DESIGN AND SIMULATION OF SCREW CONVEYOR FOR SESAME COMBINE HARVESTER CUTTING TABLE
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芝麻联合收获机割台螺旋输送装置的设计与仿真

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DOI: https://doi.org/10.35633/inmateh-76-69

Keywords: *Cutting table, Screw conveyor; Sesame capsule, EDEM simulation*

ABSTRACT

Aiming at the problems of high crushing rate and severe loss of sesame capsules caused by mechanical collision in the conveying link of the header of the traditional sesame combine harvester, a low-damage screw conveying device has been optimized and designed. This study analyzed the operation mechanism of the low-damage screw conveyor based on the characteristics of the sesame capsule and determined the key parameters affecting the crushing rate of the sesame capsule, including diameter, pitch and rotational speed. Taking the crushing rate as the evaluation index and with the aid of EDEM discrete element simulation technology, the interaction model of sesame capsule - sesame stem - low-damage screw conveying device was constructed, and the single-factor and Box-Behnken response surface experimental designs were systematically carried out. Through simulation analysis and optimization, the optimal parameter combination of the low-damage screw conveyor device was determined: diameter 302 mm, pitch 422 mm, and rotational speed 200 r/min. Under these conditions, the crushing rate of sesame capsules can be reduced to less than 3%. This study provides a theoretical basis and technical reference for the structural optimization of the screw conveyor device of the sesame combine harvester and the reduction of the header loss rate.

摘要

针对传统芝麻联合收获机割台输送环节因机械碰撞导致的芝麻蒴果破碎率高、损失严重等问题，优化设计了一种低损伤螺旋输送装置。本研究基于芝麻蒴果特性分析了低损伤螺旋输送装置的作业机理，确定了影响芝麻蒴果破碎率的关键参数，包括直径、螺距和转速。以破碎率作为评价指标，借助 EDEM 离散元仿真技术，构建了芝麻蒴果-芝麻茎秆-低损伤螺旋输送装置的互作模型，系统开展了单因素和 Box-Behnken 响应面试验设计。通过仿真分析与优化，确定了低损伤螺旋输送装置的最优参数组合：直径 302mm、螺距 422mm、转速 200r/min，此条件下，芝麻蒴果破碎率可降至 3%以下。本研究为芝麻联合收获机螺旋输送装置的结构优化与割台损失率的降低提供了理论依据和技术参考。

INTRODUCTION

Sesame as a high economic value of oil crops, its mechanized harvesting has been a difficult point in agricultural production *(Wang et al., 2024; Dou, 2025; Tian et al., 2025)*. During the harvesting process of traditional combine harvester, the cutting table conveyor is prone to cause violent collision and extrusion of sesame pods, resulting in high seed breakage rate, high loss rate and other problems, which seriously affects the quality and yield of sesame *(Lian et al., 2023)*. The existing harvester has serious seed breakage, which is difficult to meet the demand of fine agriculture *(Ni et al., 2023; Xiaoyuan et al., 2025; Pezo M. et al., 2025)*. Therefore, designing a cutting table conveyor with low crushing rate is of great significance to realize efficient and low-loss harvesting of sesame. At present, domestic and foreign research for sesame harvesting machinery mainly focuses on the optimization of cutting table structure and the improvement of threshing system, while the analysis of the mechanical characteristics of the seeds in the conveying process is insufficient, resulting in the lack of theoretical support for low damage conveying technology *(Liu et al., 2021)*. Derald Ray Langham bred the non-cracking (ND) sesame variety S55. The capsule does not crack and has a high seed retention rate, reducing the loss of sesame seeds (*Derald Ray Langham*., *2011*).

Developed countries represented by the United States have achieved the reduction of sesame seed loss and the increase of sesame yield by screening non-cracked (ND) sesame varieties and replacing the header of the harvester.

Although the Quantum series of combine harvesters from Wintersteiger in Austria are not specifically designed for sesame, they can be compatible with small-grain crops such as sesame by changing the header and adjusting parameters (such as low-speed flexible threshing and air flow cleaning system)

To address this problem, this study combines the biological characteristics and mechanical properties of the sesame plant to design a low-crushing rate cutting table conveying device, three-dimensional modeling of the screw conveying device through SolidWorks, to determine the diameter, rotational speed, pitch, and other parameters and dimensions, and the use of the EDEM discrete element model, to obtain the optimal parameters of the low-crushing rate, for the low-damage conveying of the sesame combine harvester to provide the technological Reference.

