Compression Characteristics and the Influencing Factors of Sweet Sorghum Straw: Experimental Study

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The rheological properties of the compression process of sweet sorghum straw were studied. The selected experimental factors comprised of the compression density, cutting length, compression speed, and moisture content, and specific energy consumption were selected as the evaluation index of the compression characteristics. The Box-Behnken test scheme was used to analyze the response surface test. The results showed that the selected compression model and specific energy consumption model of the sweet sorghum straw compression process were obtained. The primary factors contributing to energy consumption were the cutting length, moisture content, and compression density. The optimal parameters were as follows: a compression density of 500 kg/m^3, a cutting length of 20 mm to 30 mm, a moisture content of 60.06%, and a specific energy consumption of 66 kJ/kg. The results provided methods for reducing the total energy consumption of the compression process and a theoretical basis for the compression and bundling of sweet sorghum.

Keywords: Sweet sorghum; Compression model; Reduce energy consumption; Optimization

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INTRODUCTION

Straw is a valuable and abundant renewable resource, and also it is an important option for fuel replacement and emission reduction (Bai *et al.* 2018). With the growing global demand for energy, the depletion of fossil fuels, and an increasing concern about the environment, straw has been attracting attention as a source of energy (Moriarty and Honnery 2011; Rasool *et al*. 2019). Sweet sorghum is a crop with high economic value. In addition, its biological output and sugar content are remarkably high. Sweet sorghum straw contains cellulose, lignins, hemicellulose, pectin, crude protein, and other substances, as well as trace amounts of tannins, crude fats, and minerals; therefore, sweet sorghum straw is widely used in the production of feed (Thomas *et al.* 2013; Harper *et al.* 2017). Chai *et al.* (2010) compared the sweet sorghum "Keller" at the late stage of milk maturity with corn stalks and found that the sugar content and nitrogen-free extract of sweet sorghum were twice that of corn stalks. Chai *et al.* (2010) pointed out that sweet sorghum stalks have a higher nutritional value and broader fields of development in comparison with other straw types. Sweet sorghum has a higher bio-productivity than green-fed maize (*Zea mays*), and can save arable land, reduce production costs, and increase agricultural production efficiency (Li *et al.* 2016; Shao *et al.* 2016). When sweet sorghum is used as silage, it can be stored for a long time without a reduction in its nutrient content and palatability. It can also promote the secretion of digestive glands in livestock, enhance animal immunity, improve digestibility, prevent livestock constipation, *etc.* (Wang *et al.* 2013; Du *et al.* 2018). Nevertheless, crop straw always has a high moisture content, a heterogeneous nature, poor biological stability, and a low energy density. These drawbacks make it difficult to use and increase processing, transportation, and storage costs (Li *et al.* 2012; Toscano *et al.* 2015; Yu *et al.* 2018).

Mechanical compaction is an effective method to reduce the volume of biomass. Pellets, cubes, and briquettes have a higher density than bales or grinds; this gives the compacted biomass an advantage in terms of transportation and storage (Johnson *et al.* 2013; Li *et al.* 2013).

Mewes *et al.* (1959) established a mathematical model between the compression force and material density under different compression conditions. Guo *et al.* (1995) used corn stalk as the raw material for compression molding tests. It was found that with an increase of moisture content, the particle density decreased, and the optimum moisture content was approximately 30%. The density of the formed particles was 1000 kg/m^3. Tabil and Sokhansanj (1996) studied four compression models and found that the Cooper-Eaton model was the best fit for the compaction of alfalfa grinds. Ma *et al.* (2016) studied the vibration compression process of corn stalks with a moisture content of 18%, a particle size of 0 mm to 4 mm, and a compression speed of 4.6 mm/s, which provided a theoretical basis for the study of new biomass compacting equipment. In addition, although previous studies have shown that the compression density, moisture content, material type, and compression speed have a major influence on the rheological properties of the compressed material, *e.g.*, corn, alfalfa, and rice straw (Adapa *et al.* 2009; Wang *et al.* 2016; Guo *et al.* 2017), only the studies by Gong (2017) were dedicated to analyzing the effects of silage corn straw with a moisture content less than 65% and different chopped lengths on compression force.

