DESIGN AND EXPERIMENTAL STUDY OF FLEXIBLE THRESHING UNIT FOR CHINESE CABBAGE SEEDS
/
大白菜种子柔性脱粒装置设计与试验

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ABSTRACT
In order to solve the problems of low efficiency of artificial harvesting method and high breakage rate and undepurated rate of traditional threshing method, a new flexible threshing device of Chinese cabbage seeds was designed, which was composed of flexible round head nail teeth and circular tube concave plate. Hertz contact collision theory was used to analyze and determine the structural parameters of the new threshing unit. The interaction force of different threshing elements materials were analyzed by using EDEM. The feasibility of the flexible threshing unit was verified by the comparison test of the distribution of threshed mixture. Finally, the orthogonal test was carried out to study the influence of the movement parameters of each structure on the cleaning rate and the rate of undepurated, and the weight matrix method was used to optimize it. The results indicate that under the condition the rotating speed of the threshing cylinder 750 rpm, the concave clearance 20 mm, and the feeding rate 1.4 kg/s, the threshing performance of the flexible threshing unit was the best. At this time, the breaking rate was 0.064%, and the un-threshing rate was 0.67%, which both met the relevant industry standards.

摘要
针对大白菜种子人工收获方式效率低、传统脱粒方式存在破碎率及未脱净率较高的问题，设计了一种新型的柔性圆头钉齿和圆管凹板组合的大白菜种子柔性脱粒装置。采用 Hertz 接触碰撞理论确定了柔性圆头钉齿及圆管凹板的结构参数，采用离散元仿真软件 EDEM 对比分析了不同脱粒元件及凹板与物料接触时的受力情况，结合脱出物分布对比试验结果进一步验证了该柔性脱粒装置的可行性。最后以滚筒转速、脱粒间隙及喂入量为试验因素，以种子破碎率、未脱净率为试验指标，开展正交试验，采用权矩阵法优化得到了该脱粒装置的最佳工作参数组合。结果表明：当脱粒滚筒转速为 750r/min，脱粒间隙为 20mm，喂入量为 1.4kg/s 时，该柔性脱粒装置的脱粒性能达到最佳，此时破碎率为0.064%，未脱净率为0.67%，满足国家相关行业标准。

INTRODUCTION
Chinese cabbage has excellent taste and high nutritional value. It is one of the vegetables with high domestic demand. In recent years, with the diversity of consumer demand, the Chinese cabbage breeding industry has also developed rapidly, and the planting area has grown rapidly *(Li et al, 2018)*. The manual harvesting method of direct seed harvesting is low in efficiency and cannot meet the large-area harvesting requirements of the breeding base; when the existing harvesting models on the market are used for operation, the structure or working parameter configuration is not good, which may easily cause a higher seed breakage rate and greater loss *(Wu et al, 2014; Ji et al, 2020; Steponavicius et al, 2018)*. Therefore, there is an urgent need to solve the problem of mechanized harvesting of Chinese cabbage seeds, and the threshing device is the core working component of the cabbage seed combine harvesting equipment. Improving its threshing performance has become a key issue restricting the development of Chinese cabbage seed combine harvesting equipment.

At present, domestic and foreign research on low-loss threshing devices for Chinese cabbage seeds is still a blank field. Generally speaking, there are currently two ways to reduce the threshing loss of grains. One is to use intelligent control and automation technology to adjust the working parameters of the threshing device in combination with the crop attributes and the operating conditions of the machine, so as to reduce

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the crushing rate and loss rate *(Rahman et al, 2019; Jahanbakhshi et al, 2017; Badretdinov et al, 2019; Bello et al, 2019).* The second is to improve the threshing effect by improving the structure and material of the threshing and separating device, such as the structure and material of the threshing element, the structure of the concave plate and the size of the sieve hole. For example, *Pužauskas et al*, *(2016),* conducted theoretical analysis, simulation and verification tests on three different shapes of concave grids, and obtained the conclusion that the inclined concave grids are more effective for corn ear threshing*. Dhananchezhiyan et al., (2013),* designed a kind of flexible spikes, established a dynamic model of the flexible threshing process of rice, and verified through experiments that the flexible spikes can meet the needs of rice separation while effectively reducing the seed breakage rate and have good adaptability.

Based on the above theory and experimental research, in order to solve the problem of low-loss threshing of Chinese cabbage seeds and combine the characteristics of Chinese cabbage seed harvesting, this paper proposes the use of flexible round-head spikes and round tube concave plates for flexible low-loss threshing of Chinese cabbage seeds. Taking the collision contact and mechanical analysis between the material and the threshing element as the starting point, the contact force of the flexible threshing element and the concave plate is studied and analyzed, the structural parameters are determined, the EDEM simulation analysis and the bench test results are combined, and the matrix weight is adopted. Method optimization obtained the optimal structure and working parameter combination of the flexible threshing device, which proved the feasibility of the flexible threshing device.

