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Design and Key Parameter Optimization of Conic Roller Shelling Device Based on Walnut Moisture-Regulating Treatments

Jiannan Wang [1,2], Minji Liu [1], Huichang Wu [1], Jinyi Peng [2], Baoliang Peng [1], Yanshan Yang [1], Minzhu Cao [1], Hai Wei [1] and Huanxiong Xie [1,*]

[1] Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China; wangjiannan@caas.cn (J.W.); liuminji@caas.cn (M.L.); wuhuichang@caas.cn (H.W.); pengbaoliang@caas.cn (B.P.); yang_yan_shan@163.com (Y.Y.); caomingzhu@caas.cn (M.C.); weihai@caas.cn (H.W.)
[2] College of Engineering, Nanjing Agricultural University, Nanjing 210000, China; 9213020314@stu.njau.edu.cn
* Correspondence: xiehuanxiong@caas.cn

Abstract: The quality of walnuts deteriorates owing to the poor quality of the shelling equipment. The improvement of shelling quality is urgently required for walnut processing. In this study, systematic research was carried out on the changes in walnut mechanical properties, mechanical model of walnut shelling, and the key parameters of the equipment. The key parameters were determined as the angles of the shelling conic roller (X_1), speeds of the shelling conic roller (X_2), clearance between the shelling conic roller and the static roller (X_3), and the moisture content of walnuts (X_4). The Box–Behnken design method was used for the experimental design, an analysis of variance was applied to determine the graded significance of each variable on the rate of high-quality kernel (RHQK) and rate of shell rushing (RSC), and the multi-objective optimization method was used to obtain the optimal parameters for RHQK and RSC. The ranking of factors affecting RHQK and RSC were: (X_3) > (X_4) > (X_2) > (X_1) for RHQK, and (X_2) > (X_3) > (X_4) > (X_1) for RSC. The ranks of significant interactive effects among the factors were as follows: (X_1 X_2) > (X_2 X_3) for RHQK and (X_2 X_3) > (X_3 X_4) > (X_2 X_4) for RSC. The multi-objective optimization results showed that the optimal combination was X_1 = 15.83°, X_2 = 17.93 rpm, X_3 = 45 mm, and X_4 = 9.5%, yielding RHQK = 84.54%, and RSC = 99.15%. The verification test of the optimal results further illustrates the accuracy of the optimization. The obtained results showed that the quality of walnut shelling can be improved by adjusting the moisture content of walnuts and optimizing key parameters of the equipment. This method also represents a potential solution for improving the shelling quality of other nuts.

Keywords: agricultural machinery; walnut shelling; optimization

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1. Introduction

Walnuts are the most widely planted nuts worldwide [1]. They are rich in vitamins B and E, unsaturated fatty acids, tocopherols, phytosterols, flavonoids, etc., and the content of monounsaturated fatty acids and polyunsaturated fatty acids is the highest in the nut world [2–5]. It has obvious advantages in reducing cholesterol, preventing cardiovascular diseases, and is deeply welcomed by consumers. In 2020, the global planting area was approximately 1.3 million hectares, and the total export volume reached 4.42 million tons [6]. China, the United States, and Turkey are the three major countries that grow walnuts in the world [7]. China is the world's largest producer of walnuts. According to the official website of the FAO, in 2020, China's walnut planting area was 284,375 ha, with a total output of 110 million tons, accounting for 25% of the world's total output [6].

Walnut shelling is the key step in the walnut food industry. At present, walnut shelling technology and equipment still have the characteristics of a low rate of high-quality kernels (RHQK) and a poor rate of shelling crushing (RSC) [8]. Damaged nuts not only cause great losses and reduce the economic benefits of walnuts, but also affect the quality of the walnuts and their products, which poses a great threat to food safety [9]. As the walnut shell is mainly composed of lignin, cellulose, and hemicellulose, it is hard and thick, irregular in shape, with multiple partitions and a small gap between the shell and the kernel, which results in a difficult shelling process, slow development of walnut shelling machinery, and poor shelling quality. For a long time, China, Turkey, and other main walnut-growing countries have sold walnuts with shells, high transportation costs, and low added value of products [10]. Presently, the processing rate of walnuts in Xinjiang, the main walnut-producing area in China, is only 2% [11]. Consequently, the development of the walnut industry has been seriously restricted by the progress in shelling technology and equipment. Therefore, high-quality mechanized shelling of walnuts has become a trending issue worldwide.

Numerous studies have been conducted to obtain high-quality shelling. Ercisli, et al., studied the variety, edge length, and thickness of walnut; analyzed the influence law of these factors on walnut shelling; and obtained the force direction of the minimum rupture force [12]; Khir, et al. studied the characteristics of walnut size and moisture content, and revealed the law of walnut shell rupture [13]. Using a mechanical testing device, Sharifian et al. reported that the force loading speed, moisture content, and loading direction had a significant impact on the rupture of walnut shells and concluded that the best shelling results appeared with the moisture content of walnut at 21%, and a loading speed of 500 mm/min along the X direction [14]. Koyuncu et al. studied the force, energy, and specific deformation before initial rupturing and kernel extraction quality by compressing walnuts with a universal testing machine and found that cracking nuts at the length position required less force and yielded the best kernel extraction quality [15]. Li et al. designed a model of a conic basket walnut shelling device, carried out the relevant tests, and determined that the clearance of the shelling device, conic angle of the roller, walnut size, and walnut shell thickness were the key parameters affecting the shelling quality [16]. Wang et al. studied the influence of key parameters of a conic basket shell-breaking equipment on the operation quality by using an orthogonal test, obtained the optimal parameters of the fixed cylinder speed, distance between the fixed cylinder and the moving cylinder, and the shelling operation quality under the best parameters [17]. Liu et al. studied the mechanism of walnut shelling by shear extrusion using a flexible belt and designed a belt sheller for walnuts. Taking belt spacing, the speed difference between the two belts, and the extrusion angle as the key operation parameters, they carried out a single-factor test and an orthogonal test and obtained the optimal parameters of this type of belt-shelling equipment [18]. Wang et al. studied the characteristics of a walnut crack based on the finite element method using a workbench, compared the results with the experimental method, and obtained the best direction of force for walnut cracking [19].