This study aims to solve the key bottleneck in the mechanized harvesting of sesame, to provide new ideas for the research and development of low-damage harvesting equipment for crops with high oil content, and to promote the development of mechanization of special economic crops with practical application value.

MATERIALS AND METHODS

Overall structure of the cutting table

The overall structure of the operating platform is shown in Fig. 1.

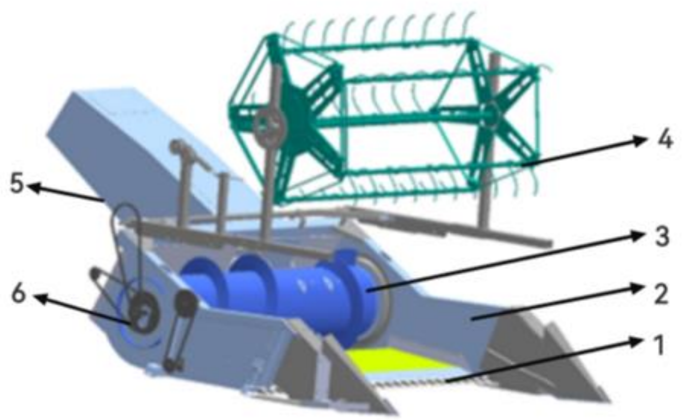


Fig. 1 - Overall structure of cutting table

1 – cutter; 2 - baffle; 3 - screw conveyor; 4 - paddle wheel; 5 - conveyor chute; 6 - drive system

Principle of operation

When working, the machine travels forward, the pivoting wheel rotates, and its popping teeth are inserted into the sesame plant clumps, pivoting backward and downward and supporting the plant to guide it steadily to the cutter. The guided plant stalks enter between the moving and fixed blades of the cutter and are cleanly cut off. The pivoting wheel continues to rotate, pivoting the freshly severed plant away from the cutting area and backward, so that it lays relatively neatly on the cutting platform. The screw conveyor rotates, and the screw blades at both ends of the screw conveyor will spread the sesame plants on the left and right sides of the cutting platform to the center area to be quickly pushed and concentrated, and concentrated backward to the conveyor chute for backward movement for subsequent processing.

Static analysis of sesame capsule

As shown in Fig. 2 in the horizontal screw conveying device, the sesame capsule conveying process is realized under the combined action of the propulsion and friction of the screw blades, as well as the friction of the bottom plate wall. The action of these forces on the sesame capsule is actually very complex. In this study, in order to simplify the analysis, a single-mass model is used to describe the forces on the sesame capsule, and the surface of the screw blade is assumed to be an inclined plane *(Zhao, 2024; Song et al., 2016; Song et al., 2016)*. When the seeds are stationary in the screw conveyor, they are in static equilibrium under the force of gravity G and the support force N provided by the tube wall. When the spiral blades begin to rotate, the seeds begin to move under the positive thrust F_n of the blades and the frictional force f.

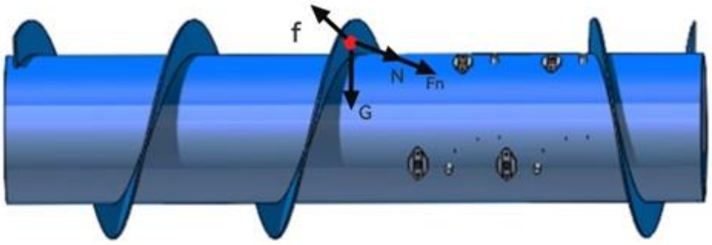


Fig. 2 - Conveying state of sesame capsule in screw conveyor device

Dynamic analysis of sesame capsule

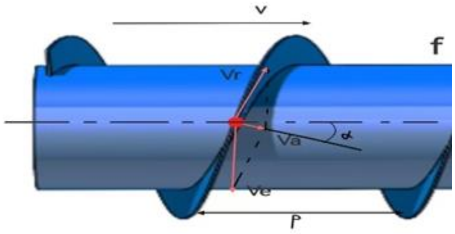


Fig. 3 - Kinematic modeling of sesame capsule in screw conveyor device

As shown in Fig.3, the relative, implicit and absolute speeds of the sesame capsule are related not only to the rotational speed of the spiral shaft, but also to the pitch of the spiral blades. In the same pitch, the more against the outer edge of the spiral blade, the faster the conveying speed.

