PARAMETER OPTIMIZATION AND EXPERIMENTAL RESEARCH ON THE HAMMER MILL
/
锤片式粉碎机参数优化与试验研究

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ABSTRACT
Low productivity and high electricity consumption are considered problems of the hammer mill, which is widely used in current feed production. In this paper, the mechanical properties of corn grain ground by a hammer mill were analysed, and the key factors affecting the performance of the hammer mill were determined. The single-factor experiment and three-factor, three-level quadratic regression orthogonal experiment were carried out with the spindle speed, corn grain moisture content and number of hammers as experimental factors and the productivity and electricity consumption per ton as evaluation indexes. The results showed that the order of influence on the productivity was spindle speed > corn grain moisture content > number of hammers and that the order of influence on the electricity consumption per ton was corn grain moisture content > spindle speed > number of hammers. The parameters were optimized based on the response surface method with the following results: the spindle speed was 4306 r/min, the corn grain moisture content was 10%, and the number of hammers was 24. The validation experiment was carried out with the optimal parameters' combination. The productivity and electricity consumption per ton were 988.12 kg/h and 5.37 kW·h/t, respectively, which were consistent with the predicted results of the model.

摘要
针对目前生产中普遍使用的锤片式粉碎机存在生产率低、能耗高的问题。对锤片式粉碎机粉碎玉米颗粒力学特性进行分析，确定了影响锤片式粉碎机性能的关键因素。为确定锤片式粉碎机最佳工作参数组合，以主轴转速、玉米颗粒含水率、锤片数量为试验因素，以生产率和吨料电耗为评价指标，开展了单因素试验和三因素三水平二次回归正交试验。结果表明，影响生产率的主次因素为：主轴转速>玉米颗粒含水率>锤片数量；影响吨料电耗的主次因素为：玉米颗粒含水率>主轴转速>锤片数量。基于响应面法进行参数优化，优化结果为：主轴转速为 4306 r/min，玉米颗粒含水率为 10 %，锤片数量为 24。以优化后参数组合进行试验验证，结果为：生产率和吨料电耗分别为 988.12 kg/h，5.37 kWh/t，与模型预测结果一致。

INTRODUCTION
Feed grinding can increase the surface area of feed and improve its palatability and digestibility for livestock. Therefore, a large amount of feed needs to be ground every year (*Mugabi et al., 2017; Xie., 2016; Barnwal et al., 2015*). The hammer mill is a widely used piece of equipment in feed processing, and it has the advantages of low price, simple structure and easy operation (*Chen et al., 2017; Wang. et al, 2013; Liu et al., 2011*). However, there are still some problems, such as low productivity and high energy consumption with the hammer mill (*Li et al., 2019; Cao et al., 2016*).

In recent years, research on the hammer mill by scholars at home and abroad has mainly focused on the structural improvement and application experiments of the main parts, including the hammer, the shape of grinding chamber, the structure of rotor, etc. *Xu Wei et al.,* (*2021*), took the minimum deformation of the hammer as the optimization objective and used the response surface method and genetic algorithm to optimize the structure parameters of the hammer. *Bochat et al.,* (*2015*), designed a new hammer and performed comparative experiments. The results showed that the new hammer was more efficient than the traditional hammer. *Moiceanu et al.,* (*2019*), used the finite element method to analyse the rotor of the

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hammer mill and obtained some mechanical data on the hammer mill. *Zhang Yongjie et al.,* (*2019*), used ANSYS Workbench software to carry out static calculation and modal analysis of hammer frame plate and carried out topology optimization design for the hammer frame plate according to the analysis results.

In this paper, considering the existing problems with the hammer mill, the mechanical properties of corn grain grinding were analysed, and the key factors affecting the performance of the hammer mill were determined. The orthogonal experiment and response surface method were used to optimize the working parameters of the hammer mill, and the optimal parameters combination was determined. The research results can provide a reference for the optimal design of the hammer mill.

MATERIALS AND METHODS

- **Experiment materials and equipment**

Corn grain was selected as the experiment material, and the variety of corn used was XIANYU-355. The experimental equipment included a frequency converter, a tachometer, a grain moisture meter, an electronic scale (accuracy of 0.01 kg), an electric energy meter and a stopwatch.