Walnut shelling is the interaction between the key components of shelling equipment and walnut materials. The shelling process involves complex mechanisms and mutual mechanics. Existing research mostly separates the physical characteristics of walnut and the mechanical key parameters, but systematical studies, and optimization of multiple factors including the physical characteristics of walnut and parameters of the machinery are seldom seen. However, the mechanical analysis of the shelling process and physical characteristics of walnuts were not mentioned. Consequently, the separation between agricultural machinery and walnut agronomic characters has led to a slow improvement in walnut shelling machinery, resulting in a low profit for walnut farmers, which is a fatal blow to the development of the walnut industry in China. Therefore, the improvement of the shelling quality of walnut shellers is an urgent issue. To improve the shelling quality, it is necessary to systematically combine the analysis of the mechanical properties of walnut shells, research on the mechanical properties of walnuts, parameter design and optimization of key components, and mutual coupling effects of the factors on RHQK and RSC. However, tremendous experiments must be carried out while considering these factors together and studying them systematically, which costs a lot of time.

In this study, a key component of the walnut shelling device was designed based on the principle of friction extrusion. First, we assumed the mechanical extrusion model of walnut shelling, then analyzed the mechanics between the walnut and the key components to obtain reasonable parameters for the conic roller. It was assumed that the application of the Box–Behnken design (BBD) method would help simplify the complexity of the experiment and enable us optimize the system in affordable laboratory work. The Box–Behnken test was used to design the walnut shelling experiment, and the multi-objective optimization method was used to optimize the key parameters affecting the shelling quality, obtain the best quality of walnut shelling operation, and provide a reference for improving the operation quality of walnut shelling equipment.

2. Materials and Method

2.1. Walnut Sample Preparation

The walnuts that were used in this study were Wen185 varieties that are widely planted in Xinjiang Province, which is the main walnut-producing area in China. The walnut was ellipsoidal in shape with an average length of 4.7 cm, thickness of 3.7 cm, and width of 3.7 cm. The length, width and thickness are shown in Figure 1. A total of 100 walnuts were randomly selected and tested, and the average single walnut weight was 15.8 g, the average shell thickness was 0.8 mm, and the kernel yield of walnut was 65.9% by manual shelling. The initial average moisture content of the walnuts was determined to be 16.95% (w.b.), following the standard for oilseeds [20].

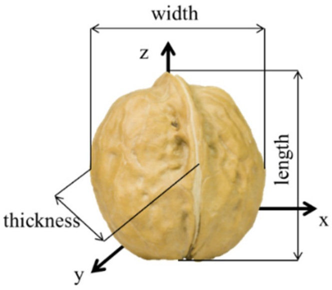


Figure 1. Diagram of length, width, and thickness.

2.2. Mediating Moisture Contents of Walnuts and Mechanical Property Test

To study the mechanical properties of walnuts with different moisture contents, it is necessary to adjust their moisture content. This implies that for practical applications, a scheme involving wetting adjustment should be devised. Distilled water was sprayed on the walnuts (ASAE standards, 1999), which were then sealed in plastic bags and homogenized for 12 h at 5 °C. The amount of water (Q_w) that was added to the samples was calculated using Equation (1) (Kumar et al., 2016).

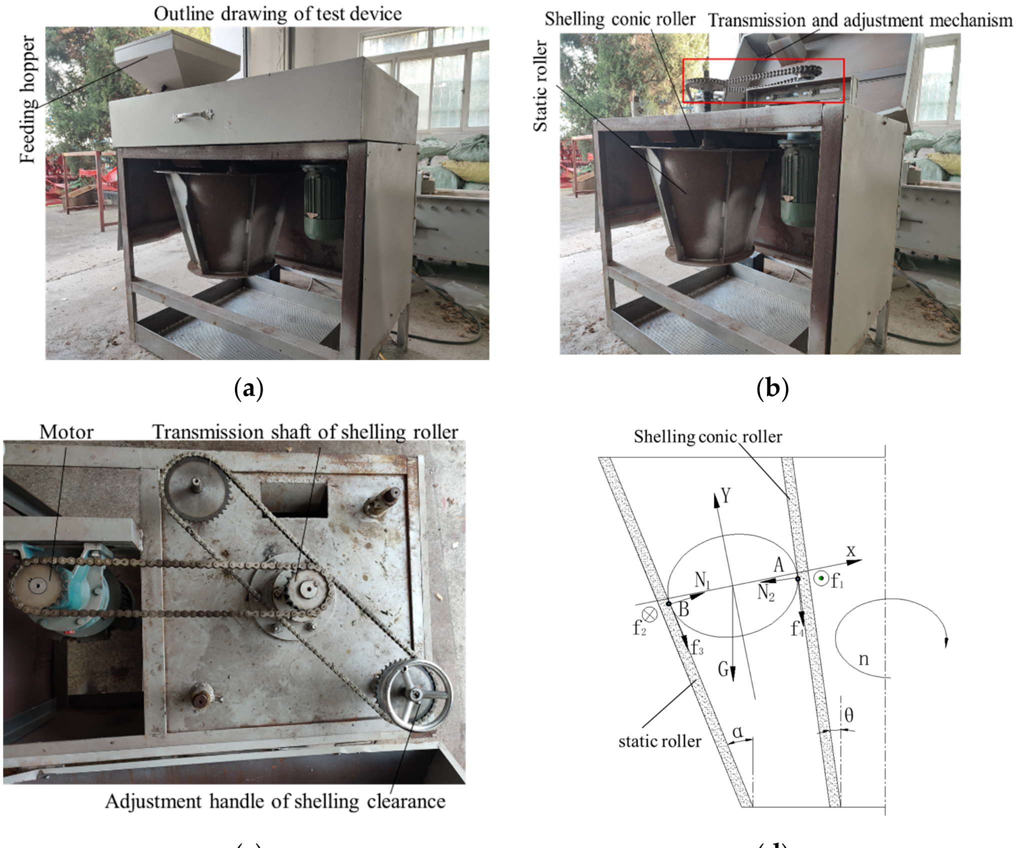
$$Q_w = Q_P(M_f - M_i)/(100 - M_f) \tag{1}$$

where Q_w is the mass of the added distilled water (kg), Q_p is the initial mass of the walnut sample (kg), M_f is the final dry basis moisture content of the sample, and M_i is the initial dry basis moisture content.

