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Structural Model of Straw Briquetting Machine with Vertical Ring Die and Optimization of Briquetting Performance

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Abstract: The solidification and molding of straw has been an effective method for comprehensive utilization of straw resources. However, the existing die-roll extrusion-type straw briquetting machine has challenges, such as the easy blockage of ring die holes and the unstable quality of the briquette. In this paper, the influence of four factors, including moisture content of straw, molding temperature, clearance between die and roller, and spindle speed on the quality of the briquette were studied. The regression model of the relaxed density and impact resistance of the briquette were established to obtain the optimal values of these factors to provide the best parameters for producing straw briquette. The results indicate that under the experimental conditions of moisture content 22.335%, temperature 85.127 °C, clearance between die and roller 3.099 mm, and spindle speed 172.712 r/min, the maximum relaxed density and impact resistance of the briquette were 1.144 g/cm^3 and 74.76%, respectively. The performance of the briquette already meets the requirements for combustion, transportation, and storage.

Keywords: straw; briquetting principle; briquetting machine; relaxed density; impact resistance

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1. Introduction

In recent years, the output of rice has exceeded 200 million tons in China, and a large amount of straw has been produced along with it. Straw is a renewable resource and has low emission of sulfur dioxide when burning, which makes it an ideal renewable and sustainable energy source for producing briquette [1,2]. In most developing countries, biomass resources are not utilized effectively, and unsustainable utilization of straw leads to straw becoming one of the sources of pollution in agriculture [3]. In addition, straw briquette instead of heating coal is more easily accepted by farmers in rural areas, and it is easier to popularize than straw returning to the field [4]. Studies have indicated that biomass briquette has 20% higher combustion performance than raw materials, and straw is one of the few proven, cost-effective, and renewable energy biomasses that can reduce CO_2 emissions [5]. The research on the utilization of crop straw has long-term significance for the recycling of agricultural waste, the improvement of rural life quality, and employment of farmers [6]. The use of biomass will promote the development of rural electrification and industrialization [7,8].

As straw was usually distributed on a large scale, logistics operation costs were greatly increased [9,10]. Straw briquetting was an effective way of comprehensive utilization of straw resources. After the unconsolidated biomass was compressed, its density was increased to about 1000–1200 kg/m^3, and its volume was reduced by 8–10 times [11]. Currently, machines for producing briquettes include screw presses, roll presses, and piston presses (mechanical or hydraulic) [12]. The commonly used vertical ring mold pressing machine had the advantages of high yield and easy maintenance. Due to the randomness of the material in the extrusion process, the torsional vibration of the briquetting machine was random, which affected the stability and reliability of the machine [13]. In the production of solid biomass briquettes, process and material significantly affected the densification process and therefore the final quality of the briquette [14]. The piston flow theory was applied to the pressure of the screw press, and it was discovered that the optimal die entry angle depends on the yield strength of the compacting material and the friction coefficient of the interface between the die and the compacting material [15]. When the briquetting machine is working, the radial load causes the radial strain of the straw, and the inner wall of the ring die hole will hinder the radial strain of the straw, so radial pressure and friction will be generated, so that the straw is continuously compressed in the ring die hole [16]. The periodic variation of the extrusion force was the main reason for the vibration of the briquetting machine, which shortens the life of the ring die and reduces its reliability and stability [17]. At present, there are many research methods for straw briquetting machine, mainly to improve the performance and life of the machine. The productivity, forming quality, and service life of different types of ring modules were different in actual production.

It is difficult to widely use and promote biomass briquette due to its low bulk density, low energy density, low mechanical strength, and high reactivity [18,19]. The properties of the briquettes mainly depend on the properties of the raw materials, such as particle size and moisture content, and the operating conditions, such as pressure and temperature [20]. In the preparation of a bean straw compacting block, the impact resistance of the briquette was over 96% at the pressing temperature of 80, the particle size of 4 mm, and the pressure of 100 MPa. Meanwhile, the interaction of pressure and temperature significantly affected density, impact resistance, and compressive strength [21]. In the process of corn straw compaction, the maximum compression stress and the feed quality had a significant effect on the dimensional stability coefficient of relaxed density and specific energy consumption, and the interaction between moisture content and maximum compression stress had a significant effect on the relaxed density and specific energy consumption [22]. The briquette must be characterized by high mechanical durability to avoid various types of damage due to impact and friction during transport and storage [23]. In order to enhance the performance and efficiency of straw briquette, it is necessary to carry out the corresponding experimental research and analysis on the physical characteristics of straw briquette.

This paper first provides the working principle of the briquetting machine for producing briquette. Considering the relaxed density and impact resistance of rice straw briquette as the responses, the effects of straw moisture content, temperature, clearance between die and roller, and rotational speed on the performance of the briquette were studied. The mathematical prediction model of the relaxed density and impact resistance of rice straw briquette were established. The optimal process parameters for producing briquette were solved through the established mathematical model. This provides a reference for producing high-quality straw briquette.

2. Structure and Forming Principle of Straw Ring Die Forming Press

2.1. Structure of Straw Briquetting Machine

The straw briquetting machine with a vertical ring die is mainly composed of a power system, feeding device, compression chamber, heating system, and frame. The ring die in the compression chamber is placed horizontally, and the ring die is composed of an upper press plate, a lower press plate, and a plurality of modules. The ring module is fixed between the upper press plate and the lower press plate, while the press roll system consists of the eccentric shaft, the press rolls, and the eccentric shaft bearing. The upper press plate and the lower press plate are provided with two rings of annular grooves near the entrance of the ring die hole, which are used to place the heating tube and resistance (Figure 1).