- **Overall structure and working principle**

The hammer mill used in this study is mainly composed of an outlet, a frame, a motor (3 kW), a feeding hopper, a sieve (sieve hole diameter is 3 mm), and a hammer. The structure diagram of the hammer mill is shown in Fig. 1. When the hammer mill is working, the feed enters the grinding chamber through the feeding hopper. It is first ground by the hammer and then further ground by the impact between the feed and sieve. When the feed grain size is smaller than the sieve hole diameter, the feed is discharged from the outlet.

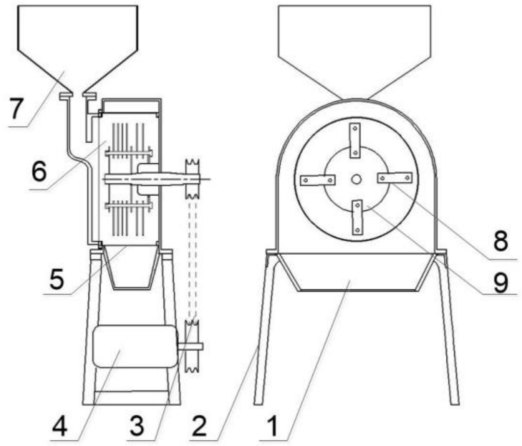


Fig. 1 – Structure diagram of the hammer mill

1 – Outlet; 2 – Frame; 3 –V-belt; 4 – Motor; 5 – Sieve; 6 – Grinding chamber; 7 – Feeding hopper; 8 – Hammer; 9 –Hammer plate

- **Mechanical properties analysis of corn grain**

After entering the grinding chamber, the corn grain was hit by the hammer, as shown in Fig. 2. According to impulse theorem and momentum theorem (*Zhang, 2009*), the following formula can be obtained:

$$m_1 v_1 + m_2 v_2 = (m_1 + m_2) v_3 \tag{1}$$

$$I = m_2 v_3 = F\Delta t \tag{2}$$

$$v_1 = \frac{\pi n R}{30} \tag{3}$$

$$v_3 = \frac{\pi n m_1 R}{30(m_1 + m_2)} \tag{4}$$

According to formula 1-4, the hitting force of corn grain was obtained as shown in formula 5 (Because v_2 is very small relative to the velocity of hammer, in this paper, v_2=0).

$$F = \frac{\pi n m_1 m_2 R}{30(m_1 + m_2)\Delta t} \tag{5}$$

Where:

v_1 is the linear velocity of the hammer, [m/s];

v_2 - the velocity of corn grain before being hit, [m/s];

v_3 - the velocity of corn grain after being hit, [m/s];

m_1 - the mass of the hammer, [kg];

m_2 - the mass of the corn grain, [kg];

n - spindle speed, [r/min];

R - the rotor radius, [m];

I - the impulse of hammer and corn grain, [N·s];

Δt - the hitting time of corn grain, [s];

F - the hitting force of corn grain, [N].

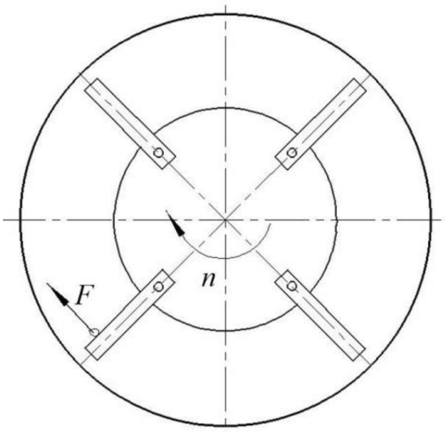


Fig. 2 – Schematic diagram of hitting force of corn grain by the hammer

An analysis of formula (5) shows that as the spindle speed increases, the hitting force on the corn grain increases. When the hitting time of corn grain is shorter, the hitting force is greater. The hitting time of the hammers on the corn grain is related to the hardness of the corn grain. The hitting time is shorter when the hardness of corn grain is greater. The hardness of the corn grain is related to the moisture content; the hardness of the corn grain is greater when the corn grain moisture content is lower (*Feng et al., 2003*). In addition, the number of hammers has a greater influence on the performance of the hammer mill. The larger the number of hammers is, the greater the hitting force, and the higher the probability of corn grain being hit. However, the larger the number of hammers, the higher the power consumption (*Zhang et al., 2013*). Therefore, the key to improving the performance of the hammer mill is to determine the optimal spindle speed, corn grain moisture content and number of hammers.