$$\begin{aligned} v_e &= \frac{2\pi nR}{60} = \frac{\pi nR}{30} \\ v_a &= v_e \sin\alpha = \frac{\pi nR}{30}\sin\alpha \\ v_r &= v_e \cos\alpha = \frac{\pi nR}{30}\cos\alpha \\ \alpha &= arc\tan\frac{P}{\pi D} \end{aligned} \tag{1}$$

where:

v_a is the absolute velocity of the sesame capsule, [m/s]; v_e is the entanglement speed of the sesame capsule, [m/s]; v_r is the relative velocity of the sesame-capsule fruit, [m/s]; α is the helix angle, [°]; R is the radius of the screw conveyor device, [mm].

Determination of diameter

The formula for the diameter is:

$$D = \sqrt{\frac{4Q}{\pi v \varphi \rho}} \tag{2}$$

where:

D is the diameter of the roller of the screw conveyor device, [mm];Q is the value of screw conveying capacity, [kg/s]; v is the axial movement speed of the sesame capsule, [m/s]; φ is the fill factor; ρ is the density of the material pile, [kg/m³]

In this paper, the screw conveying capacity Q=2.58~5.65kg/s; v≤0.5m/s; ρ=450~550kg/m³ is selected to get the range of diameter values from 270 to 400 mm.

Determination of pitch

The pitch formula is:

$$P = k D \tag{3}$$

where: k is the coefficient of proportionality between pitch and helical blade diameter.

Agricultural fiber material k takes the value range of 0.5~2.0 *(Zhao et al., 2025; Zhao et al., 2018)*, in this paper k takes 1.1 to get the range of pitch values 297~440 mm.

Determination of rotational speed

The formula for calculating the spiral speed is:

$$n = \frac{Q \times 1000}{60 A v \rho \eta} \tag{4}$$

where: n is the value of the rotational speed, [r/min];

A is the cross-sectional area of the screw conveyor, $A = \frac{\pi (D^2 - d^2)}{4}$, [m²]; η is conveying efficiency.

After calculation and design criteria to obtain the speed range of about 150~250 r/min.

Research based on EDEM conveying process simulation analysis

In this study, the crushing behavior of sesame capsules was analyzed using the Discrete Element Method (DEM). The crushing process was simulated by applying external force to the sesame capsules *(Qing et al., 2024; Jia X et al., 2025; Zhou et al., 2024)*. During the crushing, the capsules come into contact with the force-applying object. The Hertz-Mindlin with Bonding V2 contact model was employed to simulate this process, forming bonding interactions between particles *(Wang et al., 2021; Hou et al., 2018; Cheng et al., 2024)*. The crushing degree was evaluated by calculating the ratio of broken bonds to the total number of bonding interactions.

Based on the study of the seed crushing rate in the screw conveyor device, a solid model of the device was created using SolidWorks 3D software and imported into EDEM in *stl* format. The resulting simulation model is shown in Fig. 4. In order to facilitate the processing, the overall material of the screw conveyor device was set to be 65Mn steel. Based on the morphology and characteristics of the sesame seed capsule a realistic capsule model was constructed. Using the Bonding V2 contact model, a meta-particle was employed to represent the sesame seed capsule, as shown in Fig. 5.

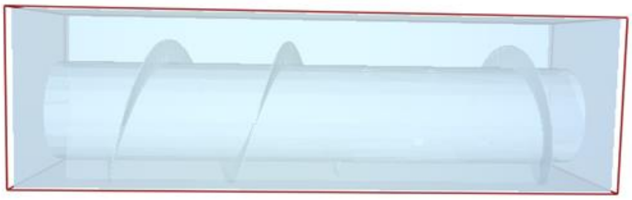
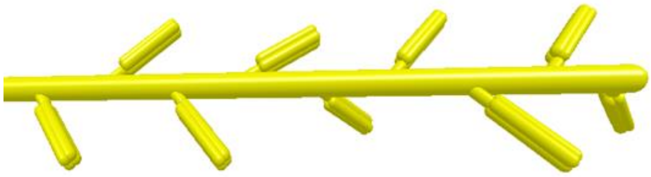
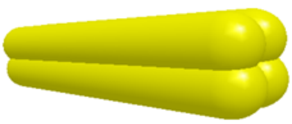


Fig. 4 - Simulation model of screw conveyor



（a）Discrete metamodeling of sesame stalks and capsules



（b）Discrete metamodeling of the sesame capsule

Fig. 5 - Simulation of the simulation model

The simulated material is a sesame seed capsule, and its mechanical properties were obtained from experimental tests and references *(Wang et al., 2018; Zhao et al., 2022; Zhang et al., 2020)* and the specific properties are shown in Table 1.

