Performance test and process parameter optimization of 9FF type square bale straw crusher

Jie Zhang[1,2], Bin Feng[2], Lei Guo[2], Lingzhuo Kong[2], Chao Zhao[2], Xiuzhen Yu[2], Wenjie Luo[2], Za Kan[1*]

(1. *School of Mechanical and Electrical Engineering, Shihezi University, Shihezi 832000, Xinjiang, China*;
2. *Research Institute of Agricultural Mechanization, Xinjiang Academy of Agricultural Sciences, Urumqi 830091, China*)

Abstract: In order to solve the problem of low productivity, unqualified segment length and high energy consumption during the process of crushing square bale straw caused by improper operation parameters, a 9FF square bale straw crusher was developed. In this study, by taking maize straw as the test material, the feeding speed, spindle speed of the crushing device and the state of the crushing device were taken as influence factors, and standard straw length rate, productivity per net working hour (hereinafter referred to as NWH) and energy consumption per ton of product as test indicators, the influence of the factors on the indicators were studied, and tests were carried out on the process of square bale straw crushing. By adopting the single factor test on the effect of the feeding speed, the spindle speed of the crushing device and the state of the crushing device on the test indicators, the suitable range of each factor was determined, respectively. Using the orthogonal test method, range method, variance method and comprehensive balance method, the experiment analyzed the significance of the influence of the three factors on various indicators and the order of priority. The test results showed that: the feeding speed was 5 m/min, spindle speed was 3000 r/min, and the state of the crushing device was a mixing cutter hammer, which was the best parameter combination ($A_1B_1C_1$) for the processing technology of the square bale forage crusher. The standard straw length rate was 93.7%, and the productivity per NWH was 2.80 t/h, with energy consumption per ton of 4.72 kW·h/t, in which the standard straw length rate and productivity per NWH reached optimal values, and the energy consumption per ton of product was slightly higher than the optimal value in the experiment. The research results can provide a reference for the optimal design of the special crusher for square bale straw.

Keywords: square bale, straw crusher, crushing, working parameter optimization, performance test
DOI: 10.25165/j.ijabe.20211403.5970

Citation: Zhang J, Feng B, Guo L, Kong L Z, Zhao C, Yu X Z, et al. Performance test and process parameter optimization of 9FF type square bale straw crusher. Int J Agric & Biol Eng, 2021; 14(3): 232–240.

1 Introduction

Maize, wheat and rice straws are the main sources of roughage for cattle and sheep breeding in Xinjiang and other parts of China. With the improvement of farmland mechanization, the mechanization technology of straw baling has been widely applied. At present, the three major types of straw are used in cattle and sheep farming, including household-based free-range farming and large-scale dry-feeding store straw as square bales.

In the household breeding of cattle and sheep, square bale straw processing is mainly accomplished by traditional low-medium power processing equipment of maize straw, such as straw machine, hammer crusher, and stalk kneader to chop long straw for feeding, as shown in Figure 1. In large-scale breeding of cattle and sheep, with the application of total mixed ration (TMR), there are mainly two ways of processing square bale straw: 1) Unbundling the square bale straw and putting it directly into the TMR equipment for the purpose of straw crushing and fine-coarse-feed mixing through TMR; 2) Chopping the straw through traditional medium-high-power maize stalk processing equipment such as hay cutter, hammer crusher, and kneading machine at first, and then putting the short straw into the TMR equipment to mix fine and coarse feed, it is shown in Figure 1.

Two production methods, household type and large-scale breeding, in terms of the processing quality, efficiency, and labor intensity have the following problems: 1) The traditional equipment, such as the guillotine, hammer crusher, and kneading machine, is mainly designed for the long-stem crops of green maize, semi-dry maize, and dry yellow maize, thus resulting in problems of low productivity, poor processing quality, high labor intensity, and poor safety in square bale processing; 2) The technology of TMR equipment derived from dairy cow feeding has achieved great success in dairy farming, but TMR equipment has not been fully utilized in cattle and sheep breeding. The first reason is that the current operating model is to put the crop straws directly into the TMR equipment, the high rigidity and toughness of the maize, wheat, and rice crop straws are difficult to meet the length requirements of straws for cattle and sheep breeding through the

Received date: 2020-06-22 **Accepted date:** 2020-10-10
Biographies: Jie Zhang, PhD candidate, Associate Professor, research interests: livestock machinery, Email: 369441769@qq.com; **Bin Feng**, Professor, research interests: livestock machinery, Email: xjwsfb@163.com; **Lei Guo**, Assistant Professor, research interests: livestock machinery, Email: 251420930@qq.com; **Lingzhuo Kong**, Assistant Engineer, research interests: livestock machinery, Email: 357489520@qq.com; **Chao Zhao**, Assistant Professor, research interests: livestock machinery, Email: 362435428@qq.com, **Xiuzhen Yu**, Senior Agronomist, research interests: horticulture, Email: 279837509@qq.com, **Wenjie Luo**, Assistant Engineer, research interests: livestock machinery, Email: 1491729808@qq.com.
***Corresponding author: Za Kan,** Professor, research interests: livestock machinery. College of Mechanical Electrical Engineering, Shihezi University, Shihezi 832000, Xinjiang, China. Tel: +86-13031321373, Email: 744692851@qq.com.

existing TMR structure and working principles. Many users have to extend the processing time of TMR equipment, which increases the load working time of TMR equipment, reduces the equipment service life, and increases the equipment maintenance cost in exchange for processing quality. At the same time, the inefficient TMR can hardly meet the needs of large-scale feeding. Secondly, when the short straws are put into TMR equipment, the processing equipment of short straws has the same problems as that in household feeding, thus traditional processing equipment of maize straws has to be applied in large-scale breeding for the purpose of using TMR equipment.