- **Experimental design**

According to the above analysis results, the spindle speed, corn grain moisture content and number of hammers were selected as the experimental factors. According to the agricultural machinery design manual (*China Agricultural Science and Technology Press, 2007*), the range for each factor was determined as follows: the spindle speed was 3800-4600 r/min, the corn grain moisture content was 10-18 %, and the number of hammers was 20-28. Each group of experiments is repeated three times, and the average value is taken.

- **Performance evaluation of the hammer mill**

According to the Chinese national standard (GB/T 6971-2007), the productivity and electricity consumption per ton were taken as the performance evaluation indexes. The calculation formulas are given by formulas (6) and (7) (*China National Standardization Committee, 2007*).

$$E_c = \frac{Q_c}{T_c} \tag{6}$$

$$G = \frac{G_n}{Q_c / 1000} \tag{7}$$

Where:

E_c is the productivity of the hammer mill, kg/h;

Q_c - the mass of the fragmented experiment sample, kg;

T_c - the duration of grinding of a single experiment sample, h;

G - the electricity consumption per ton of the hammer mill, kWh/t;

G_n - the electricity consumption during grinding of a single experiment sample, kWh.

RESULTS

- **Single-factor experiment results and analysis**

Effect of spindle speed on the performance of the hammer mill

The corn grain moisture content was set at 14%; the number of hammers was 24; and the spindle speed was adjusted to 3800, 4000, 4200, 4400 and 4600 r/min. The relationship between the spindle speed and productivity and electricity consumption per ton is shown in Fig. 3.

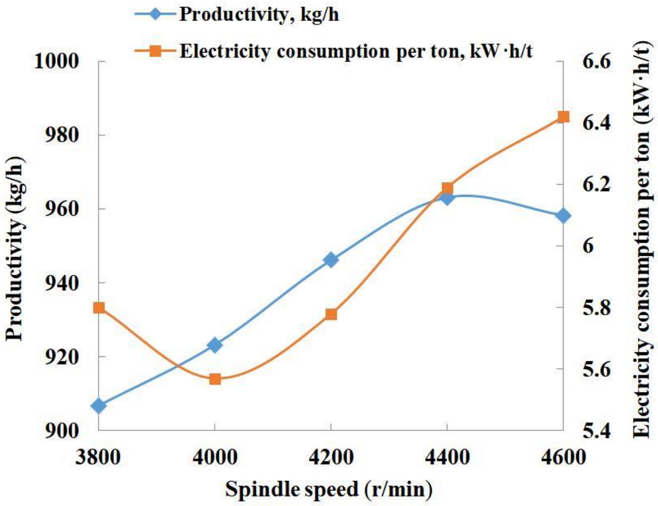


Fig. 3 – Effect of spindle speed on the machine performance

It can be seen from Fig. 3 that when the spindle speed was 3800-4600 r/min, the productivity increased first and then decreased with the increase in spindle speed, and the electricity consumption per ton decreased first and then increased with the increase in spindle speed. When the spindle speed was 4000-4400 r/min, the productivity was high, and the electricity consumption per ton was low, which was the best spindle speed range for the hammer mill.

Effect of corn grain moisture content on the performance of the hammer mill

The spindle speed was set at 4200 r/min; the number of hammers was 24; and the corn grain moisture content was adjusted to 10, 12, 14, 16 and 18 %. The relationship between the corn grain moisture content and productivity and electricity consumption per ton was obtained, as shown in Fig. 4.