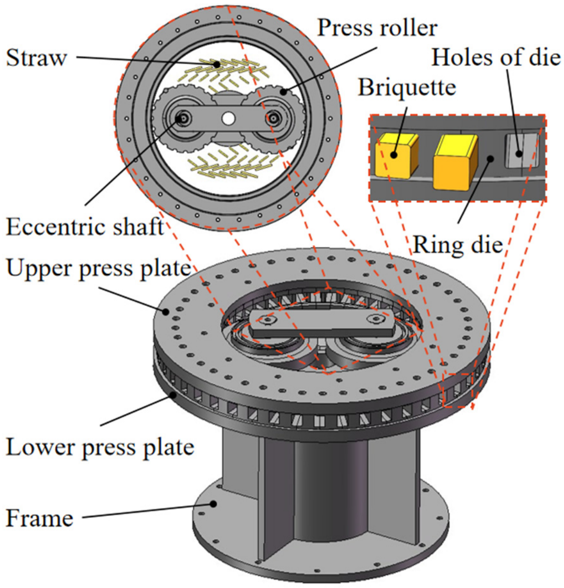


Figure 1. Structure diagram of straw ring die briquetting machine.

2.2. Working Principle of Briquetting Forming

As the press rollers rotate, the straw is continuously squeezed into the ring die holes. Under the action of friction force and heating system, the temperature inside the ring die hole increases, which causes the lignin of the straw to gradually soften. Simultaneously, the straw is bound by the softened lignin into briquettes in the ring die hole and extruded from the other side of the ring die hole. Circular and square ring die holes produce cylindrical and cuboid briquettes, respectively. Under the influence of its own gravity, the product breaks into briquettes with a length of 50–100 mm, and falls on the conveying belt from the discharge hopper. Then, the conveying belt will transport the briquette to the sieve for screening, and it is bagged and sealed after cooling. The two extrusion zones in the chamber are symmetrically distributed relative to the center, and the significant pressure gradient along the rotation direction of the ring die and the press roller causes material reflow [24]. According to the different degree of extrusion of the material, the compression room is divided into three zones, which are the feeding zone, the deformation extrusion zone, and the extrusion forming area (Figure 2) [25].

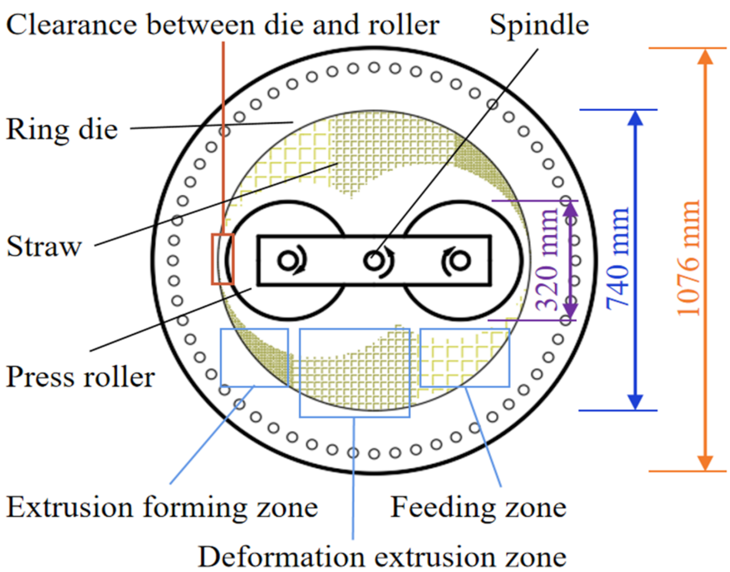


Figure 2. Schematic diagram of the distribution of straw inside the briquetting machine.

In the feeding zone, the straw material hardly contacts the pressing roller, so it can be concluded that the straw material is not squeezed in this zone. The straw material is squeezed by the press roller in the deformation extrusion zone, but the extrusion force of the straw material is not enough to overcome the friction between the ring die hole and the straw material. Therefore, the straw material does not enter the ring die hole in the deformation extrusion zone, but the density of the straw will increase. The extrusion-forming zone is the main zone of straw molding. The straw material is compacted continuously under the action of the press roller. With the rotation of the press roller, the straw material is pressed into the gap between the ring die and the press roller. At this time, the extrusion pressure on the material overcomes the friction force between the ring die hole and the straw material, and the material is pressed into the ring die hole by the press roller, and the briquette is formed in the ring die hole.

3. Materials and Methods

3.1. Materials

The straw used in the experiment was produced in Danyang, Jiangsu province, which was naturally air-dried after harvest in the field. During the experiment, the straw was fully dried by sunlight on the cement floor, and 10 straw samples were selected for drying in automatic program-controlled oven. The measured moisture content was 7.69%, 8.48%, 8.62%, 8.70%, 9.47%, 10.26%, 10.37%, 10.66%, 11.49%, and 12.08%.

