Original Article
Food Science and Technology

ISSN 0101-2061 (Print)
ISSN 1678-457X (Online)

DOI: https://doi.org/10.1590/fst.111822

Soybean crushing forms by mechanical harvesting and factors affecting the proportions of different forms

Youliang NI[1], Chengqian JIN[1*], Man CHEN[1], Zhenjie QIAN[1], Tengxiang YANG[1], Jinshan XU[1], Gangwei LIU[1]

Abstract

Aiming at the problem of serious damage in the process of soybean harvesting and production, this paper analyzes the soybean harvesting process, and determines the main crushing forms of soybeans: epidermal breakage, splitting into two flaps, and overall crushing. The influence of different operation links on soybean crushing during the harvesting process, such as header feeding auger, horizontal seed spiral conveyor, horizontal miscellaneous residue spiral conveyor, and threshing roller was studied. The influence of the operating parameters such as the forward speed of the harvester, threshing roller speed, and deflector angle on the soybean crushing form was studied experimentally. The results showed that, the degree of influence on the proportion of sepidermal breakage from high to low was the forward speed of the harvester, deflector angle and threshing roller speed. The degree of influence on the proportion of splitting into two flaps from high to low was the deflector angle, threshing roller speed and the forward speed of the harvester. The degree of influence on the proportion of the overall crushing from high to low was the forward speed of the harvester, threshing roller speed and deflector angle.The research results can provide a reference for the subsequent structural improvement of soybean harvester and optimization of operating parameters.

Keywords: agricultural machinery; harvesting; soybeans; broken form; threshing drum.

Practical Application: This manuscript is relevant for the soybean production industry, especially for the mechanized harvesting of soybean, because this study analyzes the soybean harvesting process, and determines the main crushing forms of soybeans and influence of the operating parameters.This study can provide theoretical support for optimizing the operating parameters of soybean harvester.

1 Introduction

The soybean is an important grain and oil crop in China, and a major source of oil and high-quality vegetable protein (Shi, 2010; Gao et al., 2012). It is of great significance to promote the development of the soybean industry to ensure people's health. Mechanized production is the basis for intensive, large-scale land cultivation, which can effectively improve crop yields, reduce costs, and improve land resource utilization and production capacity (Li et al., 2013). A total of 93 thousand km^2 of soybeans were sown in China in 2021 (National Bureau of Statistics, 2019), with a mechanization rate of harvesting exceeding 80%. However, soybean breakage in China's machine harvesting is a serious issue, accounting for the largest proportion of soybean machine harvesting losses. In particular, soybean pods can easily burst, and bean grains are prone to breakage under the action of the machine. This study describes a comprehensive analysis of the breakage forms due to soybean mechanized harvesting, so as to understand the causes of soybean breakage. This work can help optimize machine parts of soybean harvesters, reduce associated breakage, and improve the quality of soybean harvesting.

Much research has been conducted to develop low-breakage soybean harvesting technologies. Gao studied the mechanical damage process of soybeans, and determined that serious mechanical damage was common in mechanically threshed soybean seeds, with external and internal damage rates of 9%–12% and 5%–9%, respectively, and that mechanical damage occurred mainly in the threshing process, caused by the action of the machinery (Gao et al., 2010). Dun et al. studied the effect of collision parameters on the stress distribution and deformation displacement of soybean seeds, and their changes with time. They used an orthogonal test to analyze the effects of collision speed and contact radius on the maximum stress and displacement in the collision process (Dun et al., 2015). Chen et al. studied the detection algorithm of soybean crushing rate and established a model of soybean crushing rate based on spectral data (Chen et al., 2022). Chen et al. designed a soybean longitudinal flow double-spiral roller and studied the distribution pattern of threshed materials (Chen et al., 2020a, b). Jin et al. studied the influence of different threshing roller structures on soybean harvest quality, and determined the selection of threshing elements and optimal matching of threshing operation parameters under different moisture contents (Jin et al., 2021). Teng et al. designed a system with an adjustable threshing area to realize soybean threshing intensity control by adjusting the closing area of the concave plate screen with a motor (Teng et al., 2020a, b). Yang et al. designed a longitudinal axial flow threshing device with a small feeding capacity for soybean harvesting in hilly regions in southwestern China and optimized the roller speed and guide plate lift angle through multi-factor experiments

Received 30 Sept., 2022
Accepted 22 Nov., 2022
[1] *Nanjing Research Institute for Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing, Jiangsu, China*
*Corresponding author: jinchengqian@caas.cn

(Yang et al., 2018). Liu et al. designed a cleaning system with detectable and adjustable operating parameters, and selected different cleaning sieves for soybean cleaning adaptability tests, so as to optimize the cleaning parameters of a soybean combine harvester (Liu et al., 2020a, b, 2020c).

This paper studied the soybean harvesting process, determined the main crushing forms of soybeans, and analyzed the influence of different operation links on soybean crushing during the harvesting process, such as header feeding auger, horizontal seed spiral conveyor, horizontal miscellaneous residue spiral conveyor, and threshing roller, and determined the proportion of different crushing forms in each operation link.The influence of the operating parameters such as the forward speed of the harvester, threshing roller speed, and deflector angle on the soybean crushing form was studied experimentally, and the results can provided a reference for the optimization of the soybean harvester.

2 Materials and methods

2.1 Experimental device

The experimental device was a crawler soybean combine harvester, which is widely used in the main soybean producing areas in China. The machine, as shown in Figure 1, included a cab, grain box, seed lifter, re-threshing lifter, threshing roller, threshing wheel, cutter feed stirrer, header, undercarriage, horizontal seed spiral conveyor, horizontal trash spiral conveyor, and cleaning sieve. The unit had a working width of 1500 mm, engine power of 68 kW, machine size (length × width × height) of 4850 mm × 2000 mm × 2450 mm, feeding capacity of 1.2–3 kg/s, and operating efficiency of 0.4–0.7 hm^2/h.

