decreased by 11.74%. When harvesting peanut plants after cutting stalks, the total loss, breakage and impurity rates of the trailed combine harvester were 16.44%, 21.92%, and 8.76%, respectively; compared with harvesting intact peanut plants, the total loss and impurity rates increased by 189.44% and 13.77%, and the breakage rate decreased by 41.08%. When harvesting peanut plants after cutting stalks, the total loss, breakage, and impurity rate of the picker were 1.33%, 20.00% and 9.06%, respectively; compared with harvesting intact peanut plants, the total loss and breakage rates decreased by 31.44% and 40.64%, and the impurity rate increased by 24.28%. Analysis of variance showed that cutting stalks had a significant impact on work qualities of the three harvesters ($p<0.05$).

(2) From a loss rate perspective, the two peanut combine harvesters could not be adapted to harvest peanut plants after cutting stalks; from a breakage rate perspective, the three harvesters exhibited good adaptabilities to harvest peanut plants after cutting stalks; and from an impurity rate perspective, the three harvesters could not be adapted to harvest peanut plants after cutting stalks.

(3) When harvesting peanuts after cutting stalks, the loss rates of the two types of combine harvesters comprised mainly the pod drop and missed picking rates. The pod drop and missed picking rates accounted for 99.87% and 97.99% of the total loss rate of the two harvesters respectively, indicating that drum pickups of the two harvesters were not suitable for harvesting peanut after cutting stalks. To improve the adaptabilities of the two harvesters, the elastic teeth speed and lateral spacing between adjacent elastic teeth of the drum pickup should be optimized.

(4) When harvesting peanuts after cutting stalks, the breakage rates of the three harvesters decreased significantly ($p<0.05$), indicating that the pod picking devices of the three harvesters were suitable for harvesting peanut after cutting stalks; the impurity rates all increased significantly ($p<0.05$), indicating that the pod picking device and cleaning device of the three harvesters were not suitable for harvesting peanut after cutting stalks. To improve the adaptabilities of the three harvesters, it would be important to optimize the concave screen hole size of the pod picking device. Under the premise of reducing the breakage rate, the volume of short stalks entering the cleaning device should be reduced, and the structure and movement parameters of the cleaning device should be optimized to increase their abilities to clean short stalks.

(5) In this experiment, artificial stalk cutting and placement were adopted to simulate mechanical stalk cutting and placement process. There may be errors between the experimental results and actual operational processes. We plan to continue field experiments.

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