The main equipment and instruments used in the test process were as follows: 9JYK-2000A-type straw briquetting machine with vertical ring die (Jiangsu Zhongwei New Energy Technology Co., LTD., Suzhou, China) was used to produce rice straw briquette, its parameters were shown in Table 1; a hay cutter (Zhenjiang Jinmao Co., LTD., Zhenjiang, China) was used to chop rice straws; Fd-g2 high frequency digital moisture meter (Shanghai Jiashi Co., LTD., Shangai, China) was used to test the moisture of rice straw; Epu-s series vector inverter (Zhejiang Hebron Technology Co., LTD., Zhenjiang, China) was used to adjust the rotation speed of the motor driving the briquetting machine; Dgg-9023ad automatic program-controlled oven (Hangzhou Zhuochi Instrument Co., LTD., Hangzhou, China) was used to change the moisture content of rice straw; a JA312002 electronic scale (Shanghai Shuangxu Electronics Co., LTD., Shanghai, China) was used to measure the weight of the briquette, accuracy 0.01 g; a vernier caliper was used to measure the size of the straw briquette, accuracy 0.01 mm.

Table 1. Property parameter of 9JYK-2000A-type straw briquetting machine with vertical ring die.

The Name of Parameters	Date
Length × Width × Height	3500 × 1500 × 2200 mm
Number of die holes	60
Number of press rollers	2
Diameter of ring die hole	27 mm
Length of ring die hole	168 mm
Inner diameter of ring die	740 mm
Diameter of press roller	320 mm
The density of briquette	0.8~1.3 g/cm^3
The length of briquette	50~100 mm
Productivity	1000~2000 kg/h
Spindle speed	165 r/min

3.2. Experimental Method

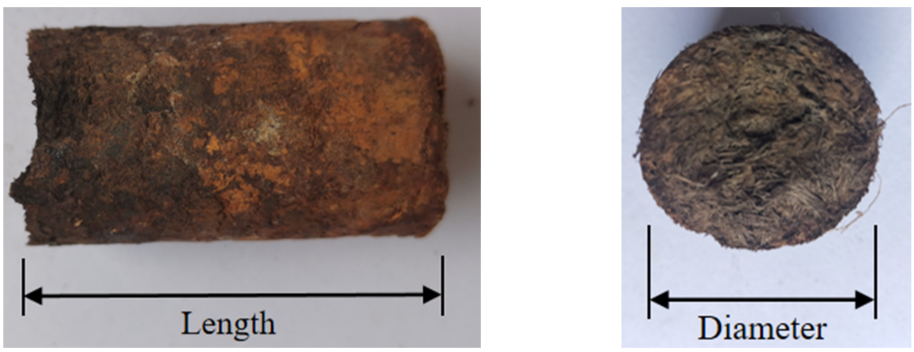
The straws were cut into pellets with a length of 30–90 mm by a hay cutter, and the straws were sealed in plastic bags and weighed. To achieve the moisture content of the test conditions, the amount of added water was calculated based on the moisture content and weight of the straw. Water was added to the straw to make the moisture content meet the test conditions, then the samples were selected to be dried in automatic program-controlled oven and weighed, in order to verify whether the moisture content of the straw was the same as the test conditions.

During the production of briquette, the temperature was changed by adjusting the electric heating wire. Simultaneously, the clearance between die and roller was changed by the clearance regulating mechanism of die and roller of briquetting machine. The briquetting machine was driven by an electric motor, so the spindle speed of the briquetting machine was controlled by adjusting the motor speed with a frequency converter. The structure and production processes of the press are portrayed in Figure 3.

Figure 3. Schematic diagram of the briquetting process: (**a**) Electric heating tubes; (**b**) Dry straw; (**c**) Cut straw; (**d**) Briquetting machine; (**e**) Conveyor belt; (**f**) Briquette; (**g**) Motor; (**h**) Variable-frequency drive.

3.2.1. Measuring Method of Relaxed Density

Relaxed density refers to the density of the briquette when it tends to be constant after the density decreases due to the action of internal stress and external elastic deformation. According to Chinese agricultural industry standard NY/T 1881.7-2010 "Biomass Solid Molding Fuel Test Method", the method for measuring the relaxed density of straw briquettes is as follows: The briquette was naturally air-dried for 24 h after production, the electronic scale was used to measure the mass of the briquette, and the size of the briquette was measured with the vernier caliper (the length of the briquette was measured twice with a vernier caliper, the diameter of the briquette was measured six times with a vernier caliper, and both ends and the middle of the briquette were measured twice each) [26]. The briquette produced by the briquetting machine is portrayed in Figure 4.



(**a**) (**b**)

Figure 4. Size of the briquette: (**a**) Length of the briquette; (**b**) Diameter of the briquette.

Then the relaxed density of the briquette was calculated by Equation (1).

$$Y_1 = \frac{m}{V} = \frac{4m}{D_m^2 \pi L} \quad (1)$$

where Y_1 is the relaxed density of briquette, g/cm^3; m is the mass of the briquette, g; D_m is the average diameter of the briquette, cm; L is the length of the briquette in cm.

3.2.2. Measuring Method of Impact Resistance

The durability of the briquette reflects the ability of the briquette to withstand loads during transportation and storage. The durability of a briquette mainly includes impact resistance, compression resistance, water absorption resistance, and water permeability. Generally, the straw briquette with good compactness has good compressive resistance and water absorption. In addition, there is no unified standard to measure the impermeability of the briquette, so this paper studies the impact resistance of briquette. The impact resistance of rice straw briquette was measured by the following method: the briquettes with a length of 60~100 mm were freely dropped from 2 m height to the concrete floor, then the briquettes with a diameter of more than 25 mm in the falling briquette were dropped again three times.