The operation process was as follows. Soybeans were cut, and then were plucked into the inside of the cutting platform through the paddle wheel. The plants were transported to the intermediate conveyor through the cutting platform feeding auger, and transported to the threshing and separating device. After the single threshing roller operation, the soybean seeds and miscellaneous residue fell on the screen surface of the cleaning device. Some residue and straw was separated from the harvester. The soybean seeds fell into the horizontal seed spiral conveyor and were transported to the grain bin through the seed lifter. Other residue and uncleaned pods entered the horizontal miscellaneous residue spiral conveyor and were transported back to the front section of the threshing roller for secondary threshing through the re-threshing lifter.

2.2 Experimental design

The experiment was conducted in October 2021 at a soybean planting base in Liangshan County, Shandong Province, China. Soybeans in the test field were free of collapse, and the plot had some undulation. The soybean type was Qi-huang 34, with a thousand grain weight of 276 g. The average height of a soybean plant was 707 mm, and the average height of the bottom pod was 239 mm. The moisture content of the soybean seed was 12.5%. Figure 2 shows the test scene.

The soybean type, maturity, and weeds in the field were recorded before harvesting. The yield of soybeans per square meter in the test field, moisture content of the seeds, minimum pod height, and degree of crop collapse were determined. According to the test conditions and soybean growth, it was necessary to adjust the header feeding auger, threshing roller, horizontal seed spiral conveyor, horizontal miscellaneous residue spiral conveyor, and cleaning sieve.

The grain box, header, horizontal seed spiral conveyor, and horizontal miscellaneous residue spiral conveyor were emptied before the test. A 10-m buffer zone was set up with a well harvested condition with no crop left. A 15-m zone was set up as the zone to be harvested. The harvesting time was recorded, and the harvester speed was adjusted in the buffer zone before the machine was driven into the area to be harvested. After the harvest was completed, the header, horizontal seed spiral conveyor, horizontal miscellaneous residue spiral conveyor, soybean seeds, and miscellaneous residue in the grain box were collected, and the harvester was in an idle condition for two minutes. Then the grain was completely unloaded. The seeds in the grain box were collected for sampling and processing.

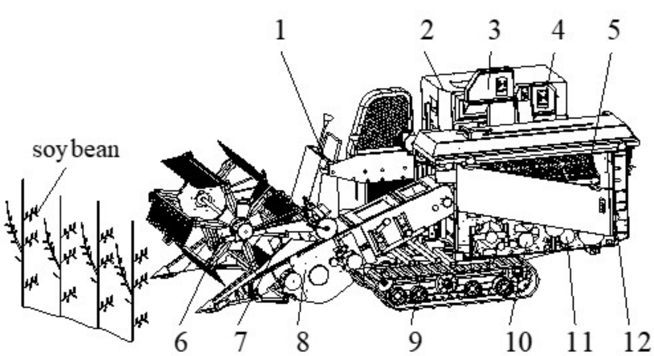


Figure 1. Structure diagram of the crawler soybean combine harvester 1. Driver's cab; 2. Grain box; 3. Seed lifter; 4. Re-threshing lifter; 5. Threshing roller; 6. Threshing wheel; 7. header feeding auger; 8. header; 9. Chassis; 10. Horizontal seed spiral conveyor; 11. Horizontal miscellaneous residue spiral conveyor; 12. Cleaning sieve.

Figure 2. Test scene of soybean machine harvest.

2.3 Measurement items and methods

This soybean harvesting test used the crushing rate P as an evaluation index to test the operational performance of the harvester based on *NY/T 738-2020 Operational Quality of Soybean Combine Harvester*. Five samples of approximately 500 g each were randomly selected from the collected seeds in the header, horizontal seed spiral conveyor, horizontal miscellaneous residual spiral conveyor, and grain box. Impurities were picked out and weighed. Broken seeds in each sample, with impurities removed, were picked out and weighed, so as to determine the crushing rate of the five soybean samples (Equation 1),

$$P(\%) = \frac{W_p}{W_y - W_z} \times 100 \quad (1)$$

where P is the crushing rate, W_z is the mass of impurities in the sample in g, W_y is the sample mass in g, and W_p is the mass of the crushed seeds in the sample in g.

The main crushing forms of soybean machine harvesting were determined by analysis. The soybean samples were further classified to pick out soybean seeds in different crushing forms to weigh their mass and calculate their crushing rate (Equation 2),

$$P_i(\%) = \frac{W_{pi}}{W_y - W_z} \times 100 \quad (2)$$

where W_{pi} is the mass of broken soybeans in a certain crushing form in the sample, in g.

3 Results and analysis

3.1 Soybean crushing forms

The samples were taken from the soybean harvester's grain box to measure their overall broken condition. The sample analysis showed that the soybean seed damage was mainly manifested in the forms of epidermal local breakage, split into two from the cotyledon joint, and broken into multiple pieces. As shown in Table 1, soybean breakage due to harvesting can be summarized by the crushing forms of epidermal breakage; splitting into two flaps, and overall crushing.

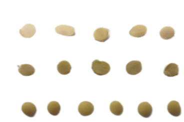
A comprehensive analysis of 100 test samples revealed the proportions of different crushing forms in soybean seed crushing. Epidermal breakage accounted for 55.3%, splitting into two flaps for 15.8%, and overall crushing for 28.9%.

3.2 Impact of major operational factors on soybean crushing

The main operational elements of soybean harvesting included the header feeding auger, horizontal spiral conveyor, horizontal miscellaneous residue spiral conveyor, and threshing roller. To fully understand the impact of different operational elements of the harvester on soybean crushing, the soybean seeds transported and threshed by these elements were sampled to comprehensively determine the proportions of different crushing forms, as shown in Figure 3. The soybean crushing form data of the main operational elements are given in Table 2.

The experimental statistics showed that in the crushing forms of different operational elements of the soybean harvester, epidermal breakage accounted for the highest proportion, followed by overall crushing of soybean seeds, and then splitting into two flaps. The splitting form had a crack by force at the junction of

Table 1. Main crushing forms of soybean seeds and their characteristics.