a. Crushing operation of corn square bales


b. Crushing operation of wheat straw square bales

Figure 1 Crushing operation of maize and wheat straw bales

In view of the above problems, it is of great significance to research the special shredder for square straw bales. In China, the researches of the mill have been carried out for decades, and a variety of crushers and grinding methods have been developed. However, there are many aspects of these researches that cannot well meet the requirements of the bundle of straw crushing need to be improved, including the energy consumption, existing crushing equipment output, material adaptability, granularity, economy, model working stability, operation safety, life span, and work performance[1,2]. At present, scholars mainly focus on the research of pulverizer theory and pulverizer performance. Gu et al.[3] chose a continuous ball mill (CBM), an air classifier mill (ACM), and a high-speed mill (HSM) to study the changes in average diameter and glucose content of corn straw after pre-grinding. Nakamura et al.[4] studied the crushing performance of different concave-angle stator impact crushers by adopting the coupling method of hydrodynamics and discrete element model. Niranatlumpong et al.[5] compared the wear situation of the blade through different surface treatment and coating technology on the blade in view of the wear problem of wheat, corn, beans, rice husk and shell on the blade of the shredding machine. Chen et al.[6] established a mathematic model of the straw crusher and optimized the straw crusher structure parameters based on the genetic optimization design method, with a knife shaft as optimization object, the work device of the knife shaft diameter of axle, inner diameter, and ratios of variables, the lightest quality knife shaft as the objective function, so as to improve the design efficiency and product quality. Hartati et al.[7] studied the rotating motor, blade angle and blade number of straw crusher, and finally determined that the optimal parameters of the multifunctional hammer mill were 1250 r/min, the blade angle was 30° and the blade number was 9. Ma et al.[8] carried out a quadratic regression orthogonal rotation combination test with five factors five levels on wheat straws for the problems of the chopping length, high energy consumption, and poor chopping effects of the TMR mixer, the test took the processing time, fixed blade number, cutting speed, tooth plate number and blade angle as experimental factors of the TMR mixe and took the standard long stalk rate and average power as evaluation indicators and reached the conclusion that with the cutting speed of 17-20 m/min, the blade angle of 70°-80°, the fixed blade number of 20-23, the processing number of 5-6 times, the tooth plate number of 4-7, the standard straw length ratio could be 70.5%-77.4%, and the average power was 5.8-7.0 kW. Yang et al.[9] used the logarithmic helical equation designed an edge curve of equal-slip corner cutting in order to solve the problems of large energy consumption, uneven force and vibration during the cutting process of the pulverized power blade, and made a kinematics analysis of corn straw particles and finally determined the optimal slide corner cutting. There are also problems with straw crushing devices such as winding shaft reamer, long discharging time, and ineffective high humidity rice stalks treatment. Zhu et al.[10] used the TRIZ theory to creatively design the synchronous conveying and cutting device of the crankshaft, and designed the arc-shaped gear meshing clearance adjustment mechanism and the secondary crushing device, also, the sliding angle parameter of the chopper was calculated, and the pass rate of the crusher was about 90% through the test. Aiming at the influence of the circulation layer on the performance of the ring-screen hammer feed mill, Tian et al.[11] proposed a combined sieve form. Through the fluid dynamics software Fluent, the airflow field of the crusher using the annular flat screen and the combined sieve was calculated. Simulation and experiments have verified that the use of this combined sieve can increase productivity and improve the crushing quality of materials. In order to study the reasonable shape of the separation device of the hammer-type feed grinder, Cao et al.[12] calculated the work done by the frictional force when the material moved along with the outer pipe wall and obtained the curve shape of the outer pipe wall when the frictional work was the smallest. Through experiments, it was concluded that the output of the new separation device is higher than that of the original separation device. Zaselskii et al.[13] used a high-speed camera and other technologies to study the crushing process of materials by hammer pieces in the crushing chamber. The results showed that materials were not hit positively but eccentrically, so the energy consumption of the crusher in the crushing process was relatively high. Wei et al.[14] took corn straw as the graduate object and studied the effects of rotational speed, moving and fixed cutter clearance and moving cutter spacing on grinding efficiency and energy consumption by using secondary rotating combination test, and found that the most suitable combination was that the qualified rate of grinding reached 90%. Wang et al.[15] analyzed the crushing process of bulk corn straw, and concluded that the linear velocity at the end of the hammer (spindle speed) and moisture content of corn straw had great influences on the crushing performance of hammer crusher, and the primary and secondary relationship of influencing factors was obtained through experiments. Chen et al.[16] optimized the quality of the cutter shaft in the straw crusher based on the genetic optimization method and the ADAMS simulation test, and further reduced the quality of the cutter shaft on the basis of meeting the production efficiency and product quality. In view of the large energy consumption, uneven force, vibration and other problems in the cutting process of the crusher, Zhang et al.[17] designed the key components such as sliding blade and cutter shaft, aiming at the problems of large resistance and straw winding during the operation of the straw returning machine. The crushing rate and power consumption of the crusher were studied by the response surface method. Wang et al.[18] carried out response surface tests on corn stalk pulverizing device by taking the rotating speed of cutter shaft, installation angle and inclination angle of tool tip as test factors and the qualified rate of straw pulverizing length and straw crushing rate as evaluation indicators. The optimal parameter combination of the three factors was determined by the quadratic orthogonal rotation test.

Because of the existing problems in the crushing of square straw bales, how to effectively improve the crushing efficiency and processing quality of square straw bales, and reduce the energy consumption of machinery and labor intensity are the key issues of the forage processing in large-scale cattle and sheep breeding at the present stage. In this study, the innovative square bale straw crusher developed by the Research Institute of Agricultural Mechanization of Xinjiang Academy of Agricultural Sciences was applied to carry out the crushing performance test to determine the effects of influencing factors on the crushing performance of the square bale straw crusher, and to get the optimized parameter combination, and thus providing a theoretical and technical reference for the development of the square bale crushers.