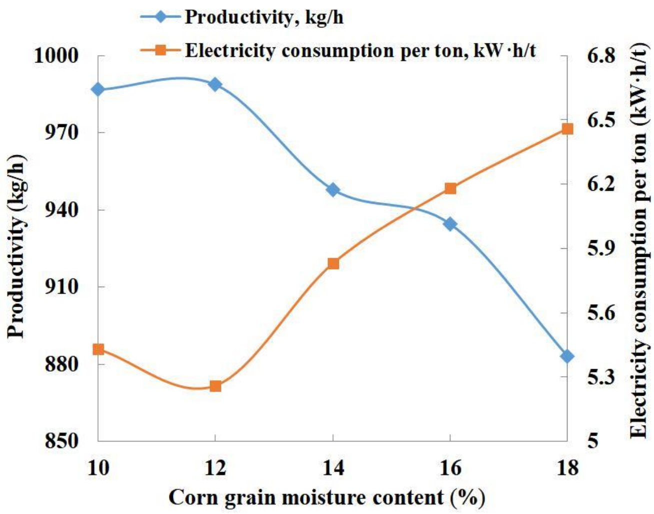


Fig. 4 – Effect of corn grain moisture content on the machine performance

As shown in Fig. 4, when the corn grain moisture content was 10-12 %, the productivity increased slowly with the increase in the corn grain moisture content, and the electricity consumption per ton decreased with the increase in the corn grain moisture content. When the corn grain moisture content was 12-18%, the productivity decreased with the increase in the corn grain moisture content, and the electricity consumption per ton increased with the increase in the corn grain moisture content.

It can be concluded that when the corn grain moisture content was 10-14%, the comprehensive performance of the hammer mill was the best.

Effect of number of hammers on the performance of the hammer mill

The spindle speed was set at 4200 r/min; the corn grain moisture content was 14%; and the number of hammers was adjusted to 20, 22, 24, 26 and 28. The relationship between number of hammers and productivity and electricity consumption per ton was obtained, as shown in Fig. 5.

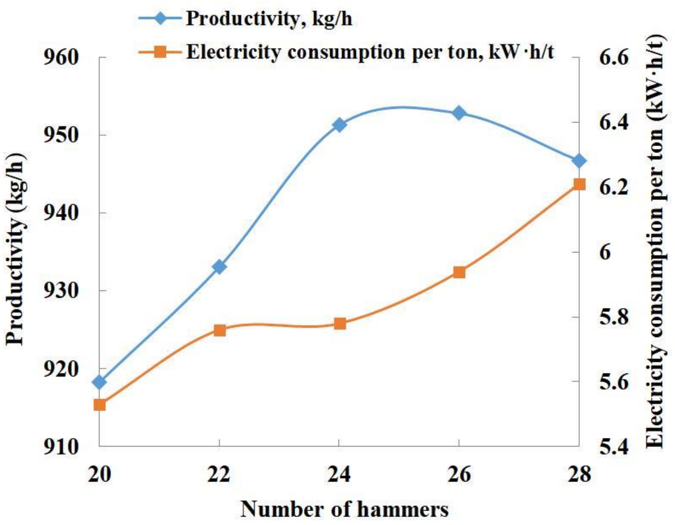


Fig. 5 – Effect of number of hammers on the machine performance

As shown in Fig. 5, the productivity increased first and then decreased slowly with the increase in the number of hammers, and the electricity consumption per ton increased gradually with the increase in the number of hammers. It can be concluded that when the number of hammers was 22-26, the comprehensive performance of the hammer mill was the best.

- **Orthogonal experiment results and analysis**

In order to obtain the optimal working parameters combination of the hammer mill, three-factor, three-level quadratic regression orthogonal experiment were carried out based on the Box-Behnken experimental method (*Du et al., 2019*).

According to the single-factor experiment results, the level of each factor was determined as shown in Table 1.

Table 1

Experimental factors and levels

Levels	**Spindle speed A**	**Corn grain moisture content B**	**Number of hammers C**
	[r/min]	[%]	[-]
-1	4000	10	22
0	4200	12	24
1	4400	14	26

The experiment results are shown in Table 2.