Table 1

Basic parameters of the discrete element simulation model

Parameters	Numerical value
Sesame density [kg·m^{-3}]	350
Sesame Poisson's ratio	0.25
Sesame shear modulus [Pa]	8×10^{6}
Steel density [kg·m^{-3}]	7850

Parameters	Numerical value
Steel Poisson's ratio	0.3
Steel shear modulus [Pa]	2×10^{11}
Sesame-Sesame coefficient of restitution	0.2
Sesame-Sesame static friction coefficient	0.6
Sesame-Sesame dynamic friction coefficient	0.05
Sesame-Steel coefficient of restitution	0.5
Sesame-Steel static friction coefficient	0.6
Sesame-Steel kinetic friction coefficient	0.01

Single-factor simulation test

Through theoretical analysis, the key parameters of the spiral conveying device - screw roller diameter *D*, pitch *P*, and rotational speed *n* were selected as test factors to analyze their influence on the crushing rate of sesame capsules and determine appropriate value ranges. Based on the results, the diameter range was set between 270 - 400 mm, the pitch between 297 - 440 mm, and the speed between 150 - 250 r/min. To meet the performance requirements for minimizing the crushing rate, the intermediate levels for the single-factor tests were defined as 335 mm for diameter, 368 mm for pitch, and 225 r/min for speed. During the single-factor tests, the other two parameters were maintained at their respective intermediate levels. The specific factor levels used in the single-factor experiments are shown in Table 2.

Table 2

Factor levels of one-way simulation test

Level	Diameter [mm]	Pitch [mm]	Speed [r/min]
1	270	297	185
2	302	332	200
3	335	368	225
4	368	404	235
5	400	440	250

Box-Behnken Design Simulation tests

In order to further determine the optimal combination of the parameters of the screw conveyor device with the best effect on the crushing rate of sesame capsules in this design, on the basis of the one-factor test, three key factors affecting the crushing rate (diameter *D*, pitch *P*, rotational speed *n*) were selected as the test factors, and a three-factor, three-level Box - Behnken design was used to study the relationship between the key factors and the test indicators. The relationship between the key factors and the test indexes was investigated using a three-factor, three-level Box-Behnken design. According to the previous theoretical analysis and the results of one-factor simulation test, the diameter of the spiral drum is 302~335 mm, the pitch is 404~440 mm, and the rotational speed is 200~235 r/min. The coding of the test factors is shown in Table 3, and the test program and results are shown in Table 4.

Table 3

Coding of test factors

Encodings	Considerations		
	D / [mm]	P / [mm]	n / [r/min]
-1	302	404	200
0	335	422	217.5
1	368	440	235