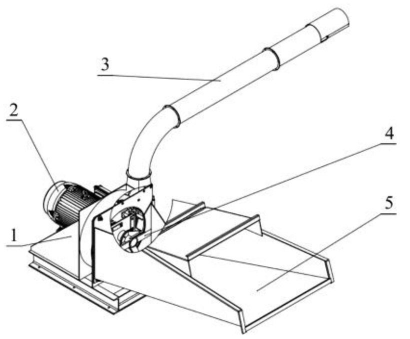
2 Materials and methods

2.1 Main instrument and equipment

The equipment machine selected for the experiment was the 9FF square bale straw crusher developed by the Research Institute of Agricultural Mechanization, Xinjiang Academy of Agricultural Sciences. The performance parameters of the equipment machine are shown in Table 1. The schematic assembly diagram of the prototype is shown in Figure 2.

Table 1 The performance parameters of the 9FF square bale straw crusher

	Model	Power of the main motor/kW	Productivity /t h^{-1}	Dimension /mm	Weight /kg
Square bale straw crusher	9FF	18.5	1.5-3.0	2350×920×1250	300



1. Base 2. Motor 3. Feeding ventilator 4. Crushing device combination 5. Feeding barrel

Figure 2 Schematic diagram of square bale straw crusher

The 9FF square bale straw crusher was mainly composed of a stirring cutter, hammer set, sieve, feeding port, discharge pipe, shell, body frame, 18.5 kW motor, and electric control cabinet. The working principle of the square bale straw crusher was as follows: after the baled straw was unwound, the bale rope was manually drawn out. Then the square bales of straw fall along the bottom of the feed port under gravity, and they were suctioned by the rotation of the crushing mechanism at the same time. After entering the crushing device, the straw was chopped by the cutter of the movable cutter set for the first time, and then chopped and hammered twice by the hammer, after which the materials with the required length entered the discharge pipe through the sieve and was sprayed into the storage bin.

Test instrument: vernier caliper (Urumqi Jindu Scientific Instrument Co., Ltd., China), JA2003 electronic analytical balance (Shanghai Jinghai Instrument Co., Ltd., China), standard sieve (Urumqi Jindu Scientific Instrument Co., Ltd., China), electric vibrating sieve machine (Shangyu Xueqin Yarn Sieve Factory, Zhejiang, China).

2.2 Test materials

The maize straws in the test were planted and harvested at the Anningqu Test Field of the Xinjiang Academy of Agricultural Sciences and dried naturally. The mass of straws was about 14 kg, the size was 50 cm×35 cm×1000 cm, and the average length of a single straw was about 300 mm to 500 mm.

2.3 Determination of test factors and test indicators

In this study, the feeding speed, spindle speed and the crushing device status were selected as the influencing factors. The standard grass length rate after crushing, the productivity per NWH, the energy consumption per ton of product as well as the successful automatic feeding were used as test indicators to study the effects of various factors on each indicator. The efficient productivity per NWH is the guarantee of the economic benefits of crushing square bales of straw. Energy saving and consumption reduction have a positive effect on the ecological environment and economic benefits, which is a goal currently pursued of production. Whether it can ensure smooth and automatic feeding is the basis for ensuring the crushing effect and improving productivity.

2.4 Test methods

2.4.1 Determination of feeding speed

The determination of the feeding speed depends on the speed setting of the square bale straw conveying device. In this test, the rated speed range of the conveying device matched with the square bale straw crusher was 2.0-11.6 m/min, thus 11.5 m/min was set as the single-factor upper limit value with a decrease of 2.0 m/min. Feeding speed was determined as follows: 11.5 m/min, 9.5 m/min, 7.5 m/min, 5.5 m/min, 3.5 m/min, respectively.

2.4.2 Determination of spindle speed

The spindle speed was 3000 r/min, thus 3000 r/min was set as the single-factor upper limit and with a decrease of 500 r/min. Selected spindle speed was 3000 r/min, 2500 r/min, 2000 r/min, 1500 r/min, 1000 r/min, respectively.

2.4.3 Crushing device status setting

Considering factors such as increasing the productivity per NWH, improving the crushing effects and reducing the processing costs, three statuses of the crushing device were formed, including stirring cutter and hammer blade; stirring cutter and cutter; double stirring cutter.

2.4.4 Standard straw length rate measurement

The straw materials studied in this study were mainly for mutton sheep feed. According to the feeding requirements of the livestock industry, the straw materials were chopped to less than 3 mm in length for the consumption of mutton sheep, and cannot be ground excessively, since it might reduce the palatability of mutton sheep and increase energy consumption.

According to the requirements of the national standard GB/T26551-2011[19] of the People's Republic of China, in the beginning, middle and final stages of the test, the sample was taken three times at the exit of the straw outlet. 500 g of sample was taken out by the cross method after mixing, and the sample was measured one by one in length each time, and the standard straw length rate was calculated according to Equation (1).

$$S_c = \frac{m_c}{m_y} \times 100\% \tag{1}$$

where, S_c refers to the standard grass length rate, %; m_c refers to the total mass of standard grass, g; m_y refers to the total mass of grass samples, g. The standard grass length meant that the length of the cut grass was 0.7-1.2 times that of the designed grass cutting length (with measured values one digit after the decimal point).

2.4.5 Measurement of productivity per NWH

According to the requirements of the national standard GB/T6971-2007[20] of the People's Republic of China, the amount of material required for 10 min of work was calculated according to the upper limit of productivity specified in the instruction manual. Under the condition that the load of the prototype met the fixed working conditions, the test could be started only after the prototype reached the normal working status. The start and the end of timing should be synchronized with the sampling process, and the quality and the corresponding time of the ground materials in this range should be determined. The test time should not be less than 10 min. The productivity was calculated according to Equation (2).

$$E_c = \frac{Q_c}{t_c} \tag{2}$$

where, E_c refers to the productivity per NWH, t/h; Q_c refers to the working amount in working time, t; t_c refers to the working time, h.