Form number	Crushing form	Characteristics	Picture
1	Epidermal breakage	Soybean seed has broken epidermis, especially at the umbilicus. Epidermal breakage affects soybean germination. Soybeans with broken epidermis generally can still be used for soybean products and soybean oil processing, but cannot be used as soybean seeds.	
2	Splitting into two flaps	Soybean seed splits at junction of the two cotyledons to form two flaps. Soybeans splitting into two flaps generally can still be used for soybean products and soybean oil processing, but processing quality is poor, and they cannot be used as soybean seeds.	
3	Overall crushing	Soybean seed has random breakage at embryo or seed coat, with at least three to four broken pieces. Soybeans with overall crushing cannot be used for soybean products and soybean oil processing, but can be used for processing animal feed. They cannot be used as soybean seeds.	

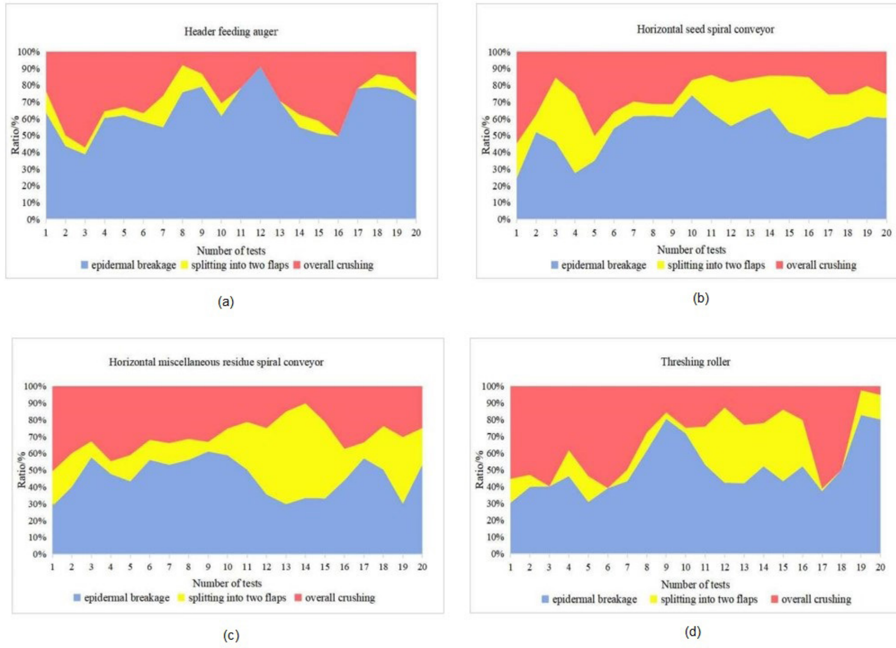


Figure 3. Distribution of different crushing forms in main operation process. (a) Header feeding auger; (b) Horizontal seed spiral conveyor; (c) Horizontal miscellaneous residue spiral conveyor; (d) Threshing roller.

Table 2. Soybean crushing form data of the main operational elements.

Data Category	header feeding auger			horizontal seed spiral conveyor			horizontal miscellaneous residue spiral conveyor			threshing roller		
	epidermal breakage	splitting into two flaps	overall crushing	epidermal breakage	splitting into two flaps	overall crushing	epidermal breakage	splitting into two flaps	overall crushing	epidermal breakage	splitting into two flaps	overall crushing
average	64.91	5.98	29.11	53.77	20.29	25.94	46.01	23.59	30.40	50.97	15.27	33.76
Maximum	90.96	18.66	57.32	73.98	47.04	54.86	61.15	56.31	50.74	82.81	44.84	61.26
minimum	38.78	0.00	8.09	24.61	6.97	13.86	28.57	5.61	10.22	30.36	0.00	2.55
Range	52.18	18.66	49.23	49.37	40.07	41.01	32.58	50.71	40.53	52.45	44.84	58.71
standard deviation	13.43	5.12	13.62	12.24	11.01	11.52	10.72	15.17	9.61	15.77	13.50	19.40
Coefficient of variation	20.69	85.65	46.79	22.76	54.26	44.40	23.31	64.29	31.60	30.93	88.41	57.47

two cotyledons. It is affected by biological characteristics of soybeans, and requires a harsh condition to develop. Hence it accounted for the lower proportion.

The distribution of crushing forms during the conveying process was calculated. The percentage of epidermal breakage ranged from 38.78% to 90.96%, with an average of 64.91%. The percentage splitting into two flaps ranged from 0 to 18.66%, with an average of 5.98%. The percentage of overall crushing ranged from 8.09% to 57.32%, with an average of 29.11%. The proportions were ranked as epidermal breakage >> overall breakage >> splitting into two flaps. The coefficient of variation of the proportion of epidermal breakage was the smallest. The main reason for these facts is that the soybean seeds were subject to friction, extrusion, and kneading by the spiral blades in the conveying process of the header feeding auger. The diameter of the spiral blade was large, and the number of transported soybean seeds was small, so the acting force was small and the crushing form was epidermal breakage. Some soybean seeds were not transported in a timely fashion by the harvester's intermediate conveying device, moving backward and remaining on the header, subject to repeated extrusion and rubbing, resulting in overall crushing.

The distribution of crushing forms in the conveying process of the horizontal seed spiral conveyor was also calculated. The percentage of epidermal breakage ranged from 24.61% to 73.98%, with an average of 53.77%. The percentage splitting into two flaps ranged from 6.97% to 47.04%, with an average of 20.29%. The percentage of overall crushing ranged from 13.86% to 54.86%, with an average of 25.94%. The proportions were ranked as epidermal breakage >> overall breakage ≈ splitting into two flaps. The proportion of epidermal breakage was less compared with the above case of the header feeding auger. The coefficients of variation of the proportions of splitting into two flaps and overall breakage decreased. The main reason for these facts is that the soybean seeds were mainly subject to friction, extrusion, and kneading by the spiral blades during the conveying process of the horizontal seed spiral conveyor. Because the diameter of the spiral blade was small and the number of conveyed soybean seeds was large, the force and forcing time both increased. The critical point of the force to cause splitting into two flaps was reached; hence the proportions of splitting and overall crushing increased.