The impact resistance of the briquette was expressed by the percentage of the mass of the crushed briquette whose diameter is still greater than 25 mm to the original briquette. Then the impact resistance of briquette was calculated by Equation (2).

$$Y_2 = \frac{m_1}{m_2} \times 100\% \quad (2)$$

where Y_2 is the impact resistance of briquette, %; m_1 is the mass of briquette with particle size greater than 25 mm after falling, g; m_2 is mass of the briquette before falling in g.

3.3. Experiment Design and Method

3.3.1. Orthogonal Experiment

According to the factors in the design of the experiment, the test conditions were changed, the relaxed density and impact resistance of the corresponding briquette were measured, and the effect of each factor on the response was analyzed. By establishing the regression model of the response, the optimal process conditions for producing briquettes were discovered.

In the work of this paper, the design-Expert experimental software (Statistical Company, Minneapolis, MN, USA) used to study the parameters for preparing briquette was originally developed by Box and Wilson [27]. Box Behnken Design (BBD) was often used in experiments where the nonlinear effects of factors needed to be studied. In the study, BBD was used to optimize process parameters for the preparation of fuel particles [28]. The advantage of Box Behnken Design (BBD) is that it does not need to conduct multiple experiments continuously. When the number of factors is the same, the combination number of BBD is smaller than that of CCD, which is more economical and effective [29].

The four-factor and three-level orthogonal experiment was designed by Design-Expert software. The factors include moisture content (A); molding temperature (B); clearance between die and roller (C); spindle speed (D). The relaxation density (Y_1) and impact resistance (Y_2) are the responses. The three quantities 1, 0, and -1 represent the three levels of the independent variable, respectively. The coding test factors and levels of independent variables were portrayed in Table 2.

Table 2. Factor level table.

Levels	Factors			
	A %	B °C	C mm	D R/min
1	25	90	4	180
0	20	85	3	165
−1	15	80	2	150

A: moisture content, B: temperature, C: clearance between die and roller, D: spindle speed.

3.3.2. Data Analysis Methods

RSM uses a regression equation as a function estimation tool to determine the influence of each factor on each response under the separate action and interaction, expressing the relationship between the factor and the response value accurately and intuitively [30]. RSM is used to study the influencing factors of lignite coal quality, which can effectively distinguish the degree and difference of the influence of each factor [31]. The quadratic polynomial regression equation was a commonly used model in RSM, and its effectiveness in particle fuel optimization has been proven by many studies [32,33].

4. Results and Discussion

4.1. Results of Orthogonal Experiment

Twenty-nine tests were carried out according to the test conditions designed by design-Expert software to measure the relaxed density and impact resistance of the produced briquette. The results are displayed in Table 3.

Table 3. Orthogonal testing program and results.

	Factors				Variables	
Test No.	A %	B °C	C mm	D r/min	Y_1 g/cm^3	Y_2 %
1	15	90	3	165	0.963	55
2	15	85	3	180	1.027	64
3	15	85	4	165	0.979	56
4	15	85	3	150	0.912	52
5	15	80	3	165	0.881	44
6	15	85	2	165	0.821	46
7	20	90	3	150	0.919	50
8	20	90	2	165	0.855	49
9	20	85	3	165	1.132	74
10	20	90	3	180	1.009	62
11	20	85	3	165	1.145	76
12	20	85	3	165	1.168	69
13	20	85	2	150	0.902	50
14	20	80	4	165	0.969	55
15	20	85	3	165	1.107	68
16	20	80	3	150	0.928	49
17	20	85	2	180	1.075	64
18	20	85	3	165	1.109	78
19	20	90	4	165	0.985	56
20	20	80	3	180	1.018	66
21	20	80	2	165	0.872	42
22	20	85	4	180	1.035	62
23	20	85	4	150	0.945	53
24	25	90	3	165	1.014	62
25	25	85	4	165	0.965	53
26	25	85	3	150	1.091	69
27	25	85	2	165	0.858	52
28	25	80	3	165	1.012	60
29	25	85	3	180	1.020	66

The residual normal distribution of the test results is portrayed in Figure 5. The relaxed density was in the range of 0.821 to 1.168 g/cm^3, and the impact resistance was in the range of 42 to 78%. Except for individual data, the overall distribution of test results was reasonable.

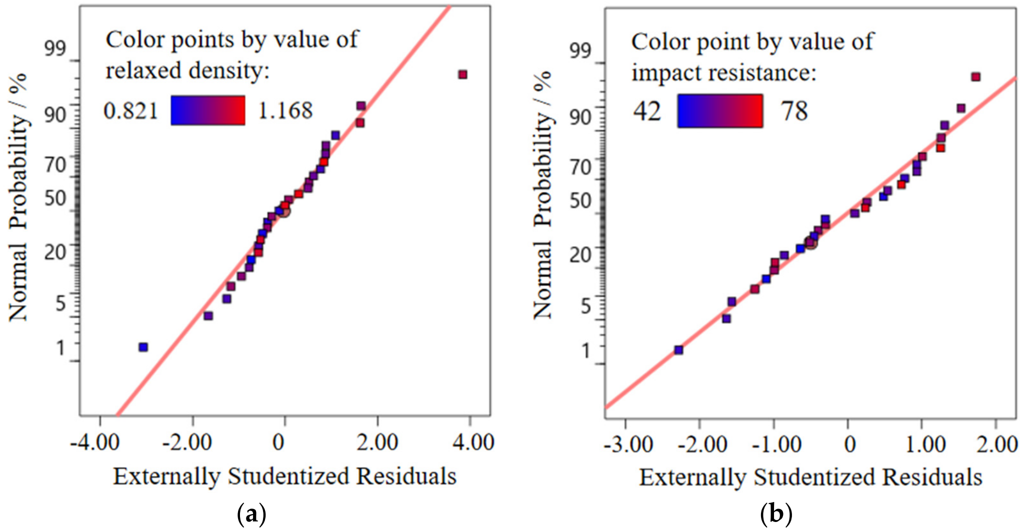


Figure 5. Normal plot of residuals of relaxed density and impact resistance: (**a**) relaxed density; (**b**) impact resistance.