Rupture forces were tested using a universal mechanical testing machine (CTM-4503, Sansi Testing Technology Co., Ltd., Shenzhen, China). The walnut was positioned in alignment with the central point of the lower pressure plate. The upper plate was set to touch the top of the walnut. The feeding speed of the applied load was 5 mm·min^{-1}. The stress-strain relationships of walnuts with different moisture contents were plotted during the test.

2.3. Mechanical Analysis of Walnut Shelling

The conic roller-shelling device is mainly composed of a shelling conic roller and a static roller, as presented in Figure 2a. Figure 2b,c show the shelling prototype. The walnuts enter the clearance between the shelling conic roller and the static roller, driven by the rotation of the shelling conic roller, and are rubbed and squeezed by the static and shelling conic roller to break the shell and release the nut shelling. In order to meet the requirements of the study, the required speed of the shelling conic roller can be obtained by the adjustment of a frequency converter, and the gap between the shelling conic roller and the static roller can be adjusted through the transmission and adjustment mechanism as showed in the red rectangle in Figure 2b.



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

(**c**) (**d**)

Figure 2. (**a**) Outline drawing of the test device, (**b**,**c**) introduction of the shelling prototype, (**d**) mechanical model of walnut shelling. Note: In Figure 2d, ⊙ indicates the direction of the force is perpendicular to the paper and outwards, and ⊗ indicates the opposite direction to ⊙.

To select reasonable key parameters and optimize the design, a stress analysis of the walnut shelling process was carried out first. The walnut was assumed to be an ellipsoid based on the basic parameters of walnuts in Section 2.1, and the coordinate system was established with the long axis and short axis of the ellipsoid as the x-axis and y-axis, respectively. The mechanical model of the walnut shelling analysis diagram is shown in Figure 2d.

In Figure 2d, A and B are the contact points of the walnut with the shelling conic and static rollers, respectively. Assuming that the walnut was in equilibrium at the moment of shell rupture:

$$G = mg \tag{2}$$

$$N_1 + G\sin\theta - N_2\cos(\alpha - \theta) = 0 \tag{3}$$

$$N_2\sin(\alpha - \theta) - G\cos\theta - f_s = 0 \tag{4}$$

$$N_1 = (\Delta V_1/V) \times E \tag{5}$$

$$N_2 = (\Delta V_2/V) \times E \tag{6}$$

$$f_1 = N_1 \times \mu \tag{7}$$

$$f_2 = N_2 \times \mu \tag{8}$$

$$\sum M = (f_1 + f_2) \times \frac{D}{2} \tag{9}$$

where, m is the mass of a walnut, g; g is the acceleration due to gravity, m·s^{-2}; N_1 is the elastic force of the contact surface when the walnut is in contact with the static roller, N; N_2 is the elastic force of the contact surface when the walnut is in contact with the shelling conic roller, N; θ is the included angle between the conical surface of the shelling conic roller and the vertical plane, °; α is the included angle between the static roller and the vertical plane, °; f_1 is the friction force of shelling conic roller on walnut, N; f_2 is the friction force of the static roller on the walnut, N; V is walnut volume, m^3; ΔV_1 is volume deformation of the walnut in contact with the static roller, m^3; ΔV_2 is volume deformation of the walnut in contact with the shelling conic roller, m^3; μ is the dynamic friction factor between the walnut and the shelling conic roller; E is the elastic modulus of the walnut; M is the moment of the walnut, n·m; D is the diameter of the walnut, m; and f_s is the static friction.

The total deformation of walnut is:

$$\Delta V = \Delta V_1 + \Delta V_2 \tag{10}$$

The volumetric strain of walnut is:

$$\delta = \Delta V/V \tag{11}$$

By combining Equations (2)–(7) and (10), we obtain:

$$N_1 = \frac{\delta G \cos(\alpha - \theta) - G \sin\theta}{1 + \cos(\alpha - \theta)} \tag{12}$$

$$N_2 = \frac{\delta G + g \sin\theta}{1 + \cos(\alpha - \theta)} \tag{13}$$

The elastic modulus of the walnut was 10 MPa, the average mass of the walnuts were calculated as 2.1 g, the dynamic friction factor between the walnut and the shelling conic roller μ was 0.23, and volume strain of walnut was 3.5×10^{-4} [16]. When the angles of the shelling conic roller and the static shelling conic roller are $\theta = 5°$ and $\alpha = 18°$, respectively, $N_1 = 153.7$ N, $N_2 = 146.3$ N, $f_1 = 38.9$ N, and $f_2 = 41.1$ N.

From the stress analysis, the walnut moves upward with an increase in force during the shelling process; therefore, the static friction force f_s is opposite to this trend, and $f_s = f_3 + f_4$. When designing the angle of the shelling conic roller θ, according to the characteristics of the sinusoidal function, the value of the sinusoidal function is more sensitive to the change in angle when the angle is small. This means that as θ is a very small angle, component $N_2 \sin(\alpha - \theta)$ will increase rapidly, and the static friction force f_s will not be sufficient to overcome the upward movement of the walnut; the walnut will move upward, and the shelling process will stop. When the θ value is too large, the change rate of the distance between the shelling conic roller and the static roller will decrease, and the range of walnut shell size that is suitable for the shelling device will become narrower, resulting in poor quality of the shelling operation.

Based on the above analysis, it is necessary to reasonably select the angle of the shelling conic roller and static roller of the shelling device. By calculating and combining the range of the walnut rupture force, the angle α of the static roller can be calculated as 16°, and the angle θ of the shelling conic roller will be greater than 5°.