Therefore, it is of great importance to study the compression characteristics of sweet sorghum silage with a high moisture content and chopped sections of different lengths. The objectives of this study were to: (1) establish a compression model and specific energy consumption model for the compression process of high-moisture-silage sweet sorghum straws; and (2) analyze the effects of different experimental factors on the compression characteristics and specific energy consumption, as well as obtain the main order and the optimal parameter combination of various factors affecting the specific energy consumption.

EXPERIMENTAL

Material

The sweet sorghum was obtained from the suburbs of Hohhot, China. The average height ranged from 2000 to 4000 mm, and the average diameter ranged from 10 to 15 mm. Sweet sorghum straw is rich in cellulose, sugar, lignins, hemicellulose, pectin, and crude protein, and it also contains traces of tannins, crude fats, and minerals (Shao *et al.* 2016). It was determined that the density of sweet sorghum straw was 20 to 40 kg/m^3 in a natural loose state (Du *et al.* 2018). Figures 1 and 2 show the material before compression and the molded block after compression, respectively.

Each of the ground straws were conditioned by cutting them to lengths of less than 10 mm, 10 to 20 mm, 20 to 30 mm, and 30 to 40 mm. The straw was harvested using a 9Z-6A silage mower (China Agricultural Machinery North China Group Co., Ltd., Henan, China), and the length of the shredding segment was controlled by changing the number of gears of the mower and the number of moving blades.

The initial average moisture content of the straw after subjecting it to natural air drying was 22.6%, which was determined *via* a DYSF-8000W automatic moisture analyzer (Hebi Electronic Research Institute Co., Ltd., Henan, China). The moisture content of the straw samples was measured according to ASAE standard S358.2 (2008). According to the test requirements, each of the ground straw specimens were conditioned to moisture contents of 50%, 57%, 64%, 71%, and 78% (by weight) by adding appropriate amounts of distilled water to the samples contained in plastic bags and stored in a cool room at 4 °C for 24 h. Each sample was done in triplicate, and the individual samples had the same weight. In addition, the sugar content was approximately 16% within the measured moisture content range (50% to 78%). Therefore, the author's ignored the influence of the sugar content on the straw compression process. The calculation formula of the moisture content of the material is shown in Eq. 1,

$$M_W = \frac{m_1 - m_2}{m_1} \times 100\% \quad (1)$$

where M_w is wet basis moisture content (%), m_1 is the quantity of fresh materials (g), and m_2 is the quantity of dry materials (g).

Fig. 1. Material before compression

Fig. 2. Molded block after compression

Compression Experiments

The compression experiments were conducted using a DDL-200 universal computer-controlled electronic tester (Changchun Research Institute for Mechanical Science Co., LTD, Changchun, China) and a self-made adjustable compression discharge device. The self-made compression unloading device consisted of two parts, the compression portion and the discharge portion, which were composed of a cylindrical sleeve with an inner diameter of 98 mm and a length of 300 mm, a circular indenter, a pressure bar, a diversion hole, a unloading bin, and a discharge unloading plate (Fig. 3). The movable beam is moved up and down by the beam of the universal computer-controlled electronic tester to complete the compression process and obtain the force-time curve.