MATERIAL AND METHODS

OVERALL STRUCTURE AND WORKING PRINCIPLE

The overall structure of the Chinese cabbage seed flexible threshing device is shown in Figure 1; it is mainly composed of threshing drum, guide plate, top cover and concave plate.

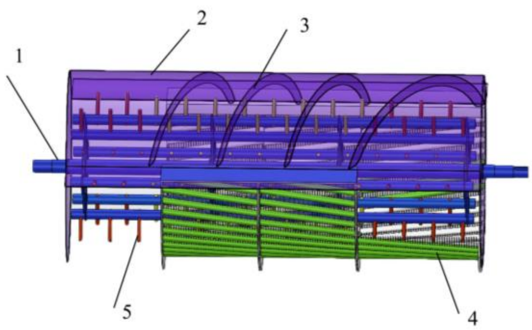


Fig.1- Key structure of Chinese cabbage seed threshing device
1. Threshing drum; 2. Top cover; 3. Deflector; 4. Concave plate; 5. Threshing element

When working, the power is provided by the frequency conversion motor, which drives the threshing drum to rotate through the drum main shaft. The Chinese cabbage plant enters the threshing chamber under the force of the rigid spike-teeth at the feeding entrance to complete the feeding process. Chinese cabbage seed siliques spiral backward under the combined action of drum threshing elements and top cover deflector. In this process, the silique completes the threshing process under the action of the threshing element and the concave plate to hit, collide and knead. In this area, the threshing element is a flexible round head spike, and the concave plate is a round tube concave plate. This structure can effectively reduce the rigid impact on the seeds, reduce mechanical damage, and prevent the seeds from staying on the concave plate. The removed Chinese cabbage seeds are separated from the long stalks, siliques and other sundries through the concave plate of the round tube to complete the separation process and be collected by the receiving device; In this process, the contact area between the concave plate of the round tube and the exudates is large, and the contact time is long, which is beneficial to the timely separation of seeds and reduces the entrainment loss; the long stalks are discharged through the grass discharge opening under the action of the rigid long spikes at the tail of the drum. Complete the cleaning process.

DESIGN OF THE KEY PARAMETER

Structure Design of Threshing Drum

The length of the horizontal axial flow threshing drum is closely related to its own threshing and separation capacity, The longer the threshing drum, the greater the amount of material that can be fed, but the power consumption and seed breakage rate of threshing also increase.

The increase of stalks, siliques and other miscellaneous residues caused excessive cleaning load. The calculation formula for the length of the horizontal axial flow threshing drum is:

$$L \geq q/q_0 \tag{1}$$

where L is the length of the threshing drum, m; q is the feed amount of the threshing device, kg/s; q_0 is the allowable feed amount per unit length of the threshing drum, generally 1.5~2.0 kg/s. The feeding amount of the flexible threshing device is calculated based on the maximum feeding amount of 2 kg/s, and the length range of the threshing drum is 1~1.3m. Taking into account that the length of the drum is restricted by the configuration and structural dimensions of the combined food harvester, this paper takes the length of the threshing drum as 1.2m.

The diameter of the horizontal axial flow threshing drum is:

$$D_Z \geq D_g + 2h_z \tag{2}$$

In the formula, D_g is the diameter of the threshing element, mm; h_z is the height of the threshing element, mm.

Because the diameter of the threshing drum is too small, it is easy to entangle the crop and reduce the separation area of the concave plate. However, if the diameter of the drum is too large, the power consumption of threshing will increase, usually D_g is greater than 300 mm. Based on comprehensive consideration, the barrel diameter of the threshing drum is determined to be 320 mm. The working height of spike-tooth threshing element is generally 50~100 mm. In order to ensure a suitable threshing line speed, the height of the threshing element in the feeding and threshing section in this study is 70 mm. In order to facilitate more thorough grass removal, the threshing element height in the trash removal section is 75 mm, so the roller diameter ranges from 460 to 470 mm.

Design of Threshing Element

Arrangement of threshing elements

The Chinese cabbage seed threshing drum adopts a three-stage combined structure, as shown in Figure 2. The feeding section uses rigid spike-tooth threshing elements to improve the ability of the threshing elements to grasp and feed plants. In order to reduce the seed damage during the threshing process, the nails of the threshing separation section are made of polyurethane rubber materials to reduce the rigid impact on the Chinese cabbage seeds during the threshing process and reduce seed damage. The tail has a long rigid spike-tooth structure to enhance the ability to discharge long stems and other debris outwards.