2.4. Performance Evaluation

According to actual production needs and relevant standards, the RHQK and RSC of walnuts are important assessment indicators for shelling equipment. During the shelling test, three samples were taken randomly at the outlet of the walnut shelling equipment, and each sample was not less than 2 kg. Thereafter, walnuts with broken shells and high-quality kernels were manually selected. According to this standard, kernels that were greater than or equal to one-quarter are defined as high-quality kernels, as shown in Figure 3.


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

Figure 3. (**a**) Half-kernels of walnuts and (**b**) quarter-kernels of walnuts.

This test mainly examines the rate of high-quality kernels and the shell crushing rate of walnuts. The calculation method is as follows:

$$\lambda = \frac{w_1}{w_0} \times 100 \tag{14}$$

$$\beta = \frac{w_2}{w_3} \times 100\% \tag{15}$$

where w_0 is the total mass of the walnut sample, kg; w_1 is the mass of cracked walnut, kg; w_2 is the mass of high-quality kernel, kg; and w_3 is the total mass of walnut kernel, kg.

2.5. Single-Factor Tests

The angles of the shelling conic roller, speeds of the shelling conic roller, clearance between the shelling conic roller and the static roller, and the moisture content of walnuts are the key parameters of shelling devices. A reasonable test range of the key parameters is key to obtaining the optimum combination of parameters. The more accurate that the selection range of the key parameters is, the better the optimization effect and quality will be Section 2.2 indicated that the angle of the shelling conic roller is not less than 3°, but the optimal range of the angle and the other parameters need to be further clarified. A single-factor test was carried out on the walnut shelling process. In the single-factor test, other factors remained fixed. Each single-factor test was conducted five times, and the average value was recorded.

2.6. Box-Behnken Design

The Box–Behnken design is an experimental method that evaluates the nonlinear relationship between indicators and factors. It is widely used in the engineering field and is an economical experimental method for simplifying experiments [21,22]. The equations of test factors and response indicators were established according to the test results. The acquired workable range of each influential factor was further normalized to −1, 0, and 1, which corresponded to the lower limit, center point, and upper limit of the workable ranges. The number of BBD tests that were performed was:

$$N = 2k(k-1) + C_0 \tag{16}$$

where k is the number of factors, and C_0 is the number of repetitions of the central test point that is used in estimating the test error. The results of the BBD experimental scheme, based on Table 1, were obtained from Design-Expert 12 (version 12.0.3.0; Stat-Ease, Inc., Minneapolis, MN, USA), and presented in Table 2. With this simplification, the total experimental work was reduced to 29 runs with $C_0 = 5$.

Table 1. Experimental design for the optimization of RHQK and SRC.

Factors	**Levels**		
	−1	**0**	**1**
X_1: Angles of the shelling conic roller (°)	8	15	22
X_2: Speeds of the shelling conic roller (rpm)	15	18	21
X_3: Clearance between shelling conic roller and static roller (mm)	35	40	45
X_4: Moisture content of walnuts (%)	7.5	15	22.5

Table 2. Test scheme and results of the RSM experiments for RHQK and RSC.

Test No.	X_1	X_2	X_3	X_4	**RHQK** Y_1 **(%)**	**RSC** Y_2 **(%)**
1	−1.00	−1.00	0.00	0.00	39.68	77.59
2	−1.00	0.00	0.00	−1.00	62.86	80.62
3	0.00	−1.00	0.00	1.00	43.59	75.69
4	0.00	1.00	0.00	−1.00	64.21	63.58
5	−1.00	1.00	0.00	0.00	61.95	53.85
6	1.00	−1.00	0.00	0.00	53.24	78.59
7	0.00	0.00	1.00	−1.00	85.67	99.15
8	0.00	1.00	−1.00	0.00	63.78	44.67
9	1.00	1.00	0.00	0.00	51.29	58.34
10	0.00	−1.00	0.00	−1.00	54.01	95.65
11	0.00	0.00	0.00	0.00	61.84	68.94
12	0.00	0.00	−1.00	1.00	55.55	70.49
13	0.00	0.00	−1.00	−1.00	65.51	73.39
14	0.00	0.00	0.00	0.00	58.24	69.58
15	0.00	−1.00	1.00	0.00	68.52	85.79
16	0.00	1.00	0.00	1.00	54.63	59.75
17	0.00	0.00	0.00	0.00	57.98	68.94
18	−1.00	0.00	0.00	1.00	49.92	71.42
19	0.00	−1.00	−1.00	0.00	45.82	79.97
20	0.00	0.00	0.00	0.00	59.45	70.21
21	1.00	0.00	0.00	−1.00	63.34	82.68
22	1.00	0.00	0.00	1.00	53.2	68.46
23	1.00	0.00	1.00	0.00	75.78	80.62
24	0.00	0.00	0.00	0.00	59.45	65.84
25	−1.00	0.00	−1.00	0.00	56.08	63.02
26	0.00	0.00	1.00	1.00	71.79	79.73
27	−1.00	0.00	1.00	0.00	73.34	81.46
28	1.00	0.00	−1.00	0.00	58.6	64.06
29	0.00	1.00	1.00	0.00	74.6	72.73

2.7. Construction of System Optimization Model

To prepare a reliable model for this study, we referenced relevant reports in the literature and proposed a polynomial equation as follows:

$$Y = \varepsilon_0 + \sum \varepsilon_i X_i + \sum \varepsilon_{ii} X_{ii}^2 + \sum \varepsilon_{ij} X_i X_j \tag{17}$$

The BBD test obtains the nonlinear equation of the operation index and uses the significance analysis method to optimize and improve the equation. By defining the optimization objectives and boundary conditions, an optimization model of the walnut shelling operation quality was established, and the optimal solution was obtained via the optimization solution from Design-Expert.