Table 2

The experiment results

Test number	Spindle speed A	Corn grain moisture content B	Number of hammers C	Productivity	Electricity consumption per ton
	[r/min]	[%]	[-]	[kg/h]	[kWh/t]
1	-1	0	-1	932.63	5.6
2	0	1	-1	928.66	5.86
3	0	0	0	974.49	5.36
4	1	0	-1	977.86	5.8
5	0	0	0	987.97	5.25
6	1	-1	0	1018.18	5.52
7	-1	0	1	953.74	5.76
8	-1	-1	0	949.26	5.25
9	1	0	1	997.42	6.26
10	1	1	0	956.58	6.21
11	0	0	0	977.75	5.34
12	0	0	0	981.17	5.29
13	0	-1	1	976.3	5.76
14	0	0	0	982.31	5.22
15	-1	1	0	923.4	5.69
16	0	1	1	936.52	5.97
17	0	-1	-1	972.44	5.2

- **Analysis of productivity**

Variance analysis of productivity

Variance analysis of productivity was performed with Design-Export 10 software, and the results are shown in Table 3. It can be concluded that the regression model was extremely significant, and the lack of fit was not significant. The regression model of productivity was established as shown in formula 8, and the fit coefficient (R^2) was 0.9788. The order of influence on the productivity was spindle speed A > corn grain moisture content B >number of hammers C.

$$E_c = 980.74 + 23.88A - 21.38B + 6.55C - 8.93AB - 0.39AC + 1.00BC - 3.48A^2 - 15.41B^2 - 11.85C^2 \quad (8)$$

where: A is the spindle speed, r/min; B is the corn grain moisture content, %; and C is the number of hammers.

Variance analysis results of productivity **Table 3**

Source	Squares	DF	MS	F Value	P Value
Model	10665.47	9	1185.05	35.86	< 0.0001**
A	4560.60	1	4560.60	138.00	< 0.0001**
B	3655.98	1	3655.98	110.63	< 0.0001**
C	343.09	1	343.09	10.38	0.0146*
AB	319.34	1	319.34	9.66	0.0171*
AC	0.60	1	0.60	0.02	0.8966
BC	4.00	1	4.00	0.12	0.7381
A^2	50.85	1	50.85	1.54	0.2548
B^2	999.57	1	999.57	30.25	0.009**
C^2	591.28	1	591.28	17.89	0.0039**
Lack of Fit	128.41	3	42.80	1.66	0.3104
Pure Error	102.93	4	25.73		
Cor Total	10896.81				

*Note: P < 0.01 (extremely significant, **), P < 0.05 (significant, *).*

Response surface analysis of productivity

The response surface of spindle speed, corn grain moisture content and number of hammers to productivity is shown in Fig. 6. When the number of hammers was 24, the productivity increased with the increase in the spindle speed and decreased with the increase in the corn grain moisture content. When the corn grain moisture content was 12%, the productivity increased with the increase in the number of hammers and spindle speed. When the spindle speed was 4200 r/min, the productivity decreased with the increase in the corn grain moisture content and increased with the increase in the number of hammers.

The overall influence trend of the experimental factors on productivity was as follows: the spindle speed was high, the number of hammers was large, and the corn grain moisture content was low, thereby increasing the productivity. The main reasons are as follows: when the spindle speed was high, the hitting force of the hammers on the corn grain was great, and the grinding efficiency increased. When the corn grain moisture content was low, the brittleness of the corn grain was greater, the hitting time of the corn grain was shorter and the corn grain was easily ground. When the number of hammers was large, the hitting force was great, and the probability of the corn grain being hit was high, thereby increasing the productivity.