The distribution of crushing forms in the conveying process of horizontal miscellaneous residue spiral conveyor was also calculated. The percentage of epidermal breakage ranged from 28.57% to 61.15%, with an average of 46.01%. The percentage splitting into two flaps ranged from 5.61% to 56.31%, with an average of 23.59%. The percentage of overall crushing ranged from 10.22% to 50.74%, with an average of 30.4%. The proportions were ranked as epidermal breakage > overall breakage > splitting into two flaps. The proportion of epidermal breakage was less compared with the above case of the header feeding auger. The coefficients of variation of the proportions of splitting into two flaps and overall breakage decreased. Similar to the conveying process of the horizontal seed spiral conveyor,the main reason for these facts is that the soybean seeds were mainly subject to friction, extrusion, and kneading by the spiral blades during the conveying process of the horizontal seed spiral conveyor. Because the diameter of the spiral blade was small and the number of conveyed soybean seeds was large, the force and forcing time both increased. The critical point of the force to cause splitting into two flaps was reached; hence the proportions of splitting and overall crushing increased.

Finally, the distribution of crushing forms given by the threshing roller was calculated. The percentage of epidermal breakage ranged from 30.36% to 82.81%, with a mean of 50.97%. The percentage splitting into two flaps ranged from 0 to 44.84%, with a mean of 15.27%. The percentage of overall crushing ranged from 2.55% to 61.26%, with a mean of 33.76%. The proportions were ranked as epidermal breakage > overall breakage >> splitting into two flaps. The coefficients of variation of all three crushing forms increased significantly, mainly because the soybean seeds were subject to the striking and collision effects of the threshing components during the threshing process. The force in the threshing process was large, and its acting time was short in each threshing action. The number of repeated threshing actions of the soybean seeds inside the threshing roller varied randomly. Soybean seeds that had a small force and a small number of threshing actions were prone to epidermal breakage and splitting into two flaps, while those that had a large force and a large number of threshing actions were prone to overall crushing.

3.3 Effects of key operating parameters of harvester on soybean crushing

The header feeding auger, horizontal seed spiral conveyor, and horizontal miscellaneous residue spiral conveyor all used a augering structure to transport the soybean seeds. The augering speed is a key parameter that affects the crushing rate of the soybean seeds, and it is related to the forward speed of the machine. Its overall adjustment can be controlled by changing the forward speed of the harvester. The parameters affecting the quality of the soybean seeds in terms of crushing rate in the threshing roller operation include the feeding amount, threshing roller speed, and threshing time. The soybean feeding amount and the harvester's forward speed were positively correlated. The threshing time was adjusted by changing the deflector angle of the upper cover of the threshing roller, and was negatively correlated with the deflector angle. Therefore, the key operating parameters of the soybean harvester affecting soybean crushing can be identified as the forward speed of the harvester, threshing roller speed, and deflector angle.

The factor levels in the test were determined according to the reasonable ranges of the structural and motion parameters of the crawler type soybean combine harvester (Jin et al., 2021, Liu et al., 2020a).The central composite design (CCD) method was used in the design of experiments (DoE). The factors and their levels are shown in Table 3. Key responses included the proportions of epidermal breakage, splitting into two flaps, and overall crushing. The response surface analysis was performed by Design Expert software (Hu et al., 2021; Mirani & Goli, 2022). The DoE test data are shown in Table 4.

Analysis of effect of each operating parameter on epidermal breakage proportion in soybean machine harvest

To determine the proportion of epidermal breakage, a polynomial regression analysis was conducted with the DoE test data, as follows (Equation 3):

$$Y_1 = 50.48 + 9.06A + 1.68B + 5.02C - 2.42A'B + 3.49A'C + 2.57B'C + 2.81A^2 + 0.89B^2 - 0.67C^2 \quad (3)$$

,where *A*, *B*, and *C* are the harvester forward speed, threshing roller speed, and deflector angle, respectively. A significance test and ANOVA were performed on the regression model, with results as shown in Table 5. *P* indicates the significance of the analysis object. $P \leq 0.01$ means that the regression model is highly significant, $0.01 < P \leq 0.05$ is significant, and $P > 0.05$ is not significant. The ANOVA results indicated that the regression model of the epidermal breakage percentage was highly significant, its coefficient of determination was $R^2 = 0.8499$, and the modified coefficient of determination was $R_a^2 = 0.7148$. The lack-of-fit terms were not significant, indicating that the gap between the measured data and the model's prediction data was small, i.e., the regression model could well fit the test data, with high significance and small test errors. The regression model could accurately predict the response.

Table 3. The factors and levels.

No.	harvester forward speed/(m·s^{-1})	threshing roller speed/(r·min^{-1})	deflector angle/°
-1.68	0.5	200	20
-1	1.0	350	26
0	1.2	450	32
1	1.4	550	38
1.68	2.0	700	45

Table 4. DoE test results.