Table 4

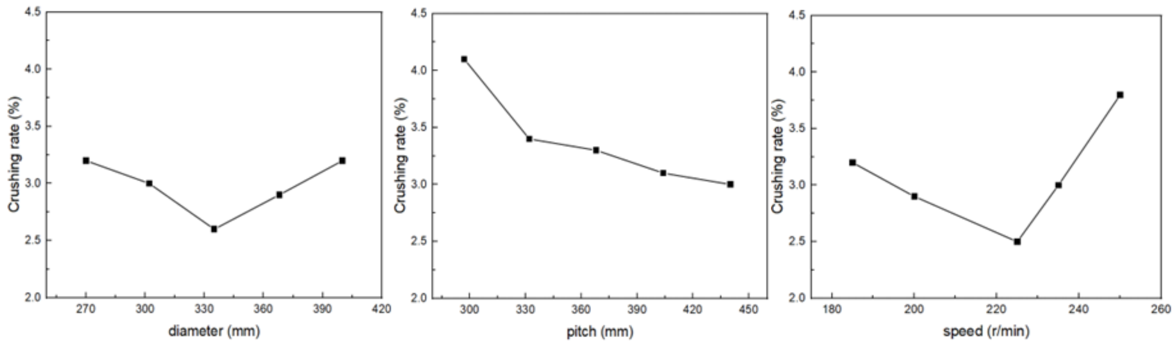
Pilot program and result

Serial Number	Considerations			Crushing rate / [%]
	D / [mm]	P / [mm]	n / [r/min]	
1	302	404	217.5	3.1
2	302	440	217.5	2.5
3	368	404	217.5	3.2
4	368	440	200	3.1
5	335	404	200	3.3
6	335	440	235	3.2
7	335	404	235	3.0
8	335	440	200	2.5
9	302	422	200	2.9
10	368	422	235	3.7
11	302	422	235	2.8
12	368	422	217.5	3.0
13	335	422	217.5	3.0
14	335	422	217.5	2.9
15	335	422	217.5	3.1
16	335	422	217.5	3.0
17	335	422	217.5	3.1

RESULTS

Analysis of single-factor test results

The results of the single-factor test are shown in Fig.6.



(a) Diameter **(b) Pitch** **(c) Speed**

Fig. 6 - Results of single-factor simulation test

(1) The influence of screw roller diameter on the crushing rate of sesame capsules was analyzed for diameters of 270, 302, 335, 368, and 400 mm. When the diameter is less than 280 mm, the rotation of the spiral blade causes the sesame capsules to move outward due to centrifugal force. However, because of the smaller diameter, the outer edge of the blade is close to the pipe wall, which forces the capsules to collide frequently with the pipe wall, leading to a higher crushing rate. Conversely, when the diameter exceeds 380 mm, the increased size of the screw roller results in a larger contact area with the sesame capsules, again causing a higher crushing rate due to more frequent and intense collisions.

(2) The effect of screw conveyor pitch on the crushing rate of sesame capsules was analyzed using pitch values of 297, 332, 368, 404, and 440 mm. When the pitch is less than 400 mm, the spiral blade exerts a stronger rubbing effect on the sesame capsules, which significantly increases mechanical stress. Additionally, the smaller pitch results in a higher filling rate, causing the capsules to become wedged in the narrow gaps between the blade and the pipe wall. This leads to compression and extrusion of the capsules, ultimately resulting in a higher crushing rate.

(3) The influence of screw conveyor speed on the crushing rate of sesame capsules was investigated using rotational speeds of 185, 200, 225, 235, and 250 r/min. At speeds below 200 r/min, the conveying time is extended, leading to material accumulation at the inlet and potential blockages. This prolonged compression causes the sesame capsules to experience sustained pressure, resulting in fatigue fractures and a high crushing rate. Conversely, when the speed exceeds 235 r/min, the centrifugal force acting on the capsules increases significantly, causing them to be flung against the inner wall of the pipe at high velocity. The resulting impact energy surpasses the structural limit of the capsules, leading to a marked increase in the crushing rate.

Analysis of Box-Behnken Design tests results

The experiment was analyzed using Design-Expert software. The variance analysis of the simulation test of the screw conveyor device is shown in Table 5. Analysis of variance shows that the diameter, pitch and rotational speed of the spiral device have extremely significant effects, and the regression equation between the breakage rate A and the diameter *D*, pitch *P* and rotational speed *n* is obtained:

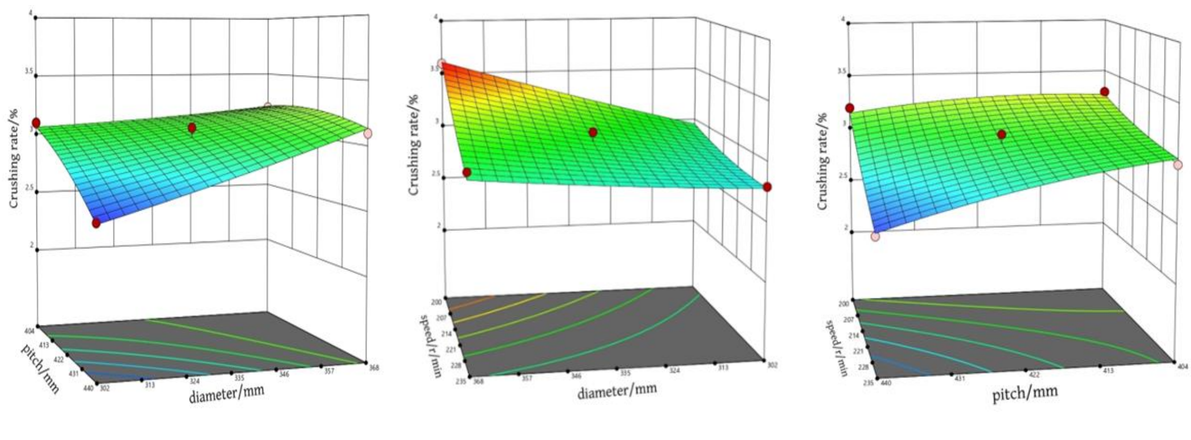
$$A=3.02-0.1625D+0.2P-0.2125n+0.125DP-0.1Dn-0.125Pn-0.06D^2+0.015P^2+0.04n^2 \quad (5)$$