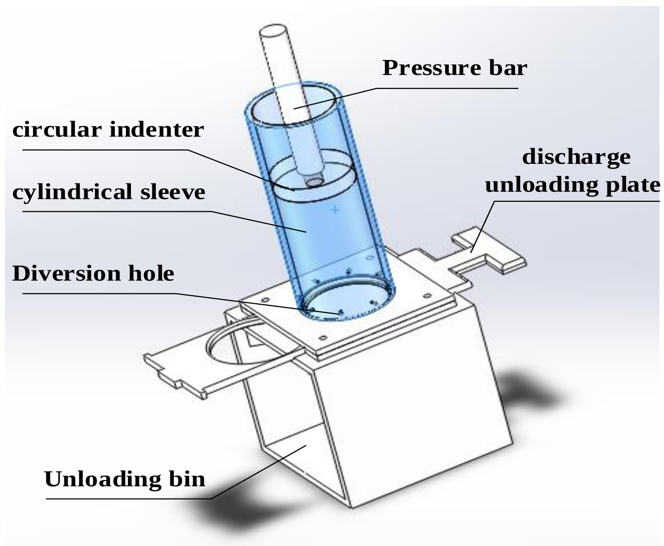

Fig. 3. Compression discharge device

RESULTS AND DISCUSSION

Compression Models

Several previously reported models were used to analyse the experimental data for the compression of straw samples. Butler and McColly (1959), Osobov (1967), Rehkugler *et al.* (1969), O'Dogherty and Wheeler (1984), and Faborode and O'Callaghan (1987) established mathematical models under different experimental factors, and each of their respective models have importance in terms of compression research. In order to obtain a compression model and specific energy consumption model of sweet sorghum straw, the experimental data were analyzed using MATLAB 2014 (MathWorks, Natick, MA). The compression models were fit to the experimental data using Origin software 8.5 (OriginLab, Northampton, MA). It was concluded that the compression characteristics of the sweet sorghum straw compression process could be described by Eq. 2, and the fitting correlation coefficient was greater than 0.99 (Fig. 4). The fitting equation is as follows,

$$y = Ae^{\frac{x}{b}} + c \tag{2}$$

where y is the compression force (N), x is compression displacement (mm), and A, b, and c are fitting coefficients of the material as it changes with displacement-force during compression.

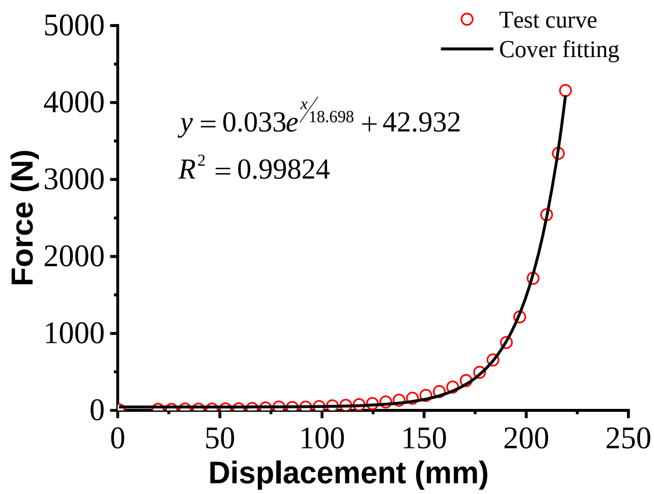

Fig. 4. Compression curve fitting

Specific Energy Consumption

Specific energy consumption (δ) is an important technical index for analyzing whether the dense molding process is reasonable, *i.e.*, the energy required for the unit mass of agricultural fiber material after compression molding (Mahdi *et al.* 2014). The specific energy consumption calculation formula is shown in Eq. 3,

$$\delta = \frac{W}{m} = \int \frac{F(x)}{m} \mathrm{d}x \tag{3}$$

where δ is the specific energy consumption of the compression process (kJ/kg), W is the total energy consumption of the compression process (kJ/kg), m is the material weight (kg), $F(x)$ is the compressive force that varies with displacement during compression (N), and dx represents an integral symbol for $F(x)$.

Moisture Content Analysis

The results of the moisture content analysis are presented in Fig. 5. High moisture content considerably increased the density of the compacted samples, confirming previous studies (Talebi *et al.* 2011; Lei *et al.* 2015; Du *et al.* 2018). Figure 5 shows the change curve of straw at different moisture content of 50, 57, 64, 71, 78%, which are for the test conditions of density of 600 kg/m^3, compression speed of 200 mm/min, and cutting length of 10 to 20 mm. With an increase in compression displacement, when the moisture content of sweet sorghum straw changed from 50% to 78%, the compressive force required to generate the same density was reduced (as shown in Fig. 5a), which indicated that a higher moisture content could result in a greater compression density under a lower pressure, thus reducing the amount of energy required. The primary reason for this effect is the increase in moisture content of the material; the more water flows out of the material during the compression process, the greater the reduction in the gap between the materials, thus reducing the air resistance. This phenomenon resulted in a reduction of the friction between the materials and accelerated the fluidity between the materials. The greater the compressibility of the material, the worse the material is able to resist deformation (Han *et al.* 2012). This demonstrated that the low moisture content was not enough to fill the gaps between the sweet sorghum stalks, and the free water formed a concave meniscus liquid film on the contact and non-contact convex bodies between the materials, leading to an increase in overall resistance. However, when the moisture content is too high, the water between the materials is squeezed out to fill the gaps between the materials, and water acts as a lubricant, thus reducing the friction resistance. Moreover, these results were consistent with the reports of Huang *et al.* (2017) and Li *et al.* (2014), who found that the addition of water could reduce the friction among particles and mold or the densification equipment.