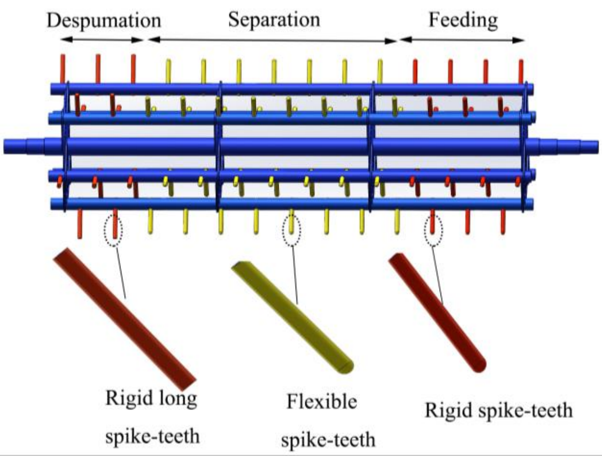


Fig. 2 - Threshing drum structure of Chinese cabbage seed

The common value of spike-tooth trace distance is 25~50 mm, 42 mm is selected for this design (*Guan et al*, *2020*). In order to realize the turning and backward movement of materials in the cycle threshing process, each threshing element is arranged in a spiral line. In order to increase the number of impacts of the threshing element per unit length on the material, the number of screw heads K=3 is selected. The number of spike-tooth rows is usually 6-12, and the tooth pitch is usually 50-100 mm. If the distance is too small, the stalk will be severely broken, and the threshing power consumption will increase. In this design, the number of tooth rows is 6, and the tooth pitch l =84 mm.

Spike-tooth collision analysis and optimization design

Compared with rigid spikes, flexible threshing spikes made of polyurethane materials will deform during the threshing process. From contact with the material to the completion of the threshing action, the angle of rotation is greater than that of rigid spikes, thus prolonging the contact time with the material. According to the friction and movement characteristics of peanut pods, we determined that the Angle of sliding screen was 40° based on experiment of test-bed under the condition that material is not congested during the decline of materials. When the rotating speed of the drum is constant, since the quality of the flexible threshing tooth is constant, the impulse to the seed is constant, from the momentum theorem; it can be known that with a constant impulse, the impact force for increasing the contact time must be reduced. Therefore, the use of flexible materials for threshing spikes can reduce the impact force on the Chinese cabbage seeds and reduce the seed breakage rate.

In references, the mechanical analysis of the contact between the spike and the seed is carried out from the two positions of the tip and the side of the spike, without considering the sharp collision with too small contact area *(Fan et al, 2019)*. In actual working conditions, the tooth tip edges and corners also collide with the seeds, and the damage to the seeds is more serious. In general, when the contact and collision force between the seed and the different threshing elements is equivalent (that is, the difference is not large), a larger contact area can weaken the stress concentration phenomenon, thereby reducing damage.

In order to further reduce the damage caused by the tip angle of the spike to the seed, the structure of the flexible spike was optimized. Based on the Hertz contact theory, a theoretical analysis of the impact process of Chinese cabbage siliques and two kinds of threshing elements before and after structural optimization *(Chuan-udom et al, 2011)* was made. The process of collision and contact between two kinds of spikes and Chinese cabbage seeds is shown in Figure 5. In order to facilitate comparative analysis, the incident angle of the collision between the Chinese cabbage seeds and the spike teeth is taken as 45°, the seeds in Figure 3 are simplified as spheres, and the model in the schematic diagram is enlarged.

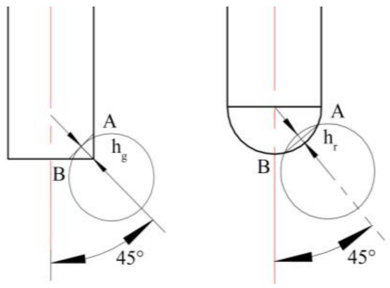


Fig. 3- Collision diagram

In Figure 3, before and after the optimization of the spike-tooth structure, the contact area with Chinese cabbage seeds is:

$$S_1=2h_g r \tag{3}$$

$$S_2=\pi\left[R^2-\left(R-h_r\right)^2\right] \tag{4}$$

Among them, r represents the diameter of the Chinese cabbage seed ball, which is taken as 2.2 mm; h_g, h_r respectively represent the compression amount of the Chinese cabbage seed when it collides with the conventional spikes and the optimized spikes, mm; R represents the diameter of the optimized spikes, mm.

Through previous compression experiments, it was obtained that when the Chinese cabbage seeds (variety Jincai No. 3) with a moisture content of 28.39-30.25% were compressed, the compression deformation range for the seeds to break was 0.4-0.6 mm. In order to prevent the seeds from breaking, this paper takes the minimum compression $h_{\min}$ = 0.4 mm.