2.4.6 Energy consumption per ton of product

Calculate the energy consumption per ton of product according to Equation (3).

$$M = \frac{N}{E_c} \times 1000 \tag{3}$$

where, M refers to energy consumption per ton of product, kW·h/t; N refers to the load power of the whole machine (including the motor of the conveying device and the motor of the crushing device), kW.

2.4.7 Determination of feeding smoothness

Feeding should be carried out at a given speed in a uniform manner. If there were no cases of square bales stopping going forward or blocking the crushing chamber to stop the motor and generate abnormal noise, then the feeding could be considered smooth. Otherwise, it should be considered as the inability to carry out automatic feeding.

2.4.8 Orthogonal test

After the single factor levels were initially selected and reduced through a large number of single-factor tests in the early stage, part of the representative factor levels was selected to carry out orthogonal tests. Temporarily disregarding the interaction between various factors, orthogonal tests of four factors and three-level were carried out. By using the orthogonal table $L_9(3^4)$, a test plan consisting of nine horizontal combinations was designed to find out better production conditions.

The feeding speed, spindle speed, and crushing device status were taken as the three factors to design the orthogonal test. The factors and levels are shown in Table 2, and the orthogonal test design is shown in Table 3[21].

Table 2 Factor level coding of orthogonal tests of four factors and three-level

Level	Test factors			
	Feeding speed A/m min^{-1}	Spindle speed B/r min^{-1}	Crushing device status C	Empty row D
1	5	3000	Stirring cutter and hammer blade	D1
2	4	2900	Stirring cutter and cutter	D2
3	3	2800	Double stirring cutter	D3

Note:The purpose of adding an empty row is to check whether there are other error factors in the experiment, the same as below.

Table 3 Orthogonal test design of four factors and three levels

Test No.	Factors			
	Feeding speed A/m min^{-1}	Spindle speed B/r min^{-1}	Crushing device status C	Empty row D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	2
5	2	2	3	3
6	2	3	1	1
7	3	1	1	1
8	3	2	2	2
9	3	3	3	3

2.5 Data statistic processing

After the test data were sorted by office software, the orthogonal test method, range analysis method, variance analysis method and comprehensive balance method were used to analyze the data and optimize the optimal production conditions.

The test data were sorted with Excel2003 software, and then the data were analyzed through the orthogonal experiment method and comprehensive analysis method.

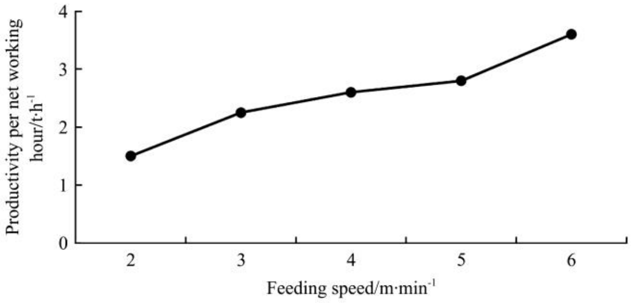
3 Results and analysis

3.1 Single factor test on indicators affecting performance

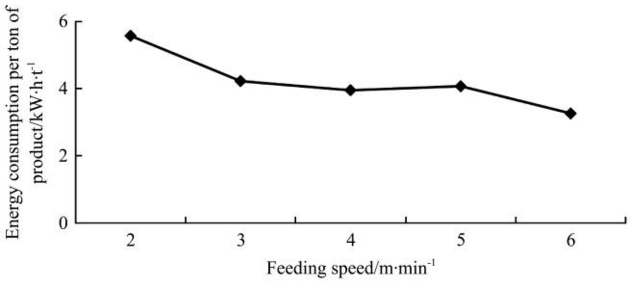
3.1.1 Effects of feeding speed on indicators

Considering expanding productivity, the spindle speed was set to the maximum speed of 3000 r/min, and the crushing device was set at status with the optimal theoretical crushing effect, which was a stirring cutter and hammer blade. To study the effects of feeding speed on the indicator, the available feeding speed value in the orthogonal test was selected.

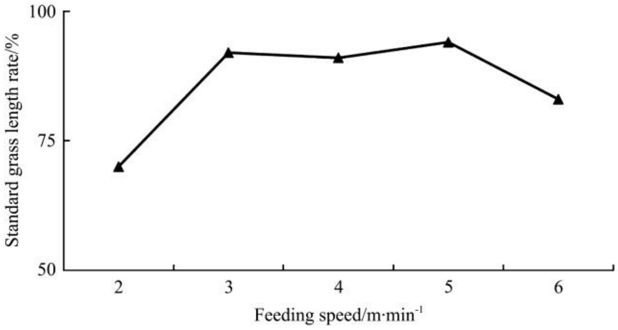
The setting of the feeding speed depends on the speed setting during the coordinated operation between the square straw conveying device and the crushing device. The rated speed range of the conveying device was 2.0-11.6 m/min, but it was found in Figure 3a, the influence of feeding speed on the productivity per NWH that when the feeding speed reached 6 m/min, the material feeding of the crushing device slowed down and slight clogging was caused, and the productivity per NWH reached 3.6 t/h. It can be seen from Figure 3b that the energy consumption per ton of product tends to be stable when the feeding speed is 3 m/min to 5 m/min, showing an insignificant change. It can also be seen from Figure 3c that the standard grass length rate is higher than 90% when the feeding speed is 3 m/min to 5 m/min, and the standard grass length rate drops below 90% when the feeding speed is close to 6 m/min. When checking the crushed sample retrieved at a feeding speed of 6 m/min, it was found that there was a fine powder. The reason after an analysis was that when the feed speed reached 6 m/min, the crushing device was slightly clogged, and part of the straw was blocked in the feeding part and affected the entry of the following materials, forcing the straw that entered the crushing chamber to be excessively crushed, and thus reducing the standard straw length rate. Taking the standard grass length rate and the limitations of manual feeding in this study, the research team abandoned the factor value of 6 m/min feeding speed and set the upper limit of the feeding speed to 5 m/min. However, when the feeding speed was 2 m/min, the test measured the productivity per NWH of only 1.5 t/h, which is far from the test expectations. At the same time, there was no high standard grass length rate, so the lower limit of feeding speed was set at 3 m/min. Taking all test results into comprehensive consideration, the feeding speed of 5 m/min, 4 m/min, and 3 m/min were finally determined as the feeding rate levels for the orthogonal test.