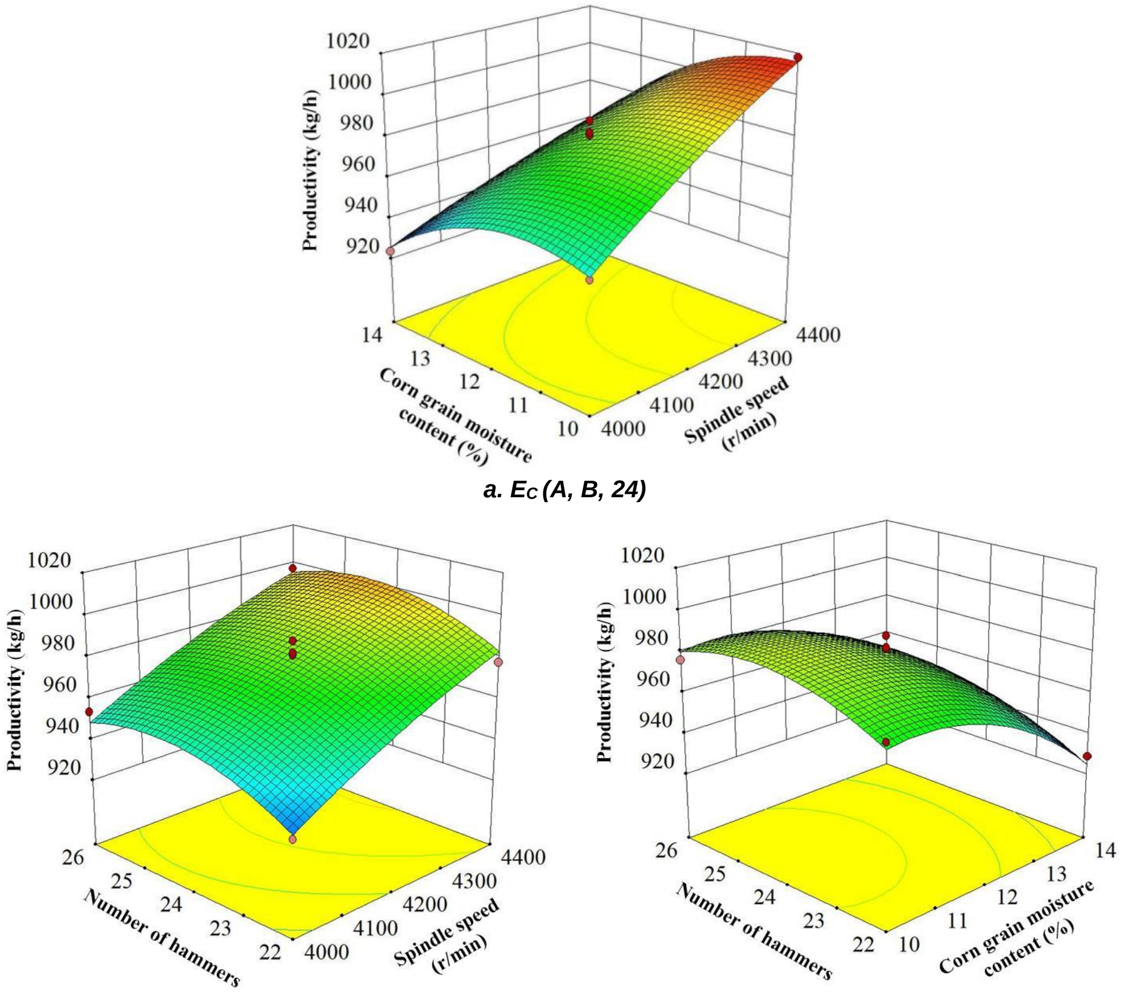


Fig. 6 – Response surface of various factors on productivity

- **Analysis of electricity consumption per ton**

Variance analysis of electricity consumption per ton

The results of the variance analysis of electricity consumption per ton are shown in Table 4. The regression model of electricity consumption per ton was established as shown in formula 9, and the fit coefficient (R^2) was 0.9875. From Table 4, we can see that the regression model was extremely significant, and the lack of fit was not significant. The order of influence on the electricity consumption per ton was corn grain moisture content B > spindle speed A >number of hammers C.

$$G = 5.29 + 0.19A + 0.25B + 0.16C + 0.063AB + 0.075AC - 0.11BC + 0.27A^2 + 0.11B^2 + 0.30C^2 \quad (9)$$

where: A is the spindle speed, r/min; B - the corn grain moisture content, %; and C - the number of hammers.