In the two contact modes,

$$S_2\text{-}S_1=\pi\cdot\left(2R-h_r\right)\cdot h_r-2h_g\cdot r \tag{5}$$

$$h_r=h_g=h_{\min} \tag{6}$$

Then, there are $S_2\text{-}S_1= h_{\min}\,(2\pi R\text{-}\pi\, h_{\min}\text{-}2r)>0$ constants established. Therefore, the contact area between the spike-tooth and the seed after the structure optimization is always larger than that before the structure optimization. Therefore, the structure-optimized round-head spikes can reduce the impact on Chinese cabbage seeds, thereby reducing threshing damage.

Comprehensively considering the threshing requirements, structural dimensions, and the difficulty of the actual processing technology, the diameter of the round head spike and the round head diameter of the final threshing separation section are both 8 mm. In order to ensure the smooth progress of the feeding and discharging process, the diameter of the rigid spikes in the feeding section and discharging section is 10 mm.

Parameter design of concave plate structure

Based on the problems of the conventional grid-type intaglio plate in the mechanized harvesting process of Chinese cabbage seeds, a round tube-shaped de-parting concave plate was optimized, as shown in Figure 4.

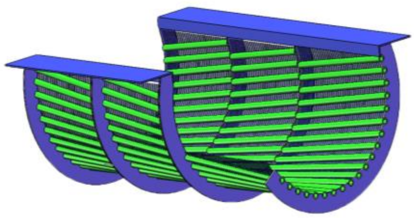


Fig. 4- Round tube for plates

Considering the requirements of the whole machine structure size and guaranteeing the performance of threshing operation, the round-tube threshing concave plate uses a round steel pipe with an outer diameter of 18 mm and a thickness of 3 mm instead of the horizontal grid plate in the grid-type concave plate. Chinese cabbage siliques are fatigued and fractured under multiple cycles of threshing elements and round tube concave plates, rather than one-time fracture, in order to achieve the purpose of reducing the rate of seed breakage. In order to further improve the possibility of the material on the circular tube-shaped concave plate, the circular tube is installed along the axis of the concave plate at an offset of 10° from the axis, which is consistent with the direction of the material's spiral movement in the axial direction when the threshing drum is working, so as to facilitate the backward pushing of the material.

The collision force between the Chinese cabbage silique and the round tube under the two installation methods is shown in Figure 5. Assume that the silique collides with the tube at the center of speed *v*.

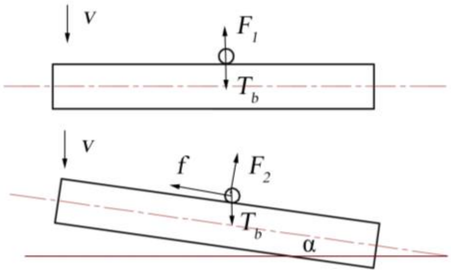


Fig. 5- Schematic diagram of collision between pod and concave tube

As can be seen from the figure, the collision reaction force of the silique by the tube is as follows:

$$F_1 = T_b \tag{7}$$

$$F_2 = T_b \cdot \cos\alpha \tag{8}$$

Among them, F_1 is the collision reaction force of the silique when the tube is installed directly, N; F_2 is the collision reaction force of the silique when the tube is installed obliquely, N; T_b is the force of gravity on the silique, N; α is the installation angle of the circular tube deviating from the axial direction of the concave plate.

Because $F_1 - F_2 = T_b \cdot (1-\cos\alpha) > 0$, so $F_2 < F_1$. Under the same conditions, the collision reaction force of the round tube straight-mounted threshing concave plate on the cabbage silique is greater than the collision reaction force of the round tube inclined threshing concave plate on the silique. Therefore, the concave plate with the round tube inclined installation method is adopted. It helps reducing the collision reaction force to the silique and reducing the rate of seed breakage. At the same time, there is friction *f* when the silique interacts with the oblique-mounted round tube, and the friction *f* has a certain rubbing effect on the silique to ensure the removal rate and improve the quality of threshing.

CONTACT MECHANICS SIMULATION OF THRESHING PROCESS BASED ON EDEM

Model creation and parameter setting

Using SolidWorks software, the simplified models of threshing devices under two combined forms were established and imported into EDEM software. Considering that the materials in the Chinese cabbage plant threshing drum mainly include seeds, stalks and cabbage siliques, referring to the relevant literature and combining with the previous testing of the physical properties of the various components of the Chinese cabbage plant, under the premise of ensuring the consistency of the model appearance characteristics, are established their own discrete element models by manual multi-ball filling, as shown in Figure 6 *(Wang et al, 2018)*. Among them, cabbage seeds are spherical with a diameter of 2.2 mm. The triaxial dimensions of siliques are 52.40 mm (length), 4.55 mm (width) and 3.14 mm (height) respectively. The long stem is a circular arc with a diameter of 9.80 mm and a length of 70 mm; Hertz-Mindlin (No Slip) contact was selected on the Globals panel in combination with the results of the previous physical property test and relevant literature, and the threshing device, material properties and mechanical property parameters of the model were set as shown in Table 1 and Table 2 *(Lu, Ma, & Qi, 2016)*.