a. Effect of feeding speed on productivity per net working hour



b. Effect of feeding speed on energy consumption per ton of product



c. Effect of feeding speed on standard grass length rate

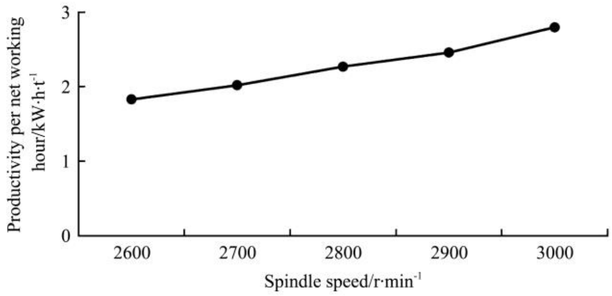
Figure 3 Effects of feeding speed on the crushing effect

3.1.2 Effects of spindle speed on indicators

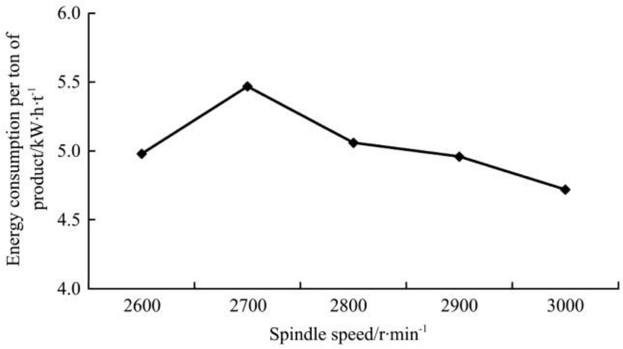
After taking the influence of feeding speed on productivity per NWH, energy consumption per ton of product and standard grass length rate into consideration, a feeding speed of 5 m/min was selected in this test, and the crushing device was set in status with the best crushing effect, with stir cutter and hammer. To study the influence of spindle speed on the indicators, the available spindle speed value in the orthogonal test was selected.

In the experiment, when the spindle speed was 2000 r/min, the NWH productivity was 1.25 t/h; when the spindle speed was 2500 r/min, the productivity per NWH was 1.34 t/h. Consider that the pure working hour productivity was an important indicator for the performance of the equipment, the factor values including 2500 r/min and beyond were eliminated. The factor values of this test were re-determined as 3000 r/min, 2900 r/min, 2800 r/min, 2700 r/min, 2600 r/min, respectively.

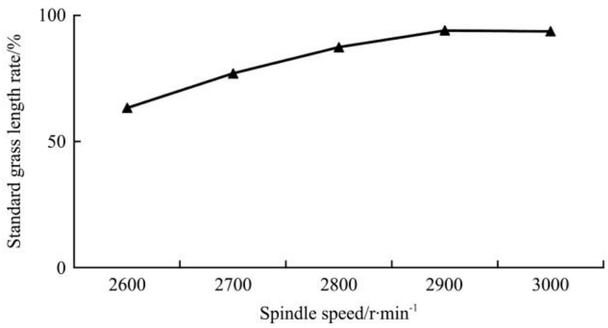
It can be seen from Figure 4a that with the increase of the spindle speed, the productivity per NWH shows a downward trend. And when the speed is reduced from 2700 to 2600 r/min, the productivity per NWH displays a significant drop. As shown in Figure 4b, with the increase of the spindle speed, the energy consumption per ton of product shows an upward trend, and when the speed reduces from 2800 r/min to 2700 r/min, there is a significant increasing trend. However, when the speed is 2600 r/min, there is a big drop. It can be drawn from Figure 4c that when the spindle speed is 3000 r/min and 2900 r/min, the standard grass length rate is above 90%, and the standard grass length rate at 2900 r/min is slightly higher than that at 3000 r/min. Looking at the retrieved samples, it was found that the sample at 3000 r/min was finer than that at 2900 r/min. The reason after analysis should be that the increase in the rotation speed increased the number of times of the act of stirring knife and hammers on the straw, producing some excessively ground straws. When the spindle speed is 2800 r/min, the standard straw length rate starts to be lower than 90%. When the spindle speed is reduced to 2600 r/min, the standard straw length rate is reduced to 63.33%. Looking at the samples retrieved from the experiment, it was found that after the spindle speed was 2800 r/min, the length of the samples increasingly became longer. The reason after analysis should be that while the spindle speed reduced, the materials were blown out of the crushing chamber before it was chopped to a certain length, thus failing to meet crushing requirements.



a. Effect of spindle speed on productivity per net working hour



b. Effect of spindle speed on energy consumption per ton of product



c. Effect of spindle speed on standard grass length rate

Figure 4 Effects of spindle speed on test indicators

3.1.3 Effects of crushing device status on indicators

Of the three optimal spindle speeds, the speed 3000 r/min with the best indicator was selected to study the influence of the crushing device on the indicator under different statuses.