As shown in Fig. 5b, the δ decreased as the moisture content of the material was increased. When the moisture content was reduced from 57% to 64%, the decreasing trend of δ slowed. When the moisture content was greater than 64%, δ tended to rapidly decline. This demonstrated that the increase in moisture content reduced the friction between the materials and accelerated the fluidity of materials, so the softening degree of materials is increased as well, which promoted the compressibility of sweet sorghum straw. In addition, the friction between the material and the inner wall of the compression device was reduced, so the greater the moisture content of the material, the less energy was required for the molding process. Similar observations were made by Bai *et al.* (2017), who reported that the energy consumption during densification decreased as the moisture content increased.

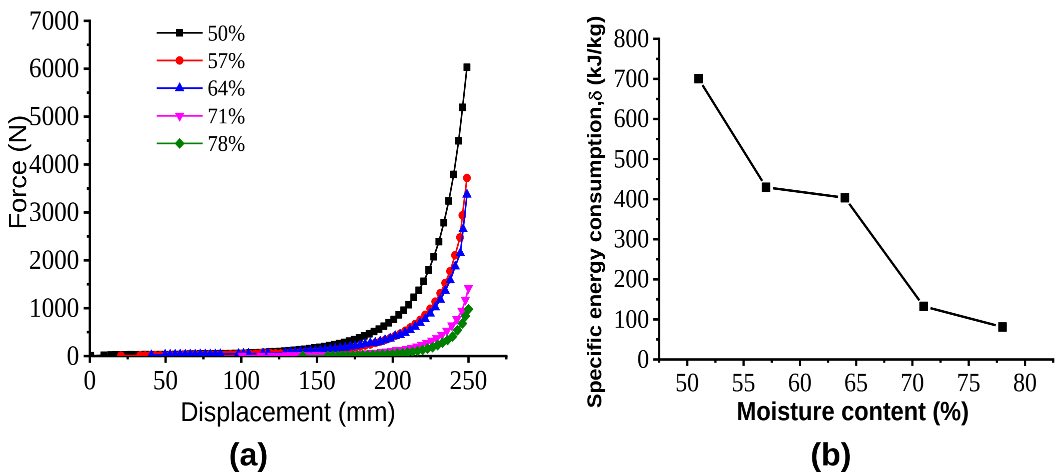

Fig. 5. Effect of (a) the moisture content on the compression characteristics of sweet sorghum straw and (b) the moisture content on compression specific energy consumption

Cutting Length Analysis

The results of the cutting length analysis are presented in Fig. 6, which are under the test conditions of density of 600 kg/m^3, compression speed of 200 mm/min and moisture content of 64%. It can be seen in Fig. 6a that when the moisture content, compression density, and compression speed stayed constant, the compression force increased as the cutting length increased. However, when the cutting length was 20 mm to 40 mm, an increase in the required compressive force was not obvious, which indicated that when the cutting length was greater than 20 mm, the change in compression force decreased. The primary reason for this phenomenon was that when the cutting length was less than 10 mm, the porosity between the materials was small, and therefore the compression force required for the compression process was relatively small. When the cutting length increased, the porosity between the materials increased. As a result, the air resistance in the compression device increased, and the compressibility of the material deteriorated, so the amount of compression force required during the compression process increased. This indicated that less compression force was required for the compression process when the cutting length of the material was small.