a. seed *b silique* *c. Long stem*

Fig. 6- Discrete element model

Table 1

Model material parameters

Materials	Poisson's ratio	Shear modulus/[MPa]	Density/[kg•m^{-3}]
Seed	0.25	52	880
Silique	0.35	0.8	300
Stalk	0.45	4.4	550
Steel	0.30	75000	7850
Polyurethane (PU)	0.33	174	1072

Table 2

Model material contact parameters

Contact form	Recovery factor	Static friction coefficient	Coefficient of rolling friction
Seed - steel	0.62	0.46	0.08
Seed - PU	0.29	1.05	0.15
Silique - steel	0.2	0.8	0.12
Silique - PU	0.29	1.05	0.16
Stalk - steel	0.2	0.8	0.12
Stalk - PU	0.29	1.05	0.16

In the Factories panel, the motion form and parameters of the threshing cylinder are set. The feeding amount of the two simulation models was set as 1.2 kg/s, and the dynamic generation method was adopted. The mass of seeds, long stalks and nuts were respectively 0.4 kg/s, 0.6 kg/s and 0.2 kg/s. The particle factory was set above the conveyor belt entrance in the form of Box. In the simulation, the threshing drum is set as rotation, the drum speed is 700 r/min, the conveyor belt is set as plane movement, and the speed is 1 m/s. The whole threshing device was gridded. The basic grid size was 3 times of the minimum particle size. During simulation, Rayleigh time step was 25% of the total step size. The total simulation time was set as 8 s, and the material entered the threshing device after 1.6 s. The threshing simulation model was finally obtained, as shown in Figure 7.

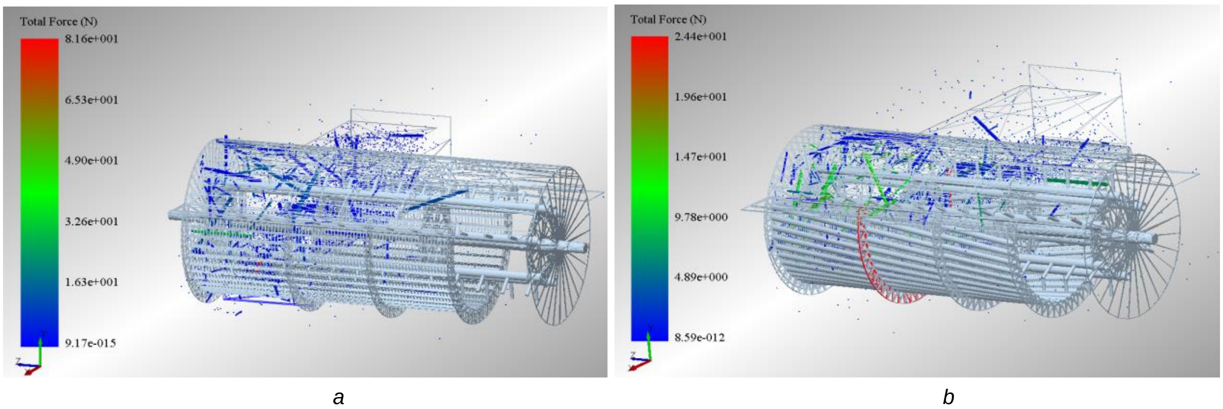


Fig. 7 - Threshing simulation model of thresher

a. Threshing simulation model of conventional threshing device b. Threshing simulation model of flexible threshing device

Simulation results and analysis

The EDEM solver is used to simulate the two kinds of threshing device models respectively. According to the simulation animation, when seeds, nuts and stalks enter the drum, they move towards the end of the drum under the action of flexible spike-tooth and concave pipe plate, and the process of feeding and straw discharge is smooth, which can realize the process of material threshing and separation. After the simulation is completed, the contact collision force between the two threshing elements and the concave plate and the material is extracted for analysis, and the results are shown in Figure 8.