No.	harvester forward speed / ($m \cdot s^{-1}$)	threshing roller speed / ($r \cdot min^{-1}$)	deflector angle/°	header feeding auger			horizontal seed spiral conveyor			horizontal miscellaneous residue spiral conveyor			threshing roller		
				epidermal breakage	splitting into two flaps	overall crushing	epidermal breakage	splitting into two flaps	overall crushing	epidermal breakage	splitting into two flaps	overall crushing	epidermal breakage	splitting into two flaps	overall crushing
1	-1	-1	-1	63.59	12.62	23.79	24.61	20.53	54.86	28.57	20.69	50.74	30.36	14.29	55.36
2	1	-1	-1	23.66	0.00	76.34	79.41	0.00	20.59	51.69	19.10	29.21	49.44	0.00	50.56
3	-1	1	-1	53.90	7.81	38.29	12.73	76.67	10.60	63.52	0.00	36.48	30.92	0.00	69.08
4	1	1	-1	66.89	0.00	33.11	42.36	17.41	40.23	31.99	15.15	52.86	61.78	30.67	7.56
5	-1	-1	1	57.07	9.95	32.98	27.58	11.82	60.61	54.78	15.92	29.30	0.00	0.00	100.00
6	1	-1	1	59.39	0.00	40.61	80.80	7.60	11.60	57.43	7.92	34.65	78.23	0.00	21.77
7	-1	1	1	51.47	32.35	16.18	68.77	7.64	23.59	50.34	13.79	35.86	47.53	13.58	38.89
8	1	1	1	100.00	0.00	0.00	54.81	6.30	38.89	61.88	11.21	26.91	75.57	7.63	16.79
9	-1.68	0	0	58.28	15.23	26.49	67.21	8.85	23.93	60.42	0.00	39.58	85.33	0.00	14.67
10	1.68	0	0	64.91	0.00	35.09	80.75	9.20	10.06	57.36	31.78	10.85	58.28	6.62	35.10
11	0	-1.68	0	91.60	0.00	8.40	46.52	35.83	17.65	43.32	24.94	31.74	47.87	38.83	13.30
12	0	1.68	0	90.32	0.00	9.68	64.71	16.43	18.86	27.81	53.97	18.21	36.86	50.85	12.29
13	0	0	-1.68	50.72	0.00	49.28	58.28	28.51	13.21	31.68	56.26	12.06	47.27	18.64	34.09
14	0	0	1.68	59.18	14.98	25.84	74.36	10.26	15.38	35.27	56.36	8.37	57.09	32.73	10.18
15	0	0	0	43.07	0.00	56.93	29.55	56.99	13.46	31.06	34.55	34.39	29.56	52.46	17.98
16	0	0	0	56.06	0.00	43.94	66.46	16.46	17.08	56.94	2.78	40.28	74.83	2.65	22.52
17	0	0	0	100.00	0.00	0.00	40.24	25.61	34.15	57.14	16.07	26.79	0.00	0.00	100.00
18	0	0	0	57.95	15.19	26.86	71.30	12.04	16.67	43.51	35.71	20.78	100.00	0.00	0.00
19	0	0	0	96.05	0.00	3.95	51.09	24.45	24.45	16.77	43.35	39.87	65.61	29.30	5.10
20	0	0	0	45.74	5.32	48.94	69.61	3.76	26.63	90.00	0.00	10.00	94.69	0.00	5.31

Table 5. Variance analysis of soybean epidermal breakage.

Index	Source	Sum of squares	Degree of square	Mean square	*F*-value	*P*-value
Soybean epidermal breakage ratio Y_1	Model	1833.07	9	203.67	6.29	0.0041
	A	1119.95	1	1119.95	34.59	0.0002
	B	38.51	1	38.51	1.19	0.301
	C	343.72	1	343.72	10.62	0.0086
	AB	46.8	1	46.8	1.45	0.2569
	AC	97.23	1	97.23	3	0.1138
	BC	52.99	1	52.99	1.64	0.2297
	A^2	113.72	1	113.72	3.51	0.0904
	B^2	11.31	1	11.31	0.35	0.5677
	C^2	6.47	1	6.47	0.2	0.6645
	Residual	323.77	10	32.38		
	Lack of Fit	225.65	5	45.13	2.3	0.191
	Pure Error	98.12	5	19.62		
	Cor Total	2156.83	19			

The ANOVA results of the regression model indicated that the effects of *A* and *C* on the epidermal breakage percentage Y_1 were highly significant in the first-order terms of the regression model, and the effect of *B* was not significant. In the second-order terms of the model, the effects of A^2, B^2, and C^2 were not significant. The effects of the interaction terms $A \times B$, $A \times C$, and $B \times C$ were not significant. Based on the significance analysis, the importance of the selected factors can be ranked as follows, from high to low: harvester forward speed, deflector angle, threshing roller speed.

Design Expert 8.0 software was used to plot the response surface diagrams for the epidermal breakage percentage. The effect of each factor could be observed, and factor interactions can be determined and examined (Luan et al., 2013; Yu et al., 2018). One of the three factors of harvester forward speed, threshing roller speed, and deflector angle was fixed at the central (zero) level, and the effects of the other two factors and their interactions on the epidermal breakage percentage were analyzed. The factor interactions are shown in Figures 4a to 4c.

Figures 4a and 4b show that the harvester forward speed had a significant effect on the percentage of epidermal breakage, and the percentage increased with the harvester forward speed, mainly because increasing the forward speed caused an increase in the feeding volume, which caused an increase in the amount of

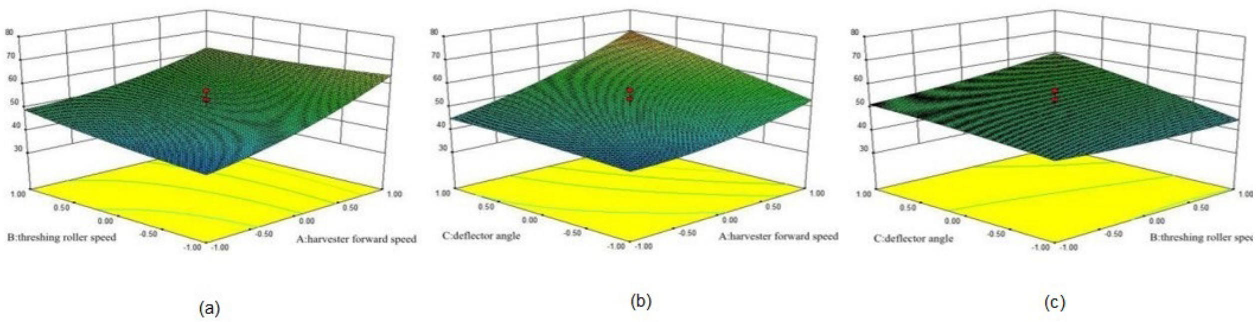


Figure 4. Influence of interactive factors on the epidermal breakage ratio. (a) Interaction between harvester forward speed and threshing roller speed; (b) Interaction between harvester forward speed and deflector angle; (c) Interaction between the threshing roller speed and deflector angle.

soybean seeds at the header feeding auger, horizontal seed spiral conveyor, and horizontal miscellaneous residue spiral conveyor. As a result, the time that the soybean seeds were squeezed by the auger increased, leading to an increase in the probability of epidermal breakage. Figures 4a and 4c show that the threshing roller speed did not have a significant effect on the epidermal breakage percentage because epidermal breakage mainly occurred during the conveying and extrusion processes of the auger, while the threshing roller percussed the soybeans during the threshing process with a long threshing time. If the roller speed was high, a soybean could break. Figures 4b and 4c show that the deflector angle had a significant effect on the epidermal breakage percentage, which increased with the deflector angle, mainly because when the deflector angle increased, the threshing time of the soybeans was significantly reduced, as was the intensity of threshing blows, causing epidermal breakage to some soybean seeds in the threshing process. When the threshing time was significantly reduced, the amount of soybeans increased at the horizontal seed spiral conveyor and horizontal miscellaneous residue spiral conveyor. With the increase in the time that soybean seeds were squeezed by the auger, the probability of epidermal breakage increased.