The cutting length reflected the crushing degree of the material; therefore, the cutting length affected the δ value of the compression process. It can be seen in Fig. 6b that as the cutting length increased, the δ value of the compression process gradually increased. However, when the cutting length was greater than 30 mm, the rate at which the δ value increased was reduced. It was shown that the smaller the cutting length of sweet sorghum straw, the easier the material was to be compressed, and the smaller the δ of the machine. On the contrary, the longer the cutting length of the material, the more energy was consumed during the compression molding process. The test results were consistent with the compression energy consumption of finely divided materials (Guo 2016). Thus, the larger the particle size of the material, the greater the δ, which indicated that the powder with a larger particle size required more energy in the compression molding process (Fan *et al.* 2008; Wang *et al.* 2018).

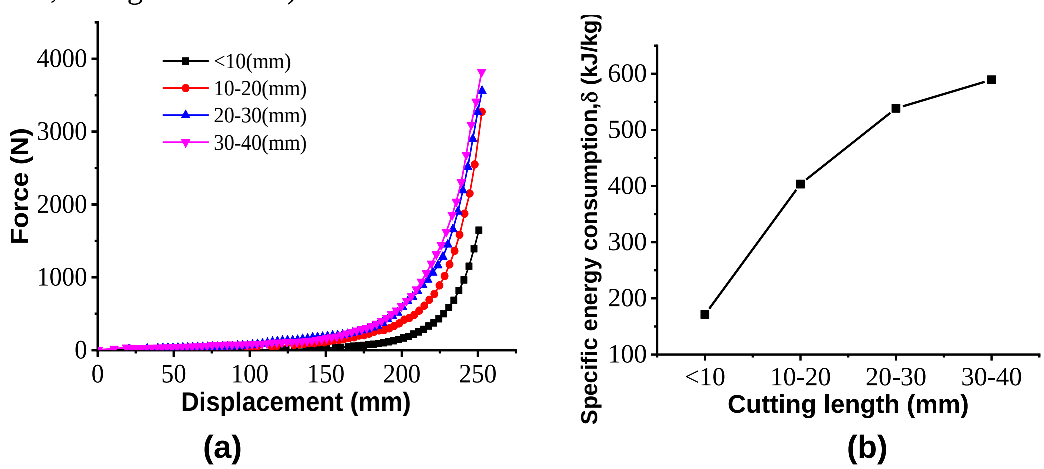

Fig. 6. Effect of the (a) cutting length on the compression characteristics of sweet sorghum straw and (b) cutting length on the compression specific energy consumption

Compression Density Analysis

The results of the density analysis are presented in Fig. 7, which are under the test conditions of cutting length of 10 to 20 mm, compression speed of 200 mm/min, and moisture content of 64%. As the compression density increased, the compression force required for the molding process increased (Fig. 7a). However, the displacement of compression remained basically the same, which indicated that the compression density had little effect on the compression time. In addition, the process of sweet sorghum straw from loosening to compaction can also be found. When the material is in the initial stage of compression, pores were present in abundance between the filled materials. Therefore, during the initial compression stage, the material undergoing the compression molding process was not affected by the compression density and was continuously pressed. In fact, during the forming process, the force of the material instantaneously changed. The primary reason for this is that as the material was compacted, the porosity between materials became almost zero; the compressibility of the material deteriorated, and the material became almost solid (Fan *et al.* 2008). As a consequence, the compression force in the compression process instantaneously increased.

The compression density reflects the degree of compaction in the straw compression process (Guo 2016). The effect of compression density on the δ value of the sweet sorghum straw compression process is shown in Fig. 7b. The analysis found that when the material density was continuously increased from 400 to 800 kg/m^3, the δ value in the compression process increased in a linear trend, which indicated that when the compressive density of the material increased, the properties of the material changed, and the internal structure was destroyed. In addition, the frictional resistance between the materials increased. When the compressive density of the material was high, the material was close to solid, and the compressibility of the material deteriorated. Therefore, the greater the compression force required for the forming process, the greater the amount of energy consumed by the forming process. Generally, this could be explained by the observation that the higher the density, the higher the energy consumption (Demirbas and Sahin-Demiras 2009).