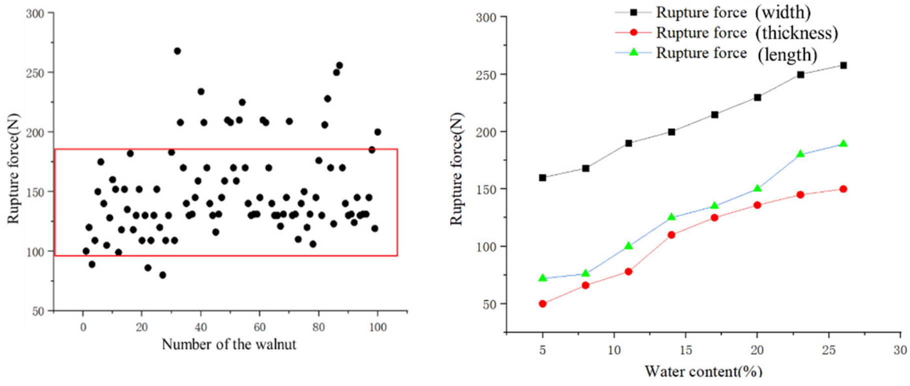
2.8. Model Evaluation

The optimization results were verified and evaluated using production trial tests that were conducted on a walnut farm. The optimal moisture content of the walnut was adjusted based on the optimized results from the BBD test, and the sheller was set to the optimal parameters. Samples were taken every 10 min while the sheller was in a steady state. A total of two kilograms of the sample was collected for each trial to determine the RHQK and RSC.

3. Results

3.1. Test Results of Mechanical Property

The mechanical test results of the walnuts with storage moisture content (16.95%) are shown in Figure 3. It can be seen from the figure that the distribution range of the rupture force under normal moisture content is relatively wide, from 80 N to 268 N, but is mainly distributed from 100 N–175 N as shown in the red rectangle area in Figure 4a. The variation in the rupture force with moisture content is shown in Figure 4b.



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

Figure 4. (**a**) Distribution range of rupture force and (**b**) the variation of rupture force with different moisture content from each direction.

It can be seen from the figure that the rupture force of walnuts gradually increases with an increase in the moisture content regardless of the width, thickness, and length of the walnuts. Additionally, the damaging force decreased successively in the width, thickness, and length directions under the same moisture content. The moisture content of walnuts had a great influence on their mechanical properties, which will inevitably lead to changes in the quality of walnut shelling operations.

3.2. Single-Factor Effects on Shelling Performance

The effects of the shelling conic roller angles, speeds of the shelling conic roller, clearance between the shelling conic roller and static roller, and the moisture content of the walnuts on RHQK and RSC are illustrated in Figure 5.

It can be seen from the figure that RHQK and RSC increase with an increase in the angle of the shelling conic roller; however, the increase is not obvious when the angle of the shelling conic roller is at the lower and higher levels. Therefore, the selection of the interval where the response index has a more significant effect is used as the selected parameter interval of the test. In this experiment, the experimental interval of the shelling conic roller angle is determined as 8–22° with a center point of 15°. Similarly, the range of the shelling conic roller speeds was 15–21 rpm with a center point of 18 rpm. The parameter range of the clearance between the shelling conic roller and the static roller was 35–45 mm with the center point at 40 mm, and the parameter range of the moisture content was 7.5–22.5% with the center point at 15%.

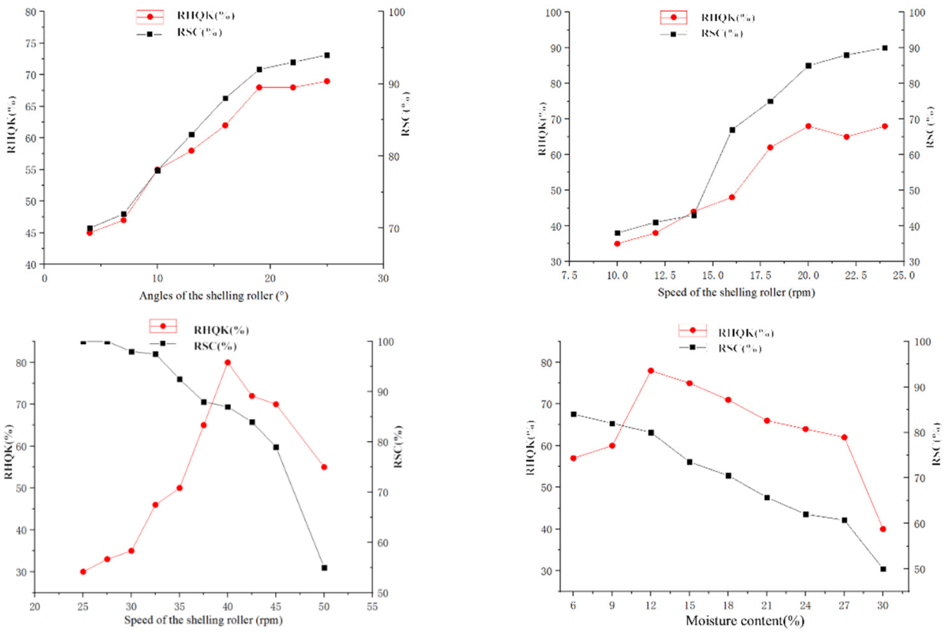


Figure 5. Effects of single-factor on RHQK and RSC.

3.3. *Constructions of Predictive Models for RHQK and RSC*

Experiments were carried out according to the experimental design that is shown in Table 2. Each group of experiments was repeated five times, and the average of the results was recorded in the table. Design-expert was used to carry out multiple regression fitting on the test results in Table 3 to obtain the regression models of RHQK and RSC. The results were analyzed by variance analysis using Design-Expert software, and the analysis of variance (ANOVA) is shown in Table 3.

Table 3. ANOVA of test results.