4.2. Regression Model of Relaxed Density and Impact Resistance

According to the data samples of test results in Table 4, the regression model of the relaxed density and impact resistance obtained according to the Design Expert 12 software is in the form of Equation (3):

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 AB + \beta_6 AC + \beta_7 AD + \beta_8 BC + \beta_9 CD + \beta_{10} A^2 + \beta_{11} B^2 + \beta_{12} C^2 + \beta_{13} D^2 \quad (3)$$

Table 4. Coefficients in terms of coded factors.

	Relaxed Density (Y_1)			Impact Resistance (Y_2)		
	β_i	Std Err	p Value	β_i	Std Err	p Value
Intercept	1.13	0.0212	0.0005	73	2.03	0.0002
A	0.0314	0.0137	0.0375	3.75	1.31	0.0127
B	0.0054	0.0137	0.698	1.5	1.31	0.2723
C	0.0412	0.0137	0.0092	2.67	1.31	0.0616
D	0.0406	0.0137	0.0102	5.08	1.31	0.0017
AB	−0.02	0.0237	0.4126	−2.25	2.27	0.3391
AC	−0.0127	0.0237	0.5988	−2.25	2.27	0.3391
AD	−0.0465	0.0237	0.0698	−3.75	2.27	0.1213
BC	0.0083	0.0237	0.7328	−1.5	2.27	0.5201
BD	0	0.0237	1	−1.25	2.27	0.5911
CD	−0.0208	0.0237	0.3958	−1.25	2.27	0.5911
A^2	−0.0838	0.0186	0.0005	−7.33	1.79	0.0011
B^2	−0.0986	0.0186	0.0001	−10.96	1.79	<0.0001
C^2	−0.1191	0.0186	<0.0001	−12.46	1.79	<0.0001
D^2	−0.0416	0.0186	0.0421	−3.83	1.79	0.0498

A: moisture content, B: temperature, C: clearance between die and roller, D: spindle speed. Note: numbers in bold print are statistically significant.

The coding coefficients of the test factors are displayed in Table 4.

Quadratic polynomial regression models for relaxed density (Y_1) and impact resistance (Y_2) were built based on experimental data.

$$Y_1 = 1.13 + 0.0314 \times A + 0.0054 \times B + 0.0412 \times C + 0.0406 \times D - 0.02 \times A \times B - 0.0127 \times A \times C \\ -0.0465 \times A \times D + 0.0083 \times B \times C - 0.0208 \times C \times D - 0.0838A^2 - 0.0986 \times B^2 - 0.1191 \times C^2 - 0.0416 \times D^2 \quad (4)$$

$$Y_2 = 73 + 3.75 \times A + 1.5 \times B + 2.67 \times C + 5.08 \times D - 2.25 \times A \times B - 2.25 \times A \times C - 3.75 \times A \times D \\ -1.5 \times B \times C - 1.25 \times B \times D - 1.25 \times C \times D - 7.33 \times A^2 - 10.96 \times B^2 - 12.46C^2 - 3.83 \times D^2 \quad (5)$$

4.2.1. Analysis of Variance for Regression Model of Relaxed Density

The mathematical equations obtained by fitting functions into experimental data may produce inaccurate results [29]. Therefore, according to previous research, it is necessary to use analysis of variance (ANOVA) to test the significance and accuracy of models [27]. The results of variance analysis of the relaxed density regression model are presented in Table 5. When the p value is less than 0.05, it means the model terms are very important. The F-value obtained a lower p value ($p < 0.05$), which means that the model is significant, and the lack of fit of the model being insignificant indicates that the equation fits well to the experiment. In the regression model of relaxed density, the significant terms were A, C, D, A^2, B^2, C^2, and D^2. Moisture content, temperature, and clearance between die and roller and spindle speed factors such as the regression model of p values were 0.0375, 0.698, 0.0092, and 0.0102. The order of influence of various factors on the relaxed density of briquette were as follows: clearance between die and roller (C) > spindle speed (D) > moisture content (A) > temperature (B). The temperature did not reach a noteworthy level, indicating that it did not have a large effect on the relaxed density.

Table 5. Analysis of variance (ANOVA) results for relaxed density.

Source	Sum of Squares	df	Mean Square	F-Value	p Value	
Model	0.2129	14	0.0152	6.78	0.0005	significant
A	0.0118	1	0.0118	5.28	0.0375	
B	0.0004	1	0.0004	0.1569	0.698	
C	0.0204	1	0.0204	9.1	0.0092	
D	0.0198	1	0.0198	8.81	0.0102	
AB	0.0016	1	0.0016	0.7131	0.4126	
AC	0.0007	1	0.0007	0.2898	0.5988	
AD	0.0086	1	0.0086	3.85	0.0698	
BC	0.0003	1	0.0003	0.1213	0.7328	
BD	0	1	0	0	1	
CD	0.0017	1	0.0017	0.7675	0.3958	
A^2	0.0456	1	0.0456	20.32	0.0005	
B^2	0.0631	1	0.0631	28.1	0.0001	
C^2	0.092	1	0.092	41	<0.0001	
D^2	0.0112	1	0.0112	5	0.0421	
Residual	0.0314	14	0.0022			
Lack of Fit	0.0288	10	0.0029	4.4	0.0831	not significant
Pure Error	0.0026	4	0.0007			
Cor Total	0.2443	28				

A: moisture content, B: temperature, C: clearance between die and roller, D: spindle speed. Note: p values less than 0.0500 indicate model terms are significant.