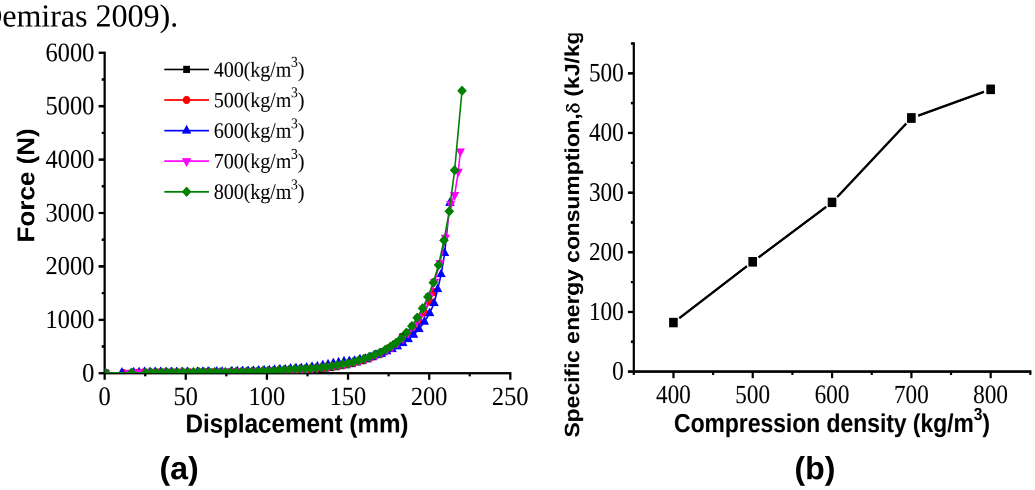

Fig. 7. Effect of the (a) compression density on the compression characteristics of sweet sorghum straw and (b) compression density on the compression specific energy consumption

Compression Speed Analysis

The results of the compression speed analysis are presented in Fig. 8, which are under the test conditions of density of 600 kg/m^3, cutting length of 10 to 20 mm, and moisture content of 64%. When the compression speed of the sweet sorghum straw molding process was increased from 100 to 500 mm/min, the compression force required for compression molding was basically consistent, and the compression displacement was basically equal (Fig. 8a). This showed that the compression speed had little effect on the compression force. The greater the compression speed when processing the material, the shorter the time required for the material compression molding process. The primary reason for this phenomenon is that the greater the compression speed, the greater the impact of the material and the greater the damage to its structure (Fan *et al.* 2008). Therefore, the expansion force of the straw was reduced, and the compression resistance was reduced, so the compression time was shortened. This showed that an increase in compression speed was beneficial for shortening the total time of the straw compression molding process and had little effect on the compression force.

As shown in Fig. 8b, when the compression speed was less than 200 mm/min, the δ in the straw compression process rapidly increased. When the compression speed was greater than 200 mm/min, the δ in the straw compression process slowly decreased. This demonstrated that the compression speed in this test had little effect on the specific energy consumption during the compression process. The primary reason for this was that the materials were squeezed at different compression speeds during the compression process. However, in terms of the whole compression molding process, the molding time of the material is proportional to the compression force, which leads to the change in the compression speed. Therefore, the influence on δ was minimal, and even showed an inconspicuous change trend.