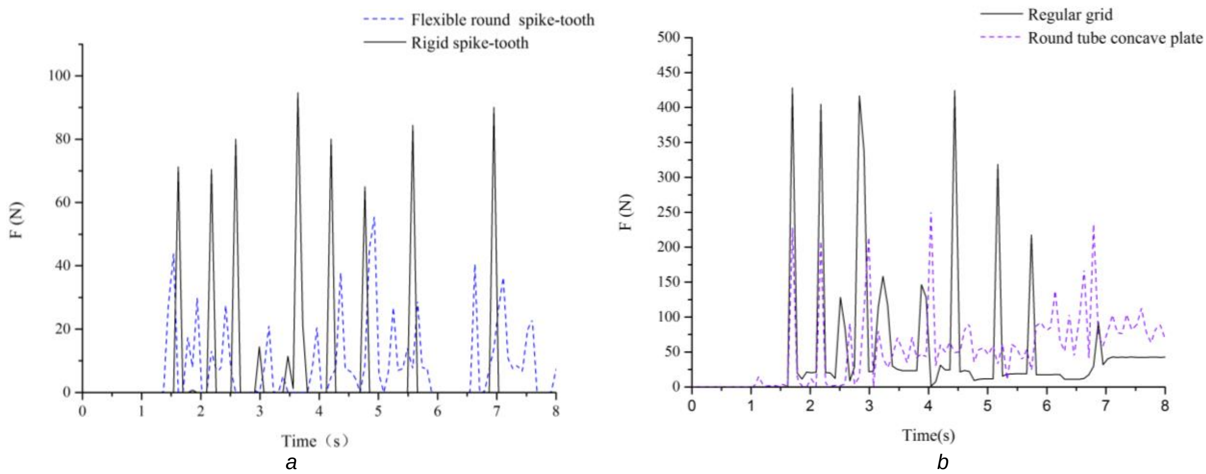


Fig. 8 - Threshing device and material stress

a. Contact force between flexible round head spike-teeth and conventional spike-teeth and materials
b. Contact force between concave tube and conventional grid and material

It can be seen from Figure 8 that the Chinese cabbage material within 0~1.6 s was produced by the particle factory and entered into the threshing drum through the conveyor belt, starting to produce contact behavior. From the peak of contact force, it can be seen that at the same roller speed, the impact force between the flexible spike-tooth and the pipe concave plate and the material is lower than that between the spike-tooth and the grid concave plate. Among them, the range of contact force between conventional rigid spike-tooth and material is 61-94n, while the range of contact force between flexible circular head spike-tooth and material is 18-52n, which reduces by 44% to 70.5%. The range of contact force between conventional grid concave plate and material is 100~ 425n, and that between pipe concave plate and material is 50~ 250n, reducing by 41.2%~50%. Therefore, the selection of flexible round head spike-teeth and pipe concave plate can effectively reduce the impact of threshing device on seeds and so on, thus reducing the effect of threshing damage.

RESULTS

EXPERMENTAL RESULTS AND OPTIMIZATION

Experimental material and methods

The threshing experiment was carried out in Jiyuan City, Henan province. The designed flexible low loss threshing device was used to carry out relevant indoor threshing experiments on Chinese cabbage seeds in the suitable harvest period. The Chinese cabbage variety Jincai No. 3 was used in the experiment, and the characteristics of some materials of this variety were measured before the experiment, as shown in Table 3.

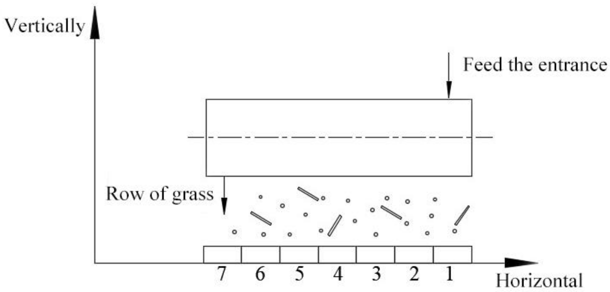
Table 3

Material characteristics of Chinese cabbage seed plants

parameter	quantity
Plant height [mm]	880~1200
Cuticle diameter [mm]	560~860
Average moisture content of the fruit [%]	13.16
Average moisture content of seeds [%]	28.39
Average stem moisture content [%]	40.12
Weight of 1000-seeds [g]	3.08~3.25
Ratio of grain to straw	0.3~0.6
Yield [kg·acre $^{-1}$]	123~160

The test shall be carried out in accordance with General Provisions on Determination Methods for Test Conditions of Agricultural Machinery GB/T 5262-2008 and Thresher Test Methods GB/T 5982-2005. The test instruments and equipment mainly include VC6234P digital display tachometer and electronic balance. Before the beginning of the test, the cabbage plants were evenly spread on one side of the conveyor belt, and an acceleration adjustment zone of 5 m was left. Start the threshing device and adjust the speed of conveying device and threshing drum to the required value through frequency converter. After stable operation of the threshing device, start the conveyor belt to complete the process of conveying, feeding, threshing and feeding. The test site is shown in Figure 9a.