4.2.2. Analysis of Variance for Regression Model of Impact Resistance

The results of variance analysis of the impact resistance density regression model are portrayed in Table 6. The p value was equal to 0.0002 (<0.05 indicates that the model is significant), indicating that the model of quadratic equation is marked. The significance test of regression analysis of variance indicated that the regression of the model was remarkable and the lack of fit was not noticeable, indicating that the equation fits well to the experiment. In the regression model of relaxed density, the significant terms were A, D, A^2, B^2, C^2, and D^2. Moisture content (A), temperature (B), clearance between die and roller (C), and spindle speed (D) of the regression model of the *p* values was 0.0127, 0.2723, 0.0616, and 0.0017. The order of influence of various factors on the impact resistance of briquette was as follows: spindle speed (D) > moisture content (A) > clearance between die and roller (C) > temperature (B). The temperature and clearance between die and roller did not reach a noteworthy level, indicating that it did not have a large effect on the impact resistance.

Table 6. Analysis of variance (ANOVA) results for impact resistance.

Source	Sum of Squares	df	Mean Square	F-Value	*p* Value	
Model	2304.79	14	164.63	7.96	0.0002	significant
A	168.75	1	168.75	8.16	0.0127	
B	27	1	27	1.31	0.2723	
C	85.33	1	85.33	4.13	0.0616	
D	310.08	1	310.08	15	0.0017	
AB	20.25	1	20.25	0.9796	0.3391	
AC	20.25	1	20.25	0.9796	0.3391	
AD	56.25	1	56.25	2.72	0.1213	
BC	9	1	9	0.4354	0.5201	
BD	6.25	1	6.25	0.3023	0.5911	
CD	6.25	1	6.25	0.3023	0.5911	
A^2	348.83	1	348.83	16.87	0.0011	
B^2	778.93	1	778.93	37.68	<0.0001	
C^2	1006.77	1	1006.77	48.7	<0.0001	
D^2	95.32	1	95.32	4.61	0.0498	
Residual	289.42	14	20.67			
Lack of Fit	213.42	10	21.34	1.12	0.4957	not significant
Pure Error	76	4	19			
Cor Total	2594.21	28				

4.2.3. Analysis of the Model

The quality analysis of the two models is displayed in Table 7. In design-Expert software analysis and related studies, an Adeq Precision value greater than 4 is considered ideal [29,32].

Table 7. RSM model fit summary output for relaxed density and impact resistance.

Parameter	Mean	Std. Dev.	R^2	Adj R^2	C.V.%	Adeq Precision
Relaxed density (Y_1)	0.9902	0.0474	0.8714	0.7429	4.78	8.4645
Impact resistance (Y_2)	58.69	4.55	0.8884	0.7769	7.75	8.8941

The coefficients of determination (R^2) were 0.8714 and 0.8884, and the corrected coefficients of determination (Adj R^2) were 0.7429 and 0.7769, respectively. It was concluded that the regression equation was in good agreement with the experimental values, and the model can reflect the experimental data well. In this study, the Adeq Precision values of relaxed density and impact resistance were 8.4645 and 8.8941, respectively, indicating sufficient signal. In conclusion, the model proposed in this paper was effective. The coefficients of variation of the two models were 4.78% and 0.96% respectively, indicating that the regression models of relaxed density and impact resistance were reliable.

Figure 6 presents the comparison between the test results and the predictive results of the model. The value of the abscissa of each point was the test result, and the value of the ordinate was the predicted value. A point near the line meant that the experimental value was closer to the predictive value. It can be observed from Figure 6 that the error between the test results and the predictive results of the model was small, and the predictive model can better reflect the test results.

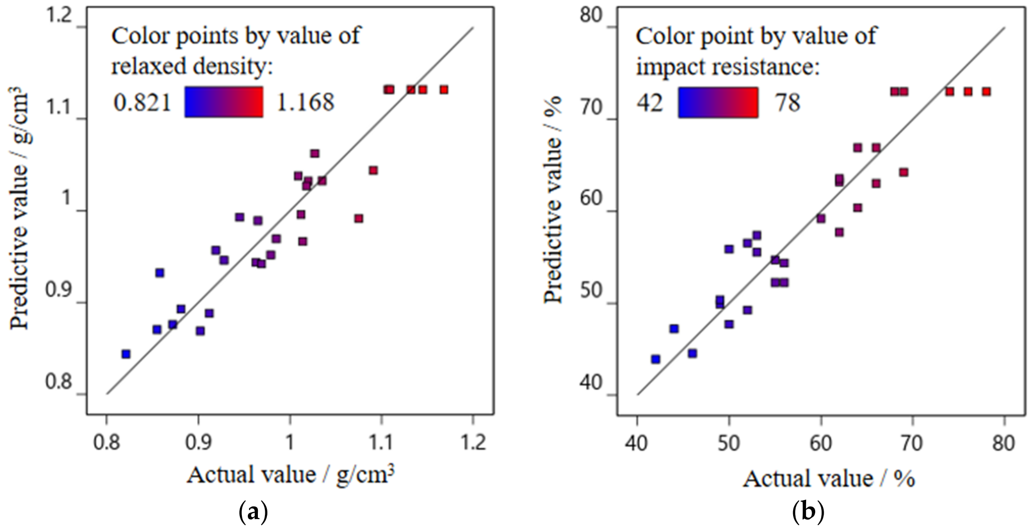


Figure 6. Relationship between experimental and predicted value: (**a**) relaxed density; (**b**) impact resistance.