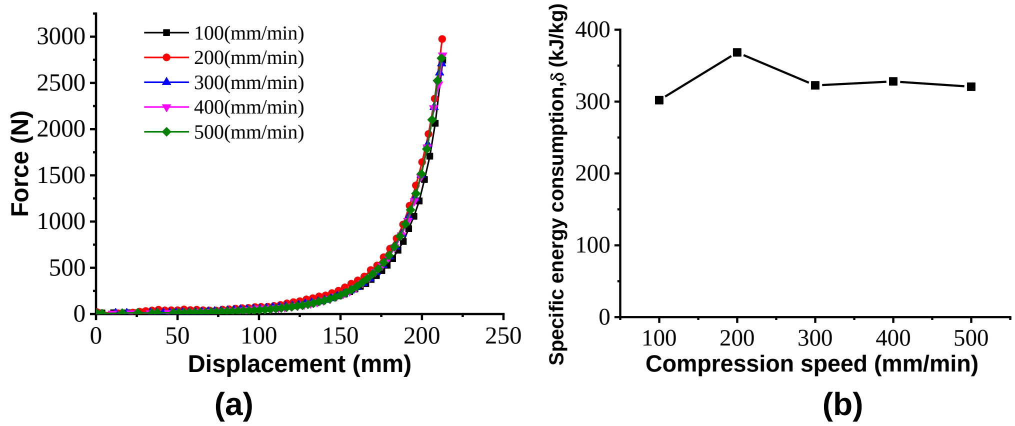

Fig. 8. Effect of the (a) compression speed on the compression characteristics of sweet sorghum straw and (b) compression speed on the compression specific energy consumption

Parameter Optimization Test and Verification

Response surface test design

Through the compression test results (shown above) of sweet sorghum straw, it can be seen that the compression density, cutting length, and moisture content of the straw had a major influence on the δ value during the compression process of sweet sorghum, while the compression speed had a lesser influence on the δ value. Therefore, using the Box-Behnken test scheme, a three-factor and a three-level response surface analysis test were carried out with the compression density, cutting length, and moisture content of the straw as the test factors, and the δ as the test index. The level of each factor is shown in Table 1. Moreover, δ was selected as the evaluation index of the compression characteristics of sweet sorghum straw.

Table 1. Experimental Factors and Levels

Level	Compression Density (kg/m^3)	Cutting Length (mm)	Moisture Content (%)
-1	500	Less than 10	57
0	600	10 to 20	64
1	700	20 to 30	71

Response Surface Test Results Analysis

Seventeen experimental runs were predicted *via* the Box-Behnken test scheme on the basis of the initial range of the operating parameters (Table 2), which indicated that the δ value of the sweet sorghum straw compression process ranged from 65.75 to 579.3 kJ/kg.

Table 2. Scheme and Results of the Response Surface Experiments Design

Test Number	Levels of Factors			δ (kJ/kg)	Test Number	Levels of Factors			δ (kJ/kg)
	A	B	C			A	B	C	
1	-1	-1	0	324.85	10	0	1	-1	109.275
2	1	-1	0	579.34	11	0	-1	1	431.59
3	-1	1	0	65.754	12	0	1	1	295.545
4	1	1	0	200.69	13	0	0	0	402.365
5	-1	0	-1	112.17	14	0	0	0	311.195
6	1	0	-1	239.045	15	0	0	0	367.505
7	-1	0	1	382.825	16	0	0	0	376.845
8	1	0	1	428.035	17	0	0	0	358.274
9	0	-1	1	319.28					

Note: A, B, and C are the coded values for the compression density, cutting length, and moisture content, respectively; *δ* is the specific energy consumption.

Specific Energy Regression Model and Specific Energy Variance Analysis

The regression model and the variance analysis of *δ* and various experimental factors were obtained using the Design Expert data analysis software (Trial Version 9.0.3.1, Stat-Ease Inc., Minneapolis, MN), as shown in Table 3, and was calculated according to Eq. 4,

$$\delta = 312.03 + 70.19A - 122.97B + 94.78C \tag{4}$$

where *A* is the compression density (kg/m^3), *B* is the cutting length (mm), and *C* is the moisture content (%).

The F-value explained the distribution of the actual data around the fitted model and the *p*-value defined the significance of the model terms (as shown in Table 3). A lower F-value was desirable, and in present study, the F-values were not high for all responses (Garg and Prasad 2016). In this study, the *p*-values of the model were less than 0.0001, *i.e.*, at probability values of less than 0.05, which demonstrated a higher significance of the model. This also further supported the fact that Eq. 4 was able to adequately predict the experimental results with a high degree of accuracy. Moreover, the fitting coefficient (R^2) of the model was 0.8244, and the coefficient of variation was 19.77% (as shown in Fig.9), which indicated that the regression model fit well with the test results.