a. Threshing test site



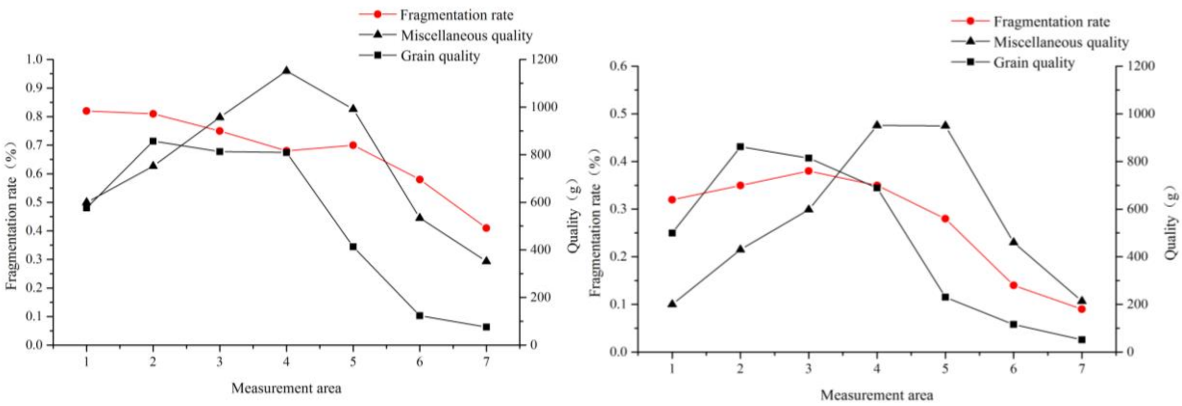
b. Drum axial test area distribution

Fig. 9 - Threshing test site and Axial survey area distribution

Comparative test of threshing mixture distribution

To explore the release distribution of the flexible threshing device, the receiving device was divided into 7 test areas along the axial direction of the threshing drum, as shown in Figure 10. After the end of the test, the distribution of impurities, seeds and broken seeds in the outcrops in each test area was counted respectively, and the test was repeated for 3 times to take the mean value. Under the threshing condition with fixed feeding rate of 1.6 kg/s, drum speed of 750 r/min, and threshing clearance of 20 mm, the results were compared with those of conventional spike-tooth - grid concave plate threshing device under the same working condition. The distribution of the outfalls in each test area is shown in Figure 9b.

It can be seen from Figure 10 that under the two threshing conditions, the accumulations of seeds, miscellaneous seeds and broken seeds distributed along the axial direction of the drum were significantly different, but the distribution rules were similar. Diagram indicated that the conventional threshing components had a greater impact on the seed of Chinese cabbage, the seed breakage rate was higher, and the excessive impurity increased the cleaning load; the flexible threshing element has less impact on Chinese cabbage seed, but it also has stronger ability of threshing and separating. According to the test results, the threshing performance of flexible circular head spike-tube concave plate is better than that of conventional spike-grid concave plate, which can meet the demand of Chinese cabbage seed threshing.



a *b*

Fig. 10- Comparison of distribution of extract

a. Distribution of extracts from conventional threshing equipment b. Distribution of extracts from flexible thresher

Orthogonal experiment

In order to explore the optimal working parameters of the flexible threshing device, the roller speed A (r/min), the concave clearance B (mm) and the feeding amount C (kg/s) which have great influence on the threshing quality are selected as the experimental factors. The orthogonal experiment of three factors and three levels was carried out with seed crushing rate and unclean rate as test indexes. The test factor levels and their coded values are shown in Table 4.

Table 4

Factor Level Coding Table

Level	Factor		
	Drum rotation speed (A)	Threshing clearance (B)	Feed quantity (C)
	[r•min^{-1}]	[mm]	[kg•s^{-1}]
1	750	15	1.2
2	850	20	1.4
3	950	25	1.6

Table 5

Orthogonal test results

Test number	Factor					
	A	B	C	Vacant column	Y_1 / Damage rate [%]	Y_2 / Loss rate [%]
1	1	1	1	1	0.115	0.821
2	1	2	2	2	0.064	0.672
3	1	3	3	3	0.235	0.894
4	2	1	2	2	0.134	0.813
5	2	2	3	3	0.289	0.772
6	2	3	1	1	0.249	0.796
7	3	1	3	3	0.352	0.715
8	3	2	1	1	0.245	0.584
9	3	3	2	2	0.172	0.613

Table 6

Variance analysis

Index	The source of variance	Quadratic sum	Degree of freedom	*F*	Significance
Y_1	A	0.382	2	16.881	*
	B	0.022	2	0.535	
	C	0.001	2	32.128	**
	Error	0.001	2		
Y_2	A	0.050	2	23.268	**
	B	0.020	2	9..165	*
	C	0.013	2	6.227	
	Error	0.002	2		

The results of orthogonal test and variance analysis are shown in Table 5 and Table 6. According to the results of variance analysis, the influences of various factors on the damage rate were as follows: extremely significant feeding amount, significant drum speed, and insignificant threshing gap. The influences of various factors on the loss rate of seeds were as follows: roller speed was very significant, threshing clearance was significant, and feeding amount was not significant.