4.3. Optimum Conditions for Producing High Quality Briquette

According to the results of the orthogonal test, Figure 7 presents the effect of the interaction of various factors on the relaxed density of briquette. In order to make the relaxed density of briquette above the optimal value of 1.1 g/cm^3, it was necessary to ensure that the test factors were as follows: moisture content was 17.7~23.9%, molding temperature was 82~87.8 °C, clearance between die and roller was 2.6~3.7 mm, and spindle speed was more than 157 r/min.

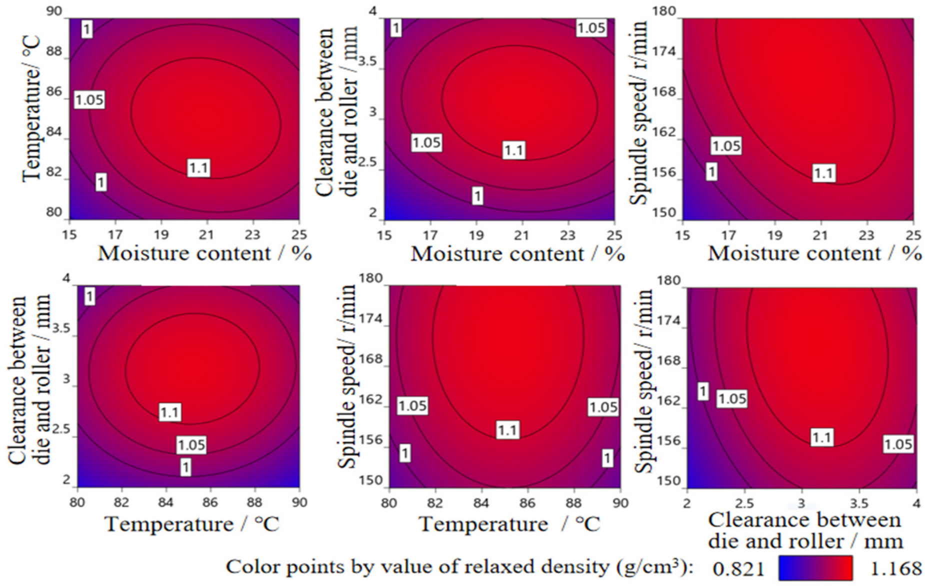


Figure 7. Contour sheet of relaxed density.

Figure 8 presents the effect of the interaction of various factors on impact resistance of briquette, in order to make the impact resistance reach the optimal value of more than 70%, the factors should be ensured as follows: moisture content is 17.6~24.8%, molding temperature is 82.5~87.8 °C, clearance between die and roller is 2.55~3.6 mm, and spindle speed should exceed 159 r/min.

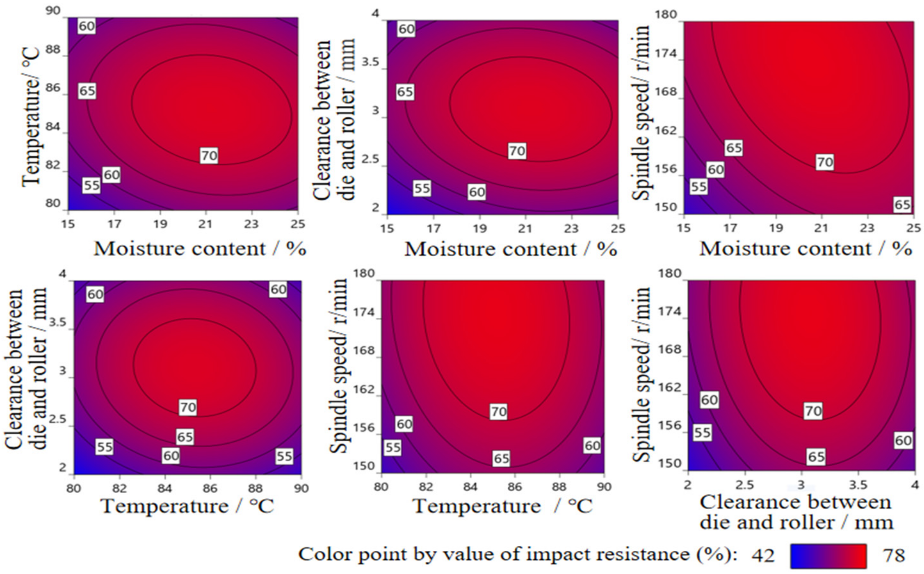


Figure 8. Contour sheet of impact resistance.

Through the optimization function in the Design–Expert software, the optimal variable parameters were solved under the condition of the maximum relaxed density and impact resistance as displayed in Figure 9.