To further analyze the interaction effects of key parameters on the crushing rate of sesame capsules in the screw conveyor device, the test data were processed using Design-Expert software. This enabled the generation of response surface plots illustrating the interactive influences of screw roller diameter, pitch, and rotational speed on the crushing rate (denoted as A), as shown in Fig. 7. From Fig. 7a, it can be observed that with a fixed diameter, the crushing rate decreases as the pitch increases. Conversely, when the pitch is held constant, the crushing rate tends to increase with larger diameters, although the increase is relatively modest. Fig. 7b shows that when the diameter is fixed, the crushing rate decreases with increasing rotational speed, while at a constant speed, the crushing rate increases with the diameter. Finally, Fig. 7c indicates that when the pitch is held constant, the crushing rate initially increases and then decreases with increasing speed; meanwhile, at a constant speed, the crushing rate consistently decreases as the pitch increases.

Table 5

Analysis of variance of crushing rate simulation experiment

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model	1.08	9	0.1199	18.45	0.0004
D	0.2113	1	0.2113	32.50	0.0007
P	0.3200	1	0.3200	49.23	0.0002
n	0.3613	1	0.3613	55.28	0.0001
DP	0.0625	1	0.0625	9.62	0.0173
Dn	0.0400	1	0.0400	6.15	0.0422
Pn	0.0625	`	0.0625	9.62	0.0173
D2	0.0152	1	0.0152	2.33	0.1706
P2	0.0009	1	0.0009	0.1457	0.7140
n2	0.0067	1	0.0067	1.04	0.3425
Residual	0.0455	7	0.0065	-	-
Lack of Fit	0.0175	3	0.0058	0.8333	0.5413
Pure Error	0.0280	4	0.0070	-	-
Cor Total	1.12	16	-	-	-



（a） （b） （c）

Fig. 7 - Response surface for the effect of interaction of factors on crushing rate

The test results show that the changes of diameter, pitch and rotational speed will all affect the breakage rate of sesame capsule. In order to obtain the optimal structural parameters of the screw conveyor device, the structural parameters were optimized by using the optimization module of Design-expert data analysis software. When D=302 mm, P=422 mm, n=200 mm, the crushing rate is 2.9%

CONCLUSIONS

(1) SolidWorks was used to construct a 3D model of the cutting table screw conveyor, followed by design calculations for its diameter, pitch, and rotational speed to determine the key structural parameters and their respective ranges. The determined ranges were: diameter 270~400 mm, pitch 297~440 mm, and rotational speed 185~250r/min.

(2) Using EDEM discrete element modeling, sesame capsules were selected as the simulation object. Single-factor tests were conducted with screw conveyor diameter, pitch, and rotational speed as test factors, and the crushing rate as the evaluation index. Analysis of the influence of each factor on the crushing rate determined that optimal parameter ranges were: diameter 302-368 mm, pitch 404-440 mm, and rotational speed 200-235 r/min.

(3) A Box-Behnken Design simulation test was conducted to explore the interactions between factors. The influence of each factor on crushing rate, in descending order of significance, was: rotational speed, diameter, and pitch. The optimal parameter combination - diameter of 302 mm, pitch of 422 mm, and rotational speed of 200 r/min - resulted in a predicted crushing rate of 2.9%.

ACKNOWLEDGEMENT

The research was funded by the National Key Research and Development Program of China (No. 2022YFD2300100).

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