Orthogonal experiment

In the optimization problem of orthogonal test, the subjective weighting method is often used to determine the weight of multiple indexes, which requires a lot of calculation and has some human factors. Therefore, this study uses matrix analysis to calculate the influence degree of each experimental factor on the index, and quickly determines the primary and secondary order of each factor according to the weight, which can well solve the optimal scheme selection problem of multi-index orthogonal experimental design *(Wei et al, 2010)*.

According to the orthogonal test scheme, the three-layer structure model (Table 7) is established, which is respectively the index layer, the factor layer and the horizontal layer. Suppose l is the number of test factors in an orthogonal experiment, *m* is the level of each factor. Where, k_{ij} represents the average value of the test index at the j-the level of factor A_i. If the test result is larger, the better, let $K_{ij}=k_{ij}$; otherwise, let $K_{ij}=1/k_{ij}$. Establish the following matrix formula:

Table 7

Matrix structure

Structural layer			
1	Test index		
2	Factor A_1	Factor A_2	Factor A_i
3	A_{11} $A_{12}\cdots A_{1m}$	A_{21} $A_{22}\cdots A_{2m}$	A_{i1} $A_{i2}\cdots A_{im}$

Establish the index layer matrix for test investigation:

$$M=\begin{bmatrix} K_{11} & 0 & 0 & \cdots & 0 \\ K_{12} & 0 & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ K_{1m} & 0 & 0 & \cdots & 0 \\ 0 & K_{21} & 0 & \cdots & 0 \\ 0 & K_{22} & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & K_{2m} & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & 0 \\ 0 & 0 & 0 & \cdots & K_{i1} \\ 0 & 0 & 0 & \cdots & K_{i2} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0 & K_{im} \end{bmatrix} \tag{9}$$

Let $T_i=1\Big/\sum_{j=1}^{m}K_{ij}$, establish the factor layer matrix:

$$T=\begin{bmatrix} T_1 & 0 & 0 & 0 \\ 0 & T_2 & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & T_l \end{bmatrix} \tag{10}$$

In the orthogonal experiment, the range of factor A_i is S_i. Let $S_i=s_i\Big/\sum_{i=1}^{l}s_i$

Establish the horizontal layer matrix:

$$S=\begin{bmatrix} S_1 \\ S_2 \\ \cdots \\ S_l \end{bmatrix} \tag{11}$$

The weight matrix affecting the test index value is:

$$\omega = MTS \tag{12}$$

$$\omega^T=\begin{bmatrix}\omega_1 & \omega_2 & \cdots & \omega_m\end{bmatrix} \tag{13}$$

The weight of each index is calculated by Formula 13. In this orthogonal test, both the crushing rate and the uncleanness rate should be taken into account in the investigation index, and it can be calculated as follows:

$$\omega_1=\left[A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2, C_3\right]^T =$$
$$\left[0.1628, 0.1121, 0.1107, 0.0160, 0.0180, 0.0291, 0.1805, 0.2115, 0.1584\right]^T$$
$$\omega_2=\left[A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2, C_3\right]^T =$$
$$\left[0.1364, 0.1370, 0.1709, 0.0932, 0.1079, 0.0952, 0.0873, 0.0914, 0.0806\right]^T$$

In this orthogonal experiment, the total weight matrix of the index is the average value of the weight matrix of the two index values, which can be calculated as follows:

$$\omega=\left[A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2, C_3\right]^T =$$
$$\left[0.2992, 0.2491, 0.2816, 0.1092, 0.1259, 0.1243, 0.2678, 0.3029, 0.2390\right]^T$$

Based on the above calculation results, the primary and secondary order (primary → secondary) of the influence of each factor on the orthogonal test index value is CAB. Factors C_2, A_1 and B_2 have the largest weight. The optimal scheme of this orthogonal experiment is $A_1B_2C_2$, that is, when the threshing drum speed is 750 r/min, the threshing gap is 20 mm, and the feeding amount is 1.4 kg/s, the threshing performance of the flexible threshing device is the best, the crushing rate is 0.064%, and the under-threshing rate is 0.67%, which meets the national industry standard.

CONCLUSIONS

1. The test bed of low loss flexible threshing device for Chinese cabbage seeds was designed. The structure and parameter determination method of key parts of the threshing device were studied.

2. The simulation models of conventional and flexible threshing systems were established by EDEM software, and the contact forces between threshing elements and concave plates and Chinese cabbage seed plant materials were analyzed. The results showed that the flexible threshing device could effectively reduce the impact on seeds. Finally, the feasibility of the flexible threshing form was verified through the comparative test of the distribution of threshing matter.

3. The orthogonal test, and the weighting matrix method were adopted according to the results of the experiment optimization to determine the optimal structure and working parameters of threshing device combination, namely the threshing cylinder rotation speed of 750 r/min, threshing clearance of 20 mm, feed rate of 1.4 kg/s, the device threshing performance index respectively, the seed damage rate was 0.064%, loss rate was 0.67%, the threshing effect was good and met the national industry standard.

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