Source	**Y_1 (RHQK)**				**Y_2 (RSC)**			
	Sum of Squares	**df**	**F**	***p***	**Sum of Squares**	**df**	**F**	***p***
Model	2845.20	14	176.41	<0.0001	3727.46	14	154.84	<0.0001
X_1	11.25	1	9.77	0.0074	1.91	1	1.11	0.3095
X_2	358.61	1	311.28	<0.0001	1641.74	1	954.76	<0.0001
X_3	907.58	1	787.80	<0.0001	899.25	1	522.97	<0.0001
X_4	373.19	1	323.94	<0.0001	402.87	1	234.29	<0.0001
X_1 X_2	146.65	1	127.30	<0.0001	3.05	1	1.77	0.2045
X_1 X_3	0.0016	1	0.0014	0.9708	0.8836	1	0.5139	0.4853
X_1 X_4	1.96	1	1.70	0.2132	6.30	1	3.66	0.0763
X_2X_3	35.28	1	30.63	<0.0001	123.65	1	71.91	<0.0001
X_2 X_4	0.1764	1	0.1531	0.7015	65.04	1	37.83	<0.0001
X_3 X_4	3.84	1	3.33	0.0892	68.23	1	39.68	<0.0001
X_1^2	43.04	1	37.36	<0.0001	0.1455	1	0.0846	0.7754
X_2^2	201.31	1	174.74	<0.0001	25.01	1	14.54	0.0019
X_3^2	572.41	1	496.86	<0.0001	111.53	1	64.86	<0.0001
X_4^2	1.96	1	1.70	0.2137	349.25	1	203.11	<0.0001
R^2	16.13	14			24.07	14		
Residual	6.81	10	0.2922	0.9479	12.72	10	0.4485	0.8615
Lack of Fit	9.32	4			11.35	4		
Pure Error	2861.33	28			3751.53	28		
Cor Total	2845.20	14	176.41	<0.0001	3727.46	14	154.84	<0.0001

The F-value of the RHQK model was 176.41, implying that the model is significant. There is only a 0.01% chance that an F-value this large could occur because of noise. The lack-of-fit F-value of 0.29 implied that the lack of fit was not significant relative to the pure error. A non-significant lack-of-fit value was good, because we want the model to fit. The lack of fit indicates that the model can be used to predict RHQK. Similarly, the prediction accuracy of the RSC model can be determined. Figure 6 also indicates that the model can accurately predict RHQK and RSC.

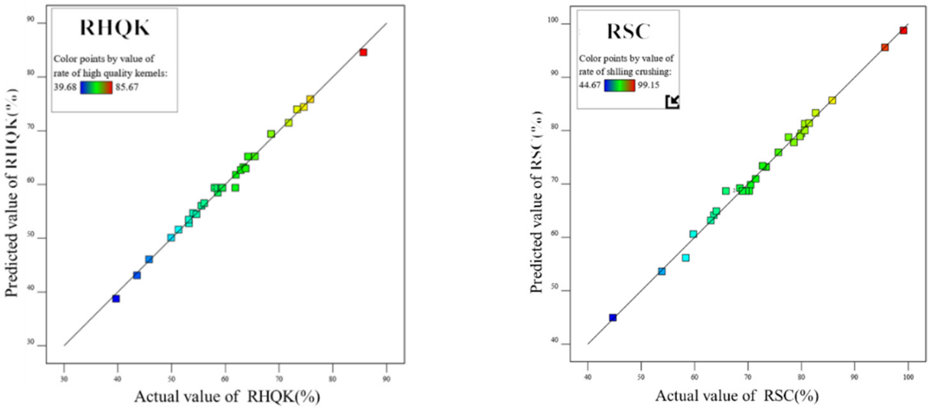


Figure 6. The comparison of the actual and predicted values.

p-values were used to identify if the terms in the model were significant; a *p*-value less than 0.05 indicated that model terms were significant. In this case, the model of RHQK was significant. X_1, X_2, X_3, X_4, X_1 X_2, X_2X_3, X_1^2, X_2^2, X_3^2 were significant, and other terms were not significant. The degree of influence of each factor on RHQK can be quantitatively determined using the F-value in the ANOVA table. The larger the F-value, the greater the influence on RHQK. Therefore, the order of the significance of each factor on RHQK was: X_3, X_3^2, X_4, X_2, X_2^2, X_1 X_2, X_1^2, X_2X_3, and X_1. Similarly, it was determined that the RSC was significant and could be used to predict the results of RSC; the same conclusion can be drawn from Table 3. X_2, X_3, X_4, X_2X_3, X_2 X_4, X_3 X_4, X_2^2, X_3^2, and X_4^2 were significant; other terms were not significant. The order of significance of each factor on RSC was: X_2, X_3, X_4, X_4^2, X_2X_3, X_3^2, X_3 X_4, X_2 X_4, X_2^2.

Reduction of insignificant terms in the model based on ANOVA can further improve the model to reduce errors and obtain more accurate optimization results. The refined models were:

$$Y_1 = 59.39 + 0.9683X_1 + 5.47X_2 + 8.70X_3 - 5.58X_4 - 6.05X_1X_2 - 2.97X_2X_3 - 2.58X_1^2 - 5.57X_2^2 + 9.39X_3^2 \quad (18)$$

$$Y_2 = 68.70 - 11.70X_2 + 8.66X_3 - 5.79X_4 + 5.56X_2X_3 + 4.03X_2X_4 - 4.13X_3X_4 - 1.96X_2^2 + 4.15X_3^2 + 7.34X_4^2 \quad (19)$$

3.4. Parameters Optimization

To improve the quality of the walnut shelling operation, it is preferable that the maximum values of RHQK and RSC appear simultaneously. Therefore, we introduced a multi-objective optimization methodology that incorporated the angles of the shelling conic roller, speeds of the shelling conic roller, clearance between the shelling conic roller and static roller, and the moisture content of walnuts as independent variables, with RHQK and RSC as objectives. The boundary conditions for X_1, X_2, X_3, and X_4 are defined as follows:

$$\begin{cases} Y_{1max} = Y_1(X_1, X_2, X_3, X_4) \\ Y_{2max} = Y_2(X_1, X_2, X_3, X_4) \\ constraint\ condition \begin{cases} 8 \ll X_1 \ll 22 \\ 15 \ll X_2 \ll 21 \\ 35 \ll X_3 \ll 45 \\ 7.5 \ll X_4 \ll 22.5 \end{cases} \end{cases} \quad (20)$$

The optimization was carried out by Design-Expert 12.0.3.0, yielding the outputs for the maximum RHQK and RSC as follows: X_1 = 15.83°, X_2 = 17.93 rpm, X_3 = 45 mm, X_4 = 9.5%, RHQK = 84.54%, and RSC = 99.15%.