In this experiment, three different status sets of crushing devices, stirring cutter and hammer blade; stirring cutter and cutter; double stirring cutter, were designed. As the first process of the crushing operation of the device, the stirring knife played an important role in the final crushing performance on the straw bales. The stirring knives proposed in this study, as shown in Figure 5, were semi-conical. During operation, flat blade 1 conducted sliding cutting on the bale after stirring and unbundling, then flat blade 2 cut the discrete straw coming out of blade 1.


a. Stirring cutter and hammer

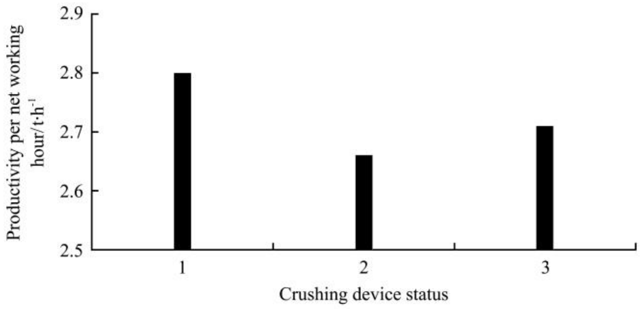

b. Stirring cutter and cutter


c. Double stirring cutter

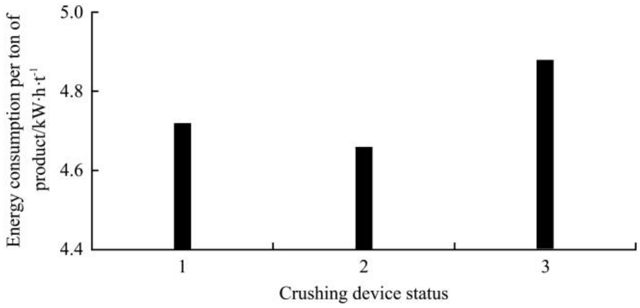
Figure 5 Three different crushing devices

In Figure 5a, the stirring cutter is connected with four groups of hammer blades, with every two pieces in a group. The groups are in a staggered arrangement in a clockwise direction. After the straw was untied by the mixing cutter hammer, it would continue to enter the secondary crushing stage. With the hammer rotating at a high speed, the straw was blown out from the discharge cylinder after was beaten and knead. As shown in Figure 5b, the mixing knife teams up with eight cutting knives staggered at 90°, in which the lower part of the cutter acts like a hammer, and the upper triangular blade does secondary chopping on the straw. In Figure 5c, two mixing knives are connected in series, to reduce the secondary beating and rubbing of the hammer and the thrashing effect of the knife.

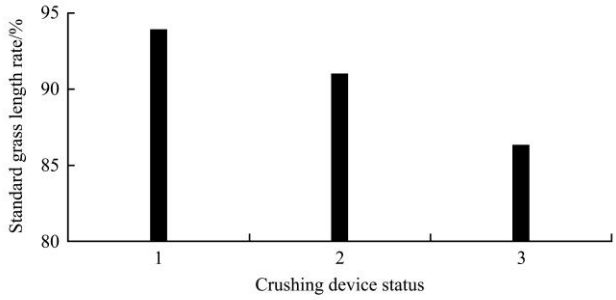
It can be drawn from Figure 6 that the indicators of the pulverization performance under the conditions of the three pulverization devices show good results, with the productivity per NWH above 2.5 t/h, and the energy consumption per ton of product controlled below 5 kW·h/t. The standard straw length rate in the double-cutter knife test was slightly lower than 90%. In the test, it was found that the stirring knife played a key role in the process of crushing the square bales. It can be seen from Figure 6 that among the combination of the three kinds of crushing devices, the combination of the stirring blade and hammer blade produce the best indicators such as the crushing effect, while the combination of the stirring blade and the cutter came second, and the combination of the double stirring blade is the last. It could be seen from the retrieved test samples that due to the lack of hitting and kneading from the hammer, straws chopped by the double cutter are too long, i.e., 8 cm on average, and the straw cut was tough without fiber, which was suitable for cattle breeding. While the straws chopped by the mixing cutter and cutter combination were thinner than those chopped by the combination of the mixing cutter and hammer blade, indicating that the cutter not only plays the role of hammering and rubbing, the triangular blades on the upper part of the cutter also help to chop straw for the second time.



a. Effect of crushing device status on productivity per net working hour



b. Effect of crushing device status on energy consumption per ton of product



c. Effect of crushing device status on standard grass length rate

Figure 6 Effects of three different crushing device status on indicators

3.2 Multi-factor orthogonal test

3.2.1 Range analysis of test results of the effects of test factors on test indicators

The range analysis method was adopted in this study to analyze the effect of the three factors on the standard straw length rate, productivity per NWH, and energy consumption per ton of product, without considering the effect of the error column on the indicator. It can be seen from Table 4 that feeding speed, spindle speed, and different statuses of the crushing device impose different effects on the standard straw length rate, productivity per NWH, and energy consumption per ton of product. A range can reflect the effects of each factor on the indicators. It could be seen from the range analysis that under various levels of factors, the status of the crushing device have a significant effect on the standard straw length rate and energy consumption per ton of product while the motor speed of the crushing device can pose an essential effect on productivity per NWH.

Table 4 Four-factor and three-level test data analysis and calculation

Experiment number	Test factor				Test indicator		
	A	*B*	*C*	*D*	Standard straw length rate /%	Productivity per NWH /t·h^{-1}	Energy consumption of tons of products/kW·h t^{-1}
1	1	1	1	1	93.70%	2.80	4.72
2	1	2	2	2	90.84%	2.43	4.54
3	1	3	3	3	80.27%	1.84	5.26
4	2	1	2	2	90.25%	2.55	4.52
5	2	2	3	3	81.75%	2.07	5.37
6	2	3	1	1	91.33%	1.55	4.67
7	3	1	3	1	82.51%	2.45	5.34
8	3	2	1	2	90.02%	1.70	4.88
9	3	3	2	3	87.89%	1.54	5.03
Standard straw length rate/%	k_1	88.270	88.820	91.683	87.780		
	k_2	87.777	87.537	89.660	88.227		
	k_3	86.807	86.497	81.510	86.847		
	R	1.463	2.323	10.173	1.380		
Productivity of pure working hour/t h^{-1}	k_1	2.357	2.600	2.017	2.137		
	k_2	2.057	2.067	2.173	2.143		
	k_3	1.897	1.643	2.120	2.030		
	R	0.460	0.957	0.156	0.113		
Energy consumption of tons of product /kW h t^{-1}	k_1	4.840	4.860	4.757	5.040		
	k_2	4.853	4.930	4.697	4.850		
	k_3	5.083	4.987	5.323	4.887		
	R	0.243	0.127	0.626	0.190		

Note: k_1, k_2, k_3 are represent the sum of indicators at each level of each factor; *R* is the measure of variation.