Analysis on effect of each operating parameter on proportion splitting into two flaps in soybean machine harvest

To determine the proportion of splitting into two flaps, a polynomial regression analysis was conducted with the DoE test data, as follows (Equation 4):

$$Y_2 = 21.07 - 0.24A + 1.46B - 5.88C - 3.37A'B - 2.20A'C + 2.95B'C - 7.20A^2 + 2.57B^2 - 1.63C^2 \quad (4)$$

A significance test and ANOVA were performed on the regression model, with results as shown in Table 6. The ANOVA results indicated that the regression model of the splitting into two flaps percentage was highly significant, its coefficient of determination was $R^2 = 0.9651$, and the modified coefficient of determination was $R_a^2 = 0.9337$. The lack-of-fit terms were not significant, indicating that the gap between the measured data and the model's prediction data was small, i.e., the regression model could well fit the test data, with high significance and small test errors. The regression model could accurately predict the response.

The ANOVA results of the regression model indicated that the effects of C on the splitting into two flaps percentage Y_2 was highly significant in the first-order terms of the regression model, and the effect of B was significant, and the effect of A was not significant. In the second-order terms of the model, the effects of A^2, B^2 on the splitting into two flaps percentage Y_2 were highly significant, and C^2 was significant. The effects of the interaction terms $A \times B$ and $B \times C$ were highly significant, and $A \times C$ was significant. Based on the significance analysis, the importance of the selected factors can be ranked as follows, from high to low: deflector angle, threshing roller speed, harvester forward speed.

Design Expert 8.0 software was used to plot the response surface diagrams for the splitting into two flaps percentage percentage. The effect of each factor could be observed, and factor interactions can be determined and examined.One of the three factors of harvester forward speed, threshing roller speed, and deflector angle was fixed at the central (zero) level, and the effects of the other two factors and their interactions on the splitting into two flaps percentage percentage were analyzed. The factor interactions are shown in Figures 5a to 5c.

Figures 5a and 5c show that the threshing roller speed had a significant effect on the percentage splitting into two flaps, which increased with the threshing roller speed, mainly because the splitting occurred in the threshing roller threshing process, and when the threshing roller speed increased, the linear speed increased accordingly, leading to an increase in the striking intensity and frequency. As a result, the striking probability and intensity of direct action of the threshing element on the soybean seed's cotyledon junction increased, leading to an increase in the percentage splitting into two flaps. Figures 5b and 5c show that the deflector angle had a significant effect on the percentage splitting into two flaps, which decreased as the deflector angle increased, primarily because as the deflector angle increased, the residence time of the soybean seeds inside the threshing roller decreased, so that the striking intensity and frequency of the threshing element decreased. As a result, the striking probability of a direct action of the threshing element on the soybean seed's cotyledon junction decreased, leading to a reduced percentage splitting into two flaps.

Table 6. Variance analysis of splitting into two flaps.

Index	Source	Sum of squares	Degree of square	Mean square	*F*-value	*P*-value
Soybean splitting into two flaps ratio Y_2	Model	1627.26	9	180.81	30.72	< 0.0001
	A	0.78	1	0.78	0.13	0.7229
	B	29.27	1	29.27	4.97	0.0498
	C	471.62	1	471.62	80.14	< 0.0001
	AB	90.92	1	90.92	15.45	0.0028
	AC	38.85	1	38.85	6.6	0.0279
	BC	69.68	1	69.68	11.84	0.0063
	A^2	747.17	1	747.17	126.96	< 0.0001
	B^2	95.45	1	95.45	16.22	0.0024
	C^2	38.3	1	38.3	6.51	0.0288
	Residual	58.85	10	5.89		
	Lack of Fit	30.18	5	6.04	1.05	0.4782
	Pure Error	28.67	5	5.73		
	Cor Total	1686.11	19			

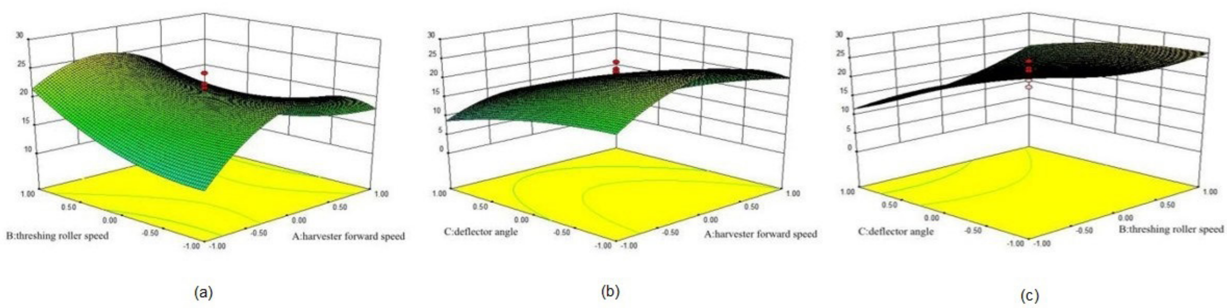


Figure 5. Influence of interactive factors on the splitting into two flaps. (a) Interaction between harvester forward speed and threshing roller speed; (b) Interaction between harvester forward speed and deflector angle; (c) Interaction between the threshing roller speed and deflector angle.