3.5. Parameter Verification

The system-optimized results were validated using a production trial test. In the test, the moisture content of the walnuts was controlled at the optimized value by adopting the above-mentioned method, a new shelling conic roller was designed according to the optimized parameters, and the speed of the shelling conic roller was set at 17.93 rpm by a frequency module. The walnuts were shelled and sampled ten times for validation purposes. A comparison between the optimized results and the production test results is shown in Table 4. The average relative errors between the optimized results and production test values of RHQK and SRC were 2.53% and 2.66%, respectively. The comparisons proved the accuracy and effectiveness of the predicted models and the validity of the system optimization results.

Table 4. Comparison of the optimized value and the production test value.

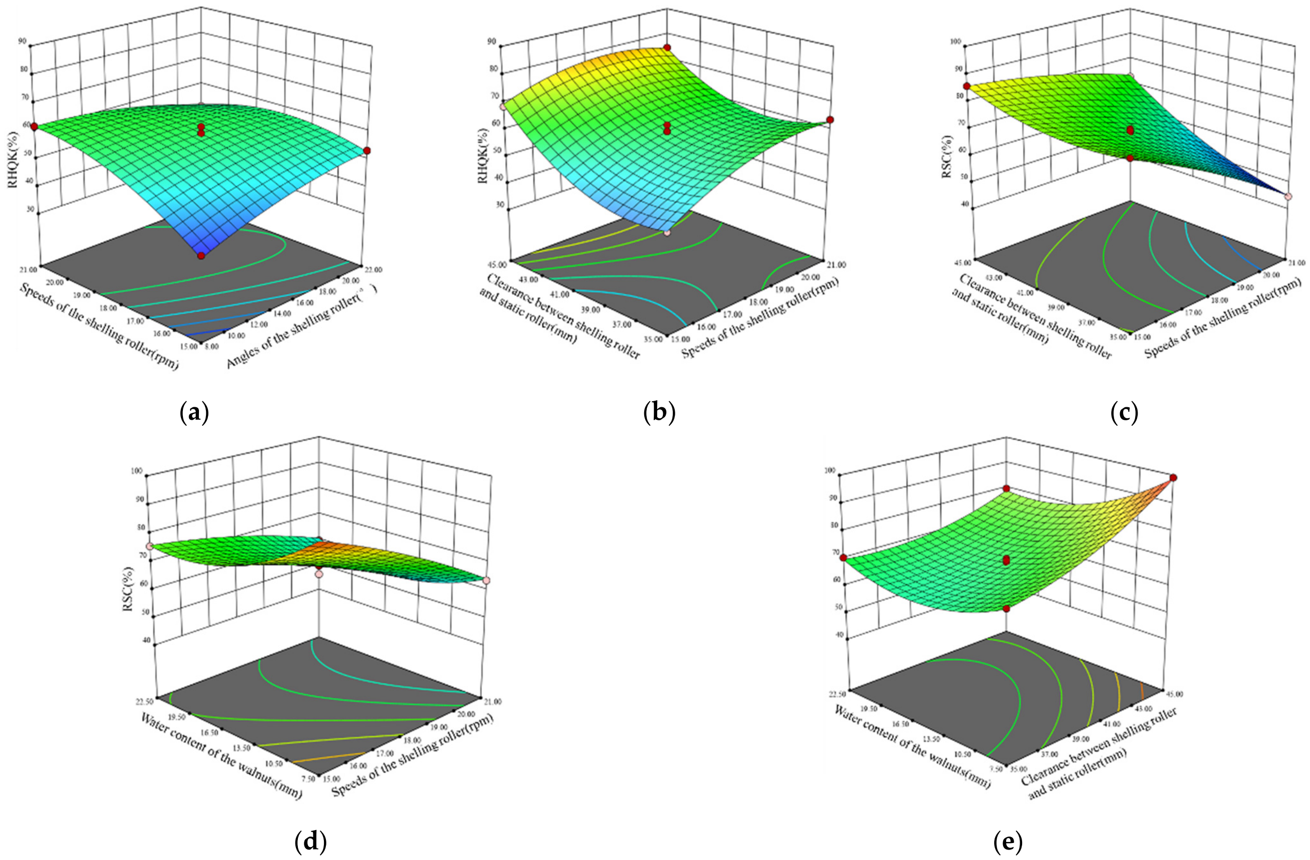
Test	RHQK/%		Relative Error/%	SRC/%		Relative Error/%
	Optimized Value	Test Value		Optimized Value	Test Value	
1	84.54	81.38	3.74	99.15	100	0.86
2		80.38	4.92		95.38	3.80
3		86.99	2.90		93.65	5.55
4		83.91	0.75		95.05	4.14
5		79.36	6.13		98.48	0.68
Mean value	/	82.40	2.53	/	96.51	2.66

4. Results and Discussion

4.1. Interactive Analysis of Variables Affecting RHQK

From the analysis in Section 3.3, the interaction of X_1 X_2 and X_2X_3 has a significant effect on RHQK, and the interaction of X_2X_3, X_2 X_4, and X_3 X_4 has a significant effect on RSC. The response surface graphs of their interactions on each response index were obtained using the Design-Expert software, which can be used to analyze the influence trend of the interaction on the response. When analyzing the influence of the interaction on the response index, other influencing factors remained at the zero level.

The interactions with RHQK are shown in Figure 7a,b. As illustrated in Figure 7a, RHQK increased with the increase in the shelling conic roller speed when the angles of the shelling conic roller were at a low level but decreased when the angles of the shelling conic roller were at a high level. Similarly, the effect of the angles of the shelling conic roller on RHQK were the same regardless of the speed of the shelling conic roller at low and high levels. However, RHQK was relatively low when the angles of the shelling conic roller and speeds of the shelling conic roller were both at low and high levels at the same time, which was detrimental to the shelling quality. The maximum value of RHQK appeared at the zero levels of the shelling conic roller angles and shelling conic roller speeds. Figure 7b shows the response surface plot of the interaction of clearance between the shelling conic roller and the static roller, and speeds of the shelling conic roller on RHQK. RHQK decreased gradually with the reduction in clearance between the shelling conic roller and the static roller, regardless of the change in speed of the shelling conic roller. Contrastingly, RHQK first increased slightly and then decreased with an increase in the speed of the shelling conic roller. The maximum value of RHQK appeared when the speeds of the shelling conic roller were maintained at zero level and clearance between the shelling conic roller and static roller was at a high level.