1) Factors affecting the standard straw length rate. It could be seen from the range value (*R*-value) of the standard straw length rate in Table 4 of the orthogonal test that the crushing device status had the most significant effect on the standard straw length rate, while the spindle speed came the second and the feeding speed showed the minimal effect on the standard straw length rate. The highest standard straw length rate was obtained in Test No.1 under the test condition of $A_1B_1C_1$.

2) Factors affecting the productivity of pure working hours. It could be seen from the range value (*R*-value) of the pure working hour productivity in Table 4 of the orthogonal test that the spindle speed had the most significant effect on productivity, while the feeding speed had less effect, and the state of the crushing device showed an insignificant effect on productivity. The highest productivity per NWH was obtained in Test No. 1 under the test condition of $A_1B_1C_1$.

3) Factors affecting energy consumption per ton of product. According to the size of the range value (*R*-value) of energy consumption per ton of products in Table 4 of the orthogonal test, the crushing device status was the greatest factor affecting the energy consumption of the ton of products, while the feeding speed had a smaller effect and the spindle speed showed the least effect. The lowest energy consumption was obtained in the No.4 test under the test condition of $A_2B_1C_2$.

3.2.2 Variance analysis of test results of effects of test factors

In order to produce more convincing test results, an analysis of variance was introduced to verify the data again.

The DPS data processing software was adopted to conduct variance analysis on the orthogonal test results with the standard straw length rate, pure working hour productivity, and energy consumption per ton of products as indicators, and the results are shown in Table 5.

The analysis of variance showed that the state of the crushing device had a significant effect on the standard straw length rate and energy consumption per ton of product, and the spindle speed had a significant effect on the pure working hour productivity. The effects of feeding speed on the three indicators were not significant.

Table 5 Variance analysis of the test results of the three factors affecting the standard straw length rate, productivity per NWH, and energy consumption of tons of products

Indicator	Factor	Deviation sum of squares	Degrees of freedom	*F* ratio
Standard straw length rate/%	*A*	3.326	2	0.071
	B	8.126	2	0.172
	C	174.013	2	3.694*
	e	2.975	2	0.063
	Sum	188.440	8	
Productivity per NWH /t h^{-1}	*A*	0.327	2	0.740
	B	1.379	2	3.120*
	C	0.038	2	0.086
	e	0.024	2	0.054
	Sum	1.770	8	
Energy consumption of tons of products /kW h t^{-1}	*A*	0.112	2	0.490
	B	0.024	2	0.105
	C	0.717	2	3.138*
	e	0.061	2	0.267
	Sum	0.910	8	

Note: * means is significant; *F* threshold is 3.110; *e* is deviation

3.2.3 Optimal production conditions after comprehensive balance analysis

The general principle of comprehensive balance was: when the significance of each indicator was different, the selection level should ensure important indicators; when the significance of each indicator similar, the selection level should give priority to the main factors or follow the major trend. Analyzing through the comprehensive balance method, the order of the three affecting factors was crusher status, feeding speed, spindle speed.

Table 6 Comprehensive balance analysis

Items	Order		
	Order of three factors on the test indicators		
Standard straw length rate/%	*C*	*B*	*A*
Productivity per NWH/t h^{-1}	*B*	*A*	*C*
Energy consumption per ton of product/kW h t^{-1}	*C*	*A*	*B*

From the calculation analysis, range analysis and variance analysis of each indicator, Factor A had an effect on each indicator, but all of them were not significant, in which A_1 was the highest and should be selected. Factor B had an effect on each indicator, especially on productivity per NWH. All test results showed that B_1 was the best. Factor C had the most significant effect on the energy consumption per ton of product. From the test results, it was concluded that the energy consumption per ton of product under condition C_2 of Test 4 is the lowest, and C_1 appears twice in the three optimal tests derived from the range analysis. At the same time, the energy consumption per ton of products in C_1 state was below 5kW h/t in nine tests, while the energy consumption per ton of products in the C_2 state exceeded 5 kW h/t once. With balanced consideration, C_1 was chosen. Therefore, $A_1B_1C_1$ was determined as the optimal processing condition in this test.

3.2.4 Test result verification of optimal production conditions

Because the production conditions of $A_1B_1C_1$ had been measured in the previous test, in order to produce more convincing test results, the processing conditions of $A_1B_1C_1$ were again verified in the test, whereby the feeding speed is 5 m/min, the spindle speed is 3000 r/min, and the crushing device with a combination of stirring knife and hammer blade. Compared with other test conditions in the orthogonal test, the obtained test results showed that the standard straw length rate and pure working hour productivity were optimum, and the energy consumption per ton of product ranked second.

4 Discussion

1) In this study, more external factors had been taken into accounts, such as test design, factor selection and indicator setting, while internal factors and structural parameters of the sample machine were not considered, since this part would be discussed in other studies.

2) In this test, the rated speed range of the conveying device matched with the square bale straw crusher was 2.3-11.6 m/min, but the single factor test showed that when the feeding speed reached 6 m/min, the crushing device would get clogged, i.e., the feeding speed can reach below 6 m/min. Therefore, the feed conveying device used in this test was too large. In the follow-up test, the conveyor should be re-considered.

3) The standard straw length rate selected in this study was for the feeding requirements of mutton sheep. The optimal crushing device status in the orthogonal test was formed by a stirring cutter and hammer blade, however, after measuring the straw crushed by the other two crushing devices, the length of the straw crushed by the double stirring cutter met the requirements of beef cattle feeding. Therefore, this experiment also proved that the design concept of a double stirring cutter was worthy of further research.