Table 4

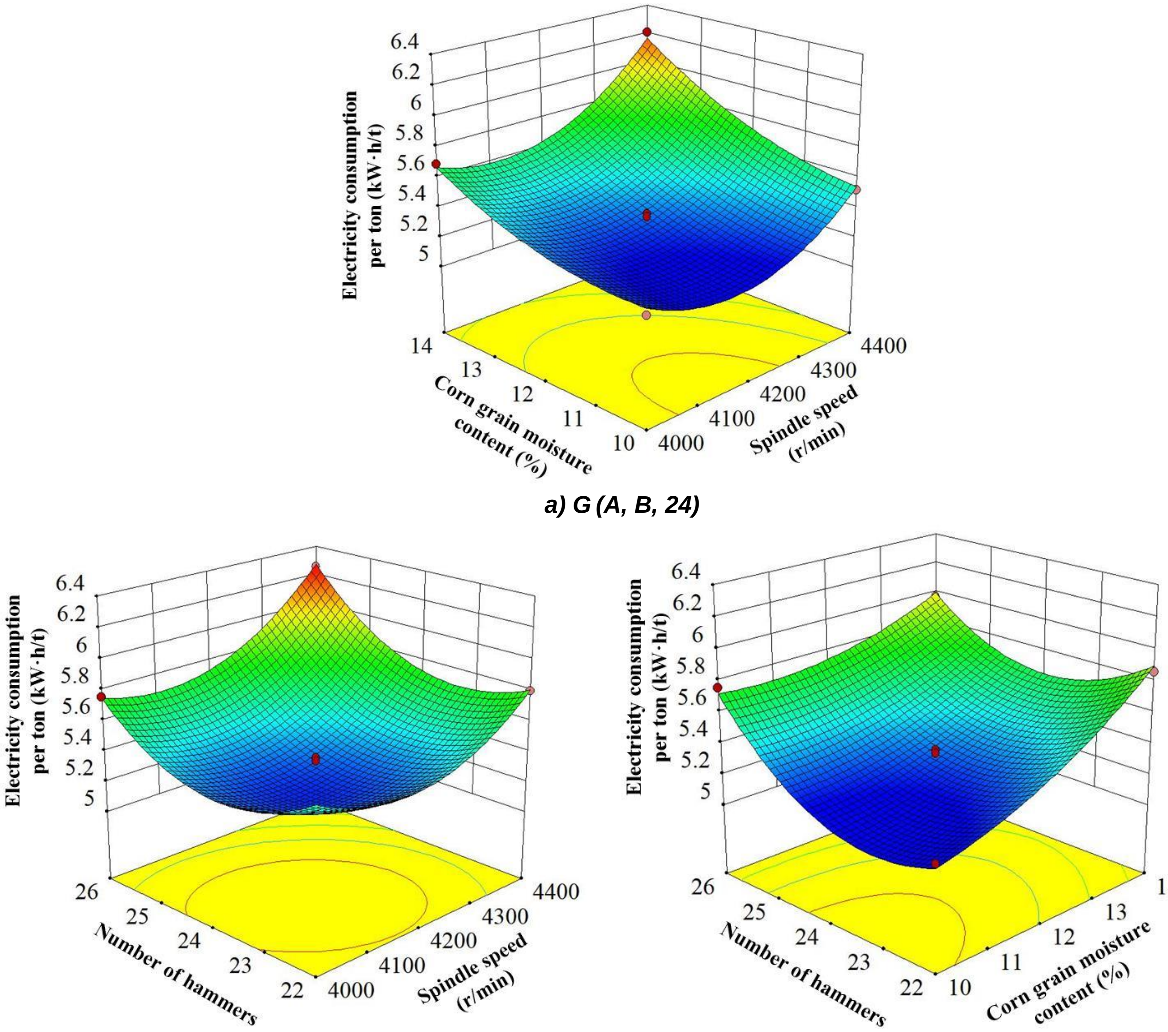
Variance analysis results of electricity consumption per ton