Analysis on effect of each operating parameter on overall crushing proportion in soybean machine harvest

To determine the proportion of overall breakage, a polynomial regression analysis was conducted with the DoE test data, as follows (Equation 5):

$$Y_3 = 28.45 - 8.81A - 3.14B + 0.86C + 5.79A'B - 1.28A'C - 5.52B'C + 4.39A^2 - 3.46B^2 + 2.30C^2 \quad (5)$$

A significance test and ANOVA were performed on the regression model, with results as shown in Table 7. The ANOVA results indicated that the regression model of the overall breakage percentage was highly significant, its coefficient of determination was $R^2 = 0.9079$, and the modified coefficient of determination was $R_a^{\ 2} = 0.8251$. The lack-of-fit terms were not significant, indicating that the gap between the measured data and the model's prediction data was small, i.e., the regression model could well fit the test data, with high significance and small test errors. The regression model could accurately predict the response.

The ANOVA results of the regression model indicated that the effects of *A* on the overall breakage percentage Y_3 was highly significant in the first-order terms of the regression model, and the effect of *B* was significant, and the effect of *C* was not significant. In the second-order terms of the model, the effects of A^2 on the splitting into two flaps percentage Y_2 was highly significant, and B^2 was significant, and C^2 was not significant. The effects of the interaction terms $A \times B$ and $B \times C$ were highly significant, and $A \times C$ was not significant. Based on the significance analysis, the importance of the selected factors can be ranked as follows, from high to low: harvester forward speed, threshing roller speed, deflector angle.

Design Expert 8.0 software was used to plot the response surface diagrams for the overall breakage percentage percentage. The effect of each factor could be observed, and factor interactions can be determined and examined.One of the three factors of harvester forward speed, threshing roller speed, and deflector angle was fixed at the central (zero) level, and the effects of the other two factors and their interactions on the overall breakage percentage percentage were analyzed. The factor interactions are shown in Figures 6a to 6c.

Figures 6a and 6b show that the harvester forward speed had a significant effect on the percentage of overall crushing, which decreased as the forward speed increased, mainly because

Table 7. Variance analysis of overall crushing.

Index	Source	Sum of squares	Degree of square	Mean square	*F*-value	*P*-value
Soybean overall crushing ratio Y_3	Model	2302.25	9	255.81	10.96	0.0004
	A	1061.16	1	1061.16	45.45	< 0.0001
	B	134.93	1	134.93	5.78	0.0371
	C	10.07	1	10.07	0.43	0.5262
	AB	268.19	1	268.19	11.49	0.0069
	AC	13.16	1	13.16	0.56	0.4701
	BC	243.98	1	243.98	10.45	0.009
	A^2	278.02	1	278.02	11.91	0.0062
	B^2	172.37	1	172.37	7.38	0.0217
	C^2	76.18	1	76.18	3.26	0.101
	Residual	233.45	10	23.35		
	Lack of Fit	194.5	5	38.9	4.99	0.0511
	Pure Error	38.95	5	7.79		
	Cor Total	2535.71	19			

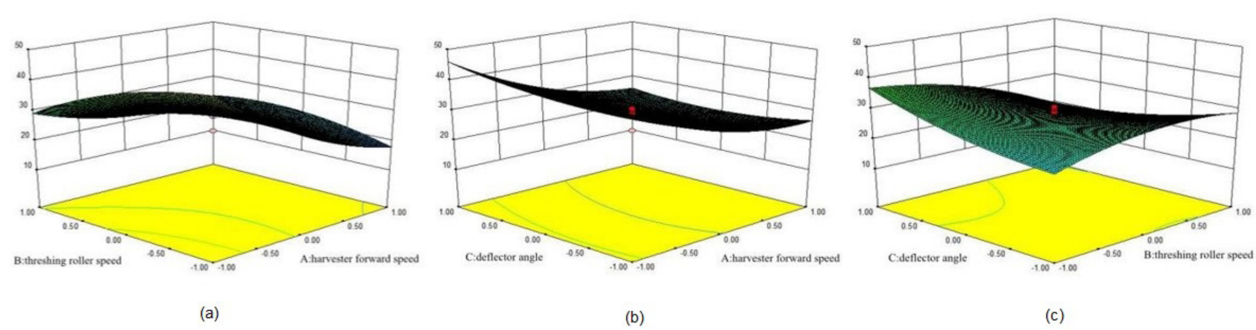


Figure 6. Influence of interactive factors on the overall crushing. (a) Interaction between harvester forward speed threshing roller and threshing roller speed; (b) Interaction between harvester forward speed and deflector angle; (c) Interaction between the speed and deflector angle.

the crushing mainly occurred in the threshing process, and the increase in the forward speed caused the feeding volume and the amount of soybean stalks to increase. Soybean stalks in the threshing process can effectively reduce the striking intensity and frequency of the threshing element on the soybean seeds, hence decreasing the overall crushing percentage. Figures 6a and 6c show that the threshing roller speed had a significant impact on the overall crushing percentage. When the harvester forward speed was low or the deflector angle was large, the overall crushing percentage decreased as the threshing roller speed increased, primarily because when the harvester forward speed was low, the soybean feed volume was low, as was the amount of the crop in the threshing process. However, when the deflector angle was large, the soybean plant moved quickly in the threshing process. The threshing roller transported the soybean plants with spiral conveying and auxiliary threshing. An increase in the threshing roller speed can promote the rapid movement of the soybean plants, reducing the striking intensity and frequency of the threshing element and leading to a reduction in the overall crushing percentage. When the harvester forward speed was high or the deflector angle was small, the overall crushing percentage increased with the threshing roller speed. The main reason is that when the harvester forward speed increased, the soybean feeding volume increased, as did the amount of the crop in the threshing process. When the deflector angle was small, the soybean plants moved slowly in the threshing process. At this time, the threshing roller mainly exerted a threshing effect on the soybean plants, and the speed increase caused the striking intensity and frequency of the threshing element to increase. As a result, the overall crushing percentage increased.

4 Conclusion

1) This paper analyzed the soybean harvesting process through experiments, and determined the main crushing forms of soybeans: epidermal breakage, splitting into two flaps, and overall crushing, of which the epidermal breakage accounted for 55.3%, the splitting into two flaps accounted for 15.8%, and the overall crushing accounted for 55.3%. was 28.9%;
2) This paper analyzed the influence of different operation links on soybean crushing during the harvesting process, such as header feeding auger, horizontal seed spiral conveyor, horizontal miscellaneous residue spiral conveyor, and threshing roller, and determined the proportion of different crushing forms in each operation link.The ratio

of epidermal breakage in the header feeding auger was 64.91%, the ratio of splitting into two flaps was 5.98%, and the ratio of overall crushing was 29.11%. The ratio of epidermal breakage in the horizontal seed spiral conveyor was 53.77%, the ratio of splitting into two flaps was 20.29%, and the ratio of overall crushing was 25.94%.