4) In the early stage of the test, "automatic feeding or not" was considered as the measurement indicator in the orthogonal test, while it played a very important role in measuring data and determining the limiting value of the influencing factors in the single-factor test in the early stage, but showed little significance in the orthogonal test. Therefore, the "successful automatic feeding" was deleted from the measurement indicators in the orthogonal test.

5 Conclusions

1) According to the variance analysis, the status of the crushing device had a significant effect on the standard straw length rate and energy consumption per ton of product, and the spindle speed had a significant effect on the productivity per NWH. While the effect of feeding speed displayed insignificant effects on all three indicators.

2) Through the comprehensive balance analysis, the primary and secondary order of the three affecting factors were crusher status, feeding speed, spindle speed.

3) Under the production conditions of $A_1B_1C_1$, the standard straw length rate was 93.70%, the Productivity per NWH was 2.80 t/h, and the energy consumption per ton of product was 4.72 kW h/t. Compared with other test conditions in the orthogonal test, the obtained test results showed the best standard straw length rate and pure working hour productivity, and the energy consumption per ton of product here was slightly higher than the optimal value. The test results proved that the optimal production conditions obtained through the orthogonal test basically conformed to the actual production situation, indicating that the combination of process parameters was reliable and optimal.

Acknowledgements

The authors acknowledge that this work was financially supported by the National Natural Science Foundation of Xinjiang Uygur Autonomous Region (Grant No. 2018D01A60).

[References]

[1] Li H, Shen W Q, Ban T. Research progress of straw utilization technology and straw crushing equipment in China. Chinese Journal of Agricultural Mechanization, 2018; 39(1): 17–21. (in Chinese)

[2] Cao L Y, Li S B, Li C D, Wang Y, Wang F. Research and development status of hammer type feed crusher. Feed Industry, 2021; 42(3): 31–36. (in Chinese)

[3] Yang M G, Kim S, Sung D, Jin H L. Feasibility of continuous pretreatment of corn stover: A comparison of three commercially available continuous pulverizing devices. Energies, 2019; 12(8):1422. doi: 10.3390/en12081422.

[4] Nakamura H, Kan H, Takeuchi H, Watano, S. Effect of stator geometry of impact pulverizer on its grinding performance. Chemical Engineering Science, 2015; 122: 565–572.

[5] Niranatlumpong P, Sukhonket C, Nakngoenthong J. Wear resistant surface treatment of pulverizer blades. Wear, 2013; 302(1-2): 878–881.

[6] Chen L Q, Zhang J Q, Kong X L. Genetic optimal design of straw crusher based on ADAMS. Advanced Materials Research, 2011; 139(141): 929–932.

[7] Hartati S, Musabbikhah M, Suryono E. Multifunction hammer mill machine design and assembling to destroy an agricultural waste. In: International Conference on Applied Science and Engineering (ICASE 2018), Atlantis Press, 2018; pp.101–104. doi: 10.2991/icase-18.2018.28.

[8] Ma P, Li L Q, Wen B Q, Li J B. Design and parameter optimization of spiral-dragon type straw chopping test rig. Int J Agric & Biol Eng, 2020; 13(1): 47–56.

[9] Yang K, Zhao L M, Zhang D B, Cao Y, Hu H. Optimization design of blade curve of straw shredder. Machine Design & Research, 2017; 33(6): 130–133. (in Chinese)

[10] Zhu Z F, Wang J, Zhang Z J, Wang Q, Zeng Y L. Design and experimental study of a new type of cutting rice stalk crusher. Machine Design & Research, 2020; 36(1): 196–201. (in Chinese)

[11] Tian H Q, Huang T, Wang D, Liu F, Han B S. Design of combination screen plate to improve crushing performance of hammer plate feed grinder. Transactions of the CSAE, 2018; 34(22): 45–52. (in Chinese)

[12] Cao L Y, Yang Z W, Jiao W, Zhang Y B, Zhang Y P, Zhang H Y. Noise source identification and noise reduction method of hammer mill. Transactions of the CSAE, 2018; 34(7): 59–65. (in Chinese)

[13] Zasel'skii V I, Zaitsev G L, Zasel'skaya T A. Influence of the granulometric composition of coal batch on the energy requirements of a hammer mill. Coke and Chemistry, 2012; 55(7): 282–285.

[14] Wei S M, Zhang Y X, Cao B, Jia F G. Effect of parameter optimization on crushing effect of straw crusher. Journal of Agricultural Mechanization Research, 2017; 39(9): 158–168. (in Chinese)

[15] Wang D F, Wang M, Li L Q. Mechanism analysis and parameter optimization of hammer mill for corn stalk. Transactions of the CSAM, 2017; 48(11): 165–171. (in Chinese)

[16] Chen L Q, Zhang J Q, Kong X L. Genetic optimal design of straw crusher based on ADAMS. Advanced Materials Research, 2010; 139–141: 929-932.

[17] Zhang X R, Wang Z Q, Li Y, Liang D. Design and experiment of a sliding-cut and anti-wrapping banana straw still-in-field machine. Journal of Agricultural Engineering, 2018; 34 (3): 26–34. (in Chinese)

[18] Wang L J, Zhang Z H, Liu T H, Wang Y J, Jia F, Jiang J X. Design and experiment of cutting and split stalk crushing device for corn harvester. Transactions of the CSAM, 2020; 51(7): 109–117. (in Chinese)

[19] GB/T 26551-2011 Livestock machinery—Fodder chopping, 2011; 11p.

[20] GB/T 6971-2007 Test method for feed mills, 2007; 10p.

[21] Liu W G, Liu W F. Experimental research on influence of the trapezium screen on hammer mill capability. Journal of Agricultural Mechanization Research, 2006; 11: 168–170. (in Chinese)