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

(**d**) (**e**)

Figure 7. (**a**) Interactions of speeds of the shelling roller and angles of the shelling roller on RHQK, (**b**) interactions of clearance between shelling roller and static roller and speed of the shelling roller on RHQK, (**c**) interactions of clearance between shelling roller and speed of the shelling roller on RSC, (**d**) interactions of water content of walnuts and speeds of the shelling roller on RSC, (**e**) interactions of water content of walnuts and clearance between shelling roller and static roller on RSC.

4.2. Interactive Analysis of Variables Affecting RSC

The interactions with RSC are shown in Figure 7c–e. As illustrated in Figure 7c, the interaction between the speeds of the shelling conic roller and the clearance between the shelling conic roller and the static roller had a greater impact on RSC. The interaction of the two had a very significant effect on RSC when the clearance between the shelling conic roller and the static roller remained at a low level and speeds of the shelling conic roller at a high level; the minimum value of RSC appeared here, which should be avoided. The maximum value of RSC appeared when the clearance between the shelling conic roller and the static roller was at a high level and the speeds of the shelling conic roller were maintained at a low level. Figure 7d shows the interaction between the moisture content of walnuts and speeds of the shelling conic roller on RSC. The moisture content had no significant effect on RSC when the speeds of the shelling conic roller were low, but a significant effect occurred when the speeds of the shelling conic roller were high. The maximum value of RSC appeared when both the speeds of the shelling conic roller and moisture content were at low levels. Figure 7e shows the variation in RSC with the interaction between the moisture content of walnuts and the clearance between the shelling conic roller and the static roller. RSC increased significantly with an increase in the clearance between the shelling conic roller and the static roller when the moisture content was at a low level, and the maximum value appeared when the moisture content was at a low level and the clearance between the shelling conic roller and the static roller was at a high level.

The operational quality of walnut shelling equipment is important for the development of the walnut industry. However, several reports have shown that development of walnut shelling equipment is slow, the proportion of walnut shelling processing is low, and most sold walnuts are in-shelled [9,11]. Prior studies have noted the importance of improving shelling quality. Some scholars have obtained the optimal force direction of the walnut rupture force through research [12,13], and others have obtained the optimal parameter combination of the equipment through orthogonal experiments [14–19]. Very little is found in literature on the question of systematic research on changes in walnut characteristics, shelling mechanical analysis, mechanical design, and shelling parameter optimization.

There are still several important issues for future research. This study only carried out shelling experiments on selected varieties; however, in China, there are many walnut varieties, with very different physical characteristics. Therefore, the adaptability of the equipment needs to be verified for different varieties. In addition, the optimal parameters in this study are fixed parameters for a variety of walnuts. It is, therefore, still necessary to optimize the design of the mechanism in future research, and design a device with adjustable key parameters to meet the operational needs of different varieties.

5. Conclusions

The poor shelling quality of walnut shelling equipment restricts progress in the walnut processing industry. Improved walnut shelling quality is of great importance in reducing shelling loss, improving farmers' income, and upgrading processed walnut quality. In this experiment, we assumed a mechanical model of walnut shelling and performed a force analysis to determine the key parameters affecting shelling quality. Via the experiment and variance analysis, we obtained the significant influencing parameters, acquired the mathematical model for the quality of the shelling operation, and optimized the key shelling parameters using the multi-objective optimization method. Surprisingly, the relative errors between the optimized results and the production test values of RHQK and SRC were 2.53% and 2.66%, respectively. The results implied that shelling quality and error were greatly improved compared to previous research results using the orthogonal test [14–19]. These findings further explained the feasibility of improving the shelling quality of walnuts by adjusting their moisture content. A comparison of the predicted and production test results also demonstrated the reliability of the assumptions from the mechanical analysis, the accuracy, and the reliability of the prediction model. The related methods can be used for optimizing the design of other nut-shelling equipment.

In this study, we proposed a mechanical model for walnut shelling and performed key parameter optimization and experimental verification. The single-factor and BBD tests were conducted using the angles of the shelling conic roller, speeds of the shelling conic roller, clearance between the shelling conic roller and the static roller, and the moisture content of walnuts. BBD, ANOVA, mathematical modeling, and multi-objective optimization were applied in the experiment. The ranking of factors that affected RHQK and RSC was as follows: clearance between the shelling conic roller and the static roller (X_3) > moisture content of the walnuts (X_4) > speeds of the shelling conic roller (X_2) > angles of the shelling conic roller (X_1) for RHQK > speeds of the shelling conic roller (X_2) > clearance between the shelling conic roller and the static roller (X_3) > moisture content of walnuts (X_4) > angles of the shelling conic roller(X_1) for RSC. The rank of significant interactive effects among the factors was as follows: angles of the shelling conic roller and speeds of the shelling conic roller (X_1 X_2) > speeds of the shelling conic roller, and clearance between the shelling conic roller and the static roller (X_2 X_3) for RHQK, clearance between the shelling conic roller and static roller (X_2 X_3) > clearance between shelling conic roller and the static roller, and moisture content of walnuts (X_3 X_4) > speeds of the shelling conic roller, and moisture content of walnuts (X_2 X_4) for RSC. Furthermore, the multi-objective optimization results were: angles of the shelling conic roller X_1 = 15.83°, speeds of the shelling conic roller X_2 = 17.93 rpm, clearance between the shelling conic roller and the static roller X_3 = 45 mm, and the moisture content of walnuts X_4 = 9.5%, yielding RHQK = 84.54% and RSC = 99.15%. A verification test of the optimal results further showed the feasibility and effectiveness of the proposed method. The method that was used in this study provides a reference for improving the shelling quality of other nuts.

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