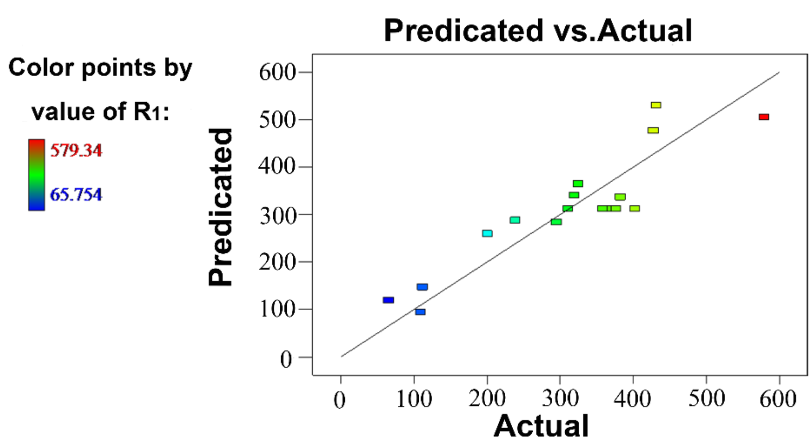

Fig. 9. Predicated versus actual for the specific energy consumption

The correlation between the predicted value and the experimental value was highly correlated and the test error rate was small, meaning that the model could be used to predict the change in δ of the sweet sorghum straw compression process. Moreover, according to the analysis of variance, it was clear that the significance of each factor of the evaluation index was determined by the F-value. The higher the F-value, the more obvious the influence of the experimental factor on the test index (Essa *et al.* 2015). From the primary item F-value shown in Table 3, the primary and secondary order of each factor to the evaluation index was as follows: B was more than C which was more than A. There was no interaction between the three factors from the primary item P-value.

Table 3. Analysis of Variance of the Regression Model of the Specific Energy Consumption

Source of Variance	Sum of Square	Degrees of Freedom	Mean Square	F-value	*p*-value
Model	2.323E + 005	3	77418.93	20.35	< 0.0001
A	39411.83	1	39411.83	10.36	0.0067
B	1.210E + 005	1	1.210E + 005	31.80	< 0.0001
C	71863.14	1	71863.14	18.89	0.0008
Lack of fit	449989.77	9	4998.86	4.48	0.0814
Pure error	4467.40	4	1116.85		
Cor total	2.817E + 005	16			

Note: a *p*-value of less than 0.01 means extremely significant and a *p*-value of less than 0.05 means significant.
Note: A, B, and C are the coded values for the compression density, cutting length, and moisture content, respectively; δ is the specific energy consumption.

Parameter Optimization Text

In order to reduce the δ value of the sweet sorghum straw compression process, the Design Expert software optimization module was used to further optimize the regression equation. The constraints are shown in Table 4.

The optimum combination of process parameters for the sweet sorghum straw compression process were as follows: a compression density of 500 kg/m^3, a cutting length of 20 to 30 mm, a moisture content of 60.06%, and a δ of 66 kJ/kg. Furthermore, the test verified that the error rate of each evaluation index was within 10%, and its prediction value was as high as 0.946, which indicated that the optimization results had high credibility. In addition, it was shown that the specific energy regression model obtained was reliable and could be used to select various parameters in an actual production process.

Table 4. Optimization Constraint Settings

Name	Goal	Lower Limit	Upper Limit
Compression density (kg/m^3)	in range	500	700
Cutting length (mm)	in range	5	30
Moisture content (%)	in range	60	70
δ (kJ/kg)	minimize	65.754	579.34

CONCLUSIONS

1. A compression model was obtained for sweet sorghum straw, and a specific energy consumption model was obtained for the compression process of high-moisture-silage sweet sorghum straws. The influence of various experimental factors on the compression process was also analyzed.
2. The primary and secondary factors affecting the specific energy consumption were obtained, and they were as follows: cutting length was more than the moisture content, which was more than the compression density.
3. The optimal combination for reducing the specific energy consumption was as follows: a cutting length of 20 mm to 30 mm, a moisture content of 60.06%, a compression density of 500 kg/m^3, and the optimal value of specific energy consumption (δ) was 66 kJ/kg. The verification test showed that the specific energy regression model was reliable and could be used to select various parameters in an actual production process.

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