Source	Squares	DF	MS	F Value	P Value
Model	1.86	9	0.21	61.28	< 0.0001**
A	0.28	1	0.28	82.12	< 0.0001**
B	0.50	1	0.50	147.96	< 0.0001**
C	0.21	1	0.21	61.56	0.0001**
AB	0.016	1	0.016	4.62	0.0686
AC	0.022	1	0.022	6.66	0.0365*
BC	0.051	1	0.051	14.98	0.0061**
A^2	0.30	1	0.30	88.49	< 0.0001**
B^2	0.050	1	0.050	14.80	0.0063**
C^2	0.37	1	0.37	109.54	< 0.0001**
Lack of Fit	0.0098	3	0.0033	0.94	0.5006
Pure Error	0.014	4	0.0035		
Cor Total	1.89	16			

*Note: P < 0.01 (extremely significant, **), P < 0.05 (significant, *).*

Response surface analysis of electricity consumption per ton

The response surface of spindle speed, corn grain moisture content and number of hammers to electricity consumption per ton is shown in Fig. 7.



a) G (A, B, 24)

b) G (A, 14, C)

c) G (4200, B, C)

Fig. 7 – Response surface of various factors on electricity consumption per ton

When the number of hammers was 24, the electricity consumption per ton decreased first and then increased with the increase in the spindle speed and increased gradually with the increase in the corn grain moisture content. When the corn grain moisture content was 12%, the electricity consumption per ton decreased slowly first and then increased with the increase in the spindle speed and number of hammers. When the spindle speed was 4200 r/min, the electricity consumption per ton increased with the increase in the corn grain moisture content, and the electricity consumption per ton decreased first and then increased with the increase in the number of hammers.

The overall influence trend was that the electricity consumption per ton was low when the spindle speed and number of hammers were moderate and the corn grain moisture content was low. The main reasons are as follows: when the corn grain moisture content was high, the cohesion of the corn grain was large, and it was not easily ground, so it consumed more electricity. When the spindle speed was low, the hitting force was small, and the grinding efficiency decreased. When the spindle speed was high, the motor load increased, resulting in increased electricity consumption. When the number of hammers was small, the hitting force was small. When the number of hammers was large, the mass of the rotor increased, and the moment of inertia increased, thus increasing the electricity consumption per ton.

- **Parameter optimization and validation**

To obtain the best working parameters of the hammer mill, the maximum productivity and the minimum electricity consumption per ton were taken as the optimization objectives, and the optimization module in Design-Export software was used to solve the optimal parameters. The objective function and constraint conditions are shown in formula 10:

$$\begin{cases} MaxE_c \\ MinG \\ A \in [4000-4400\mathrm{r/min}] \\ B \in [10-14\%] \\ C \in [22-26] \end{cases} \tag{10}$$

After optimization calculation, the optimal working parameters were obtained as follows: the spindle speed was 4306 r/min, the corn grain moisture content was 10% and the number of hammers was 24.

The predicted value of the productivity and electricity consumption per ton were 1000.94 kg/h and 5.23 kWh/t, respectively.

The validation experiment was carried out with the above optimization parameters. The results were as follows: the productivity was 988.12 kg/h, and the electricity consumption per ton was 5.37 kWh/t, which were consistent with the prediction results of the model, and the prediction errors were less than 3%.

CONCLUSIONS

1. Based on the mechanical properties' analysis of corn grain grinding, the hitting force formula of corn grain was obtained, and the key factors affecting the performance of the hammer mill were determined as follows: spindle speed, corn grain moisture content and number of hammers.

2. The variance analysis showed that the order of influence on the productivity was spindle speed > corn grain moisture content > number of hammers, and that the order of the influence on the electricity consumption per ton was corn grain moisture content > spindle speed > number of hammers.

3. Taking maximum productivity and minimum electricity consumption per ton as optimization objectives, the optimal working parameters were obtained as follows: the spindle speed was 4306 r/min, the corn grain moisture content was 10% and the number of hammers was 24. The predicted value of productivity was 1000.94 kg/h, and the electricity consumption per ton was 5.23 kWh/t. The validation experiment results showed that the productivity was 988.12 kg/h and the electricity consumption per ton was 5.37 kWh/t, which were consistent with the prediction results of the model.

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