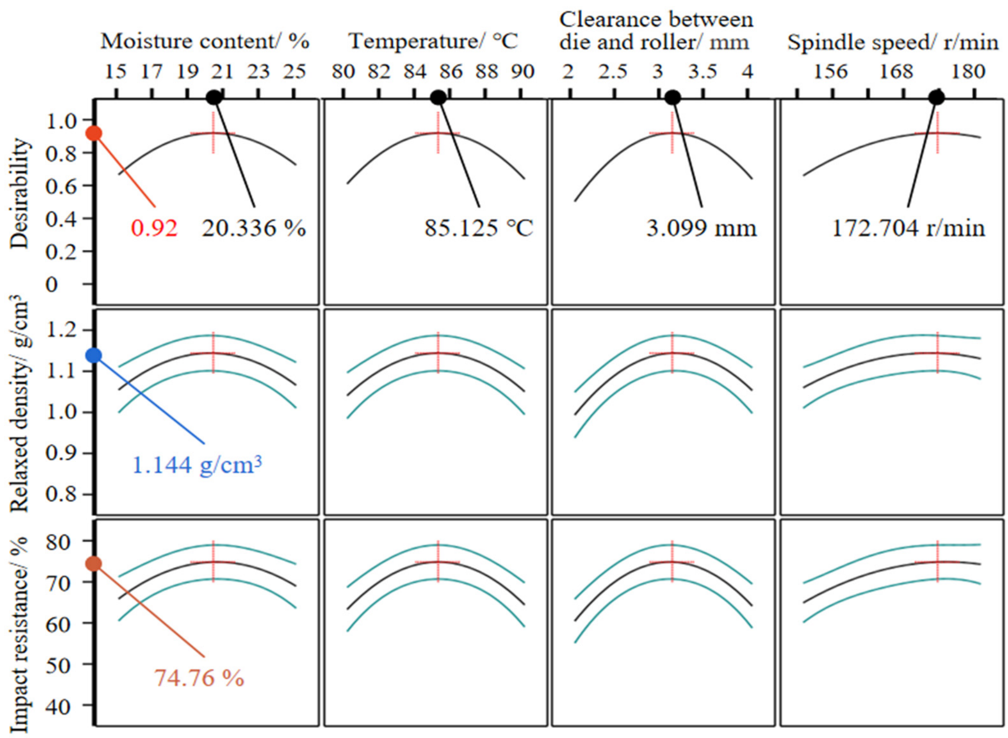


Figure 9. The result of the optimization of the Design-Expert software.

The results concluded that moisture content was 20.336%, temperature was 85.125 °C, clearance between die and roller was 3.099 mm, and spindle speed was 172.704 r/min. The maximum relaxed density of the briquette was 1.144 g/cm^3 and the maximum impact resistance was 74.76%. In previous studies, particle density of briquettes ranged from 1030 to 1290 kg/m^3 [7]. The briquette with a density of 1.011 g/cm^3 meets the agricultural industry standard of China NY/T 1882–2010 and NY/T 1883–2010 [26].

To verify the accuracy of the factor values solved by the Design-Expert software, the optimized results were used to produce briquettes for the test parameters. The results of the relaxed density and impact resistance of the briquette are presented in Table 8. The optimal process parameters predicted can make the average relaxed density of the briquette up to 1.143 g/cm^3, and the average impact resistance of the briquette up to 74%. The average error between the measured value and the predictive value of the relaxed density of the briquette was 0.1056%, for the impact resistance, the average error was 1.0636%, it indicated that predictive value was in good agreement with the measured value. Under the optimized experimental combination conditions, both the impact resistance and the relaxed density of the briquette can reach a large value.

Table 8. Relaxed density and crush resistance of briquettes based on optimal process parameters.

Relaxed Density Y_1 (g/cm^3)			**Impact Resistance Y_2 (%)**		
Predictive Value	**Actual Value**	**Error %**	**Predictive Value**	**Actual Value**	**Error %**
	1.139	0.439		74	1.027
	1.147	−0.262		73	2.410
1.144	1.140	0.351	74.76	75	−0.320
	1.146	−0.175		76	−1.632
	1.142	0.175		72	3.833
Average value	1.143	0.1056		74	1.0636

5. Conclusions

In this paper, the effects of factors of the quality of the briquette were studied, and it was discovered that the moisture content, the clearance between die and roller, and the spindle speed had significant effects on the relaxed density of the briquettes, and the moisture content and the spindle speed had significant effects on the impact resistance of the briquettes. The order of influence of various factors on the relaxed density of briquettes is as follows: clearance between die and roller > spindle speed > moisture content > temperature. The order of influence of various factors on the impact resistance of briquettes is as follows: spindle speed > moisture content > clearance between die and roller > temperature. The test factors were as follows: moisture content reaches 17.7~23.9%, molding temperature reaches 82.5~87.8 °C, clearance between die and roller is 2.6~3.6 mm, and spindle speed is greater than 159 r/min, and relaxed density and impact resistance of the briquette reached the optimal value of 1.1 g/cm^3 and more than 70%.

According to the regression model of the relaxed density and impact resistance of the straw briquette, the optimal parameters obtained by the regression model were moisture content 22.335%, temperature 85.127 °C, clearance between die and roller 3.099 mm, and spindle speed 172.712 r/min. Under these conditions, the maximum relaxed density and the maximum impact resistance of the briquette were 1.144 g/cm^3 and 74.76%, respectively. The experimental results indicate that the relative errors of the maximum relaxed density and the maximum impact resistance of the briquette were 0.263% and 1.678%, respectively, compared with the predictive maximum values. Therefore, the regression model equation established can be used to predict the relaxed density and impact resistance of the briquettes.

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