The ratio of epidermal breakage in the horizontal miscellaneous residue spiral conveyor was 46.01%, the ratio of splitting into two flaps was 23.59%, and the ratio of overall crushing was 30.4%. The ratio of epidermal breakage in the threshing roller was 50.97%, the ratio of splitting into two flaps was 15.27%, and the ratio of overall crushing was 33.76%.

3) The influence of the operating parameters such as the forward speed of the harvester, threshing roller speed, and deflector angle on the soybean crushing form was studied experimentally. The results showed that, the degree of influence on the proportion of sepidermal breakage from high to low was the forward speed of the harvester, deflector angle and threshing roller speed. The degree of influence on the proportion of splitting into two flaps from high to low was the deflector angle, threshing roller speed and the forward speed of the harvester. The degree of influence on the proportion of the overall crushing from high to low was the forward speed of the harvester, threshing roller speed and deflector angle.

References

Chen, M., Ni, Y., Jin, C., Liu, Z., & Xu, J. (2022). Spectral inversion model of the crushing rate of soybean under mechanized harvesting. *Food Science and Technology (Campinas)*, 42, e123221. http://dx.doi.org/10.1590/fst.123221.

Chen, Y., Teng, Y., Ting'en, W., Jin, C., & Yin, X. (2020a). Design and experimental analysis of longitudinal and axial flow double spiral rolle. *Nong-ji-hua Yanjiu*, 7, 62-69.

Chen, Y., Yan, K., Ting'en, W., Ning, X., Jin, C., & Yin, X. (2020b). Distribution regularities of the threshed mixtures in longitudinal axial flow flexible thresher of soybean harvester. *Zhongguo Nongye Daxue Xuebao*, 25(9), 104-111.

Dun, G., Chen, H., Liu, H., Feng, Y., Zha, S., & Hou, S. (2015). Soybean impacting simulation analysis in threshing process based on solidworks simulation and orthogonal test. *Journal of Graphics*, 36(5), 724.

Gao, L., Jiao, W., Yang, D., Shao, Z., & Zhao, X. (2012). Effect of moisture content on mechanical properties of soybean seed under static pressure. *Nongye Gongcheng Xuebao (Beijing)*, 28(15), 40-44.

Gao, L., Li, X., Jie, X., Na, X., & Zhang, Y. (2010). Investigation on characteristics and ratio of soybean kernel mechanical damage. *Shenyang Nongye Daxue Xuebao*, 41(1), 55-58.

Hu, J., Gao, J., Zhao, Z., & Yang, X. (2021). Response surface optimization of polysaccharide extraction from Galla Chinensis and determination of its antioxidant activity in vitro. *Food Science and Technology (Campinas)*, 41(1), 188-194. http://dx.doi.org/10.1590/fst.38619.

Jin, C., Yan, K., Guo, H., Wang, T., & Yin, X. (2021). Experimental research on the influence of threshing roller structures on the quality of mechanically-harvested soybeans. *Nongye Gongcheng Xuebao (Beijing)*, 37(4), 49-58.

Li, J., Zhi, C., & Yang, M. (2013). SD model and simulation of grain crop mechanization production. *Nongye Jixie Xuebao*, 44(2), 30-33.

Liu, P., Jin, C. Q., Liu, Z., Zhang, G. Y., Cai, Z. Y., Kang, Y., & Yin, X. (2020a). Optimization of field cleaning parameters of soybean combine harvester. *Nongye Gongcheng Xuebao (Beijing)*, 36(10), 35-45.

Liu, P., Jin, C., & Ning, X. (2020b). Field performance test and analysis of the cleaning sieve of soybean harvesters. *Nongye Gongcheng Xuebao (Beijing)*, 36(9), 36-43.

Liu, P., Jin, C., Yang, T., Chen, M., Ni, Y., & Yin, X. (2020c). Design and experiment of multi parameter adjustable and measurable cleaning system. *Nongye Jixie Xuebao*, 51(Suppl. 2), 191-201.

Luan, Q., Yang, Z., Xin, Z., Gong, X., & Yang, S. (2013). Optimization on extraction technology for eucommia ulmoides by single factor experiment combined with response surface. *Yaowu Fenxi Zazhi*, 33(5), 859-865.

Mirani, A., & Goli, M. (2022). Optimization of cupcake formulation by replacement of wheat flour with different levels of eggplant fiber using response surface methodology. *Food Science and Technology (Campinas)*, 42, e52120. http://dx.doi.org/10.1590/fst.52120.

National Bureau of Statistics. (2019). *China statistical yearbook*. Retrieved from http://www.stats.gov.cn/tjsj/ndsj/2021/indexch.htm

Shi, Y. (2010). Adjusting the industrial structure to ensure sustained and healthy development of soybean industry. *Journal of Chinese Institute of Food Science and Technology*, 10(4), 1-7.

Teng, Y., Chen, Y., Jin, C., & Yin, X. (2020a). Design and test on the type of spiral cylinder-segmented concave threshing system. *Asian Agricultural Engineering*, 29(1), 74-85.

Teng, Y., Jin, C., Chen, Y., Yu, K., Ni, Y., & Yin, X. (2020b). Design and test on the type of adjustable threshing strength-full circular separation threshing device. *Asian Agricultural Engineering*, 29(3), 97-107.

Yang, H., Du, Y., Chen, P., Du, Q., & Yong, T. (2018). Parameters optimization of longitudinal axial threshing unit of small feed harvester for soybean. *Gansu Nongye Daxue Xuebao*, 3, 184-189.

Yu, Z., Huai, S., Wang, W. (2018). Leakage rate and optimization of working parameters for cylinder pickup collector based on spring-finger trajectory. *Nongye Gongcheng Xuebao (Beijing)*, 34(4), 37-43.