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STUDY ON PREPARATION TECHNOLOGY OF HIGH-QUALITY BIOMASS FUEL PELLETS USING *CARAGANA KORSHINSKII* KOM. POWDER

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ABSTRACT

Caragana korshinskii Kom. powder was used as the experimental material and wheat bran as the binder to produce high-quality biomass molding fuel (BMF) pellets. A series of experiments involving pellet production were conducted in different molding temperatures and at different moisture contents with different percentage of wheat bran by a newly-developed pelletizer using a die heating production method. The biomass molding process was optimized by single factor and orthogonal test with the fuel relaxation density, mechanical durability and molding pressure as indexes. The experimental results showed that the optimum moisture content was 20% by mass percentage of wheat bran is 9% by mass and molding temperature is 140°C in order to get the best quality of high-strength BMF pellets with relative low molding pressure.

KEYWORDS: *Caragana korshinskii* Kom., wheat bran, biomass molding fuel pellets, relaxation density, mechanical durability.

INTRODUCTION

Currently, biomass is the fourth largest energy source in the world. It accounts for about 14% of the world's energy consumption (Gao et al. 2023). In recent years, more and more residues of agriculture and forestry such as wood chips, sawdust, bamboo chips, straw, rice chaff, bagasse, fruit husks, even animal excrements are usually made into BMF pellets for energy producing applications (Kažimírová et al. 2020, Zheng et al. 2022, Spirchez et al. 2019, Wang et al. 2018). The utilization of agriculture and forest renewable resources as raw materials is beneficial to the ecological balance of the earth because it can significantly reduce net carbon emissions to the atmosphere. To some extent, biomass provides a good substitute for fossil fuels (Wei et al. 2012). Currently, the BMF production in Germany, Sweden, Finland, Denmark, Canada and the United States can reach more than 20 million tons per year (Ma et al. 2019).

However, the development of BMF in China still falls behind these countries (Guan et al. 2020). In 2018, the utilization of BMF has reached 18 million tons (Zhang 2018), and began to be used to replace fossil fuel like petroleum, coal and natural gas. China has an abundance of forestry and agricultural residue resources that can be used to produce biomass molding fuels for energy applications (Liu et al. 2013). However, the relatively low relaxation density and mechanical durability of BMF pellets limit its massive application because employing these raw materials will result in problems in storage, transportation and use (Eranki et al. 2011). Various densification methods have been applied to overcome these shortcomings to increase the bulk density of biomass molding fuels (Tumuluru et al. 2010). Previous studies have shown that some variables such as raw materials species, particle sizes, moisture content and processing techniques have great effects on the quality of the BMF pellets.

China is rich in *Caragana korshinskii* Kom. resources. Only in Ulanqabu League of Inner Mongolia Autonomous Region, there are 920,700 hm^2 of Caragana korshinskii Kom. forest resources, which can produce 5.524 million tons of fresh branches. According to the parallel cropping, the annual output of fresh *Caragana korshinskii* Kom. is about 1.84 million tons. *Caragana korshinskii* Kom. has a strong ability of branching and regeneration. If it has not gotten stubbled timely, its growth and life will be affected greatly. At present, the exploitation and utilization of *Caragana korshinskii* Kom. resources in Ulanqab are mainly in three aspects: processing and utilization of *Caragana korshinskii* Kom. fodder, planting of edible fungi using *Caragana korshinskii* Kom. substrate and production of biomass molding fuel pellets. Because of the rapid lignification of the branches, the rough and hard branches, and the poor palatability of livestock, if the whole plant is fed to the livestock, it will cause a great waste to the coarse *Caragana korshinskii* Kom. branches.

In recent years, in order to expand the application range of *Caragana korshinskii* Kom., more and more research has been done on the preparation of biomass fuel using *Caragana korshinskii* Kom. powder as the raw material. Zhang et al. (2014) investigated the influence of pressure, temperature, moisture content and particle size on the physical properties (density, durability, compressive strength and impact resistance) of *Caragana korshinskii* Kom. briquettes. They found that particle size and moisture content are the two dominating factors. The rank order of each factor is particle size, moisture content, temperature, and pressure. The smaller the particle size, the lower the moisture content, and the higher the temperature, the better the quality of pellets. Zhang et al. (2021) improved the design method of the molding die of the piston roller biomass molding machine, and explored the influence of the inlet structure of the molding hole and the meshing depth of the plunger and the molding hole on the molding effect, which provided support for the design of the molding die and the improvement of the quality of the biomass molding fuel. Using caragana as raw material, Ji et al. (2021) carried out compression molding experiments on a hydraulic piston molding machine under different water content and length-diameter ratio of molding sleeve, and measured and analyzed the radial force of biomass in the molding process.

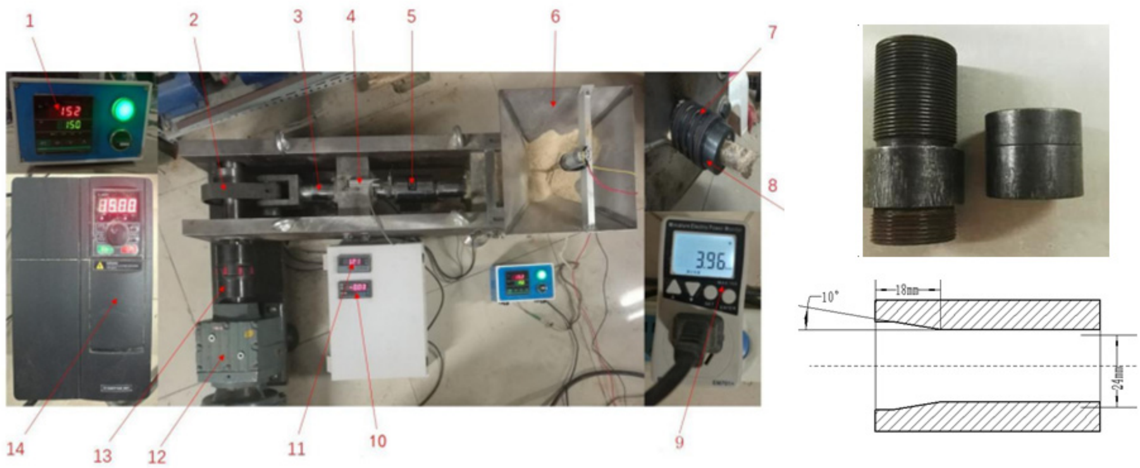
Molding pressure is an important factor affecting energy consumption. The greater the molding pressure is, the greater the energy consumption is needed for the molding process. However, very few studies have analyzed the effect of binder on molding pressure and quality of the BMF pellets. Wastes from various industries, including biomass, oil sludge, heavy coal tar fractions, sulphite liquors and lignin are used as binders to lower the cost and solve simultaneously two problems: *i)* upgrading the quality of BMF pellets to a standard level and *ii)* increasing waste utilization (Balraj et al. 2021, Zhang et al. 2018, Trubetskaya et al. 2019, Li et al. 2015, Yaman et al. 2001). Wheat bran is known to be wasted in massive amounts in the flour milling industry because of difficulties in its direct utilization as a fuel (Tabakaev et al. 2020), thus making it popular binder used in the present research. Wheat bran production in amounts up to 19% of milled wheat presents a problem for millers, since its utilization in animal and poultry feed rations may not exceed 20% (Cui et al. 2013, Warren et al. 1990, Wang et al. 2019, Ruan et al. 2015, Galliard et al. 1988).

Therefore, this paper used *Caragana korshinskii* Kom. powder as the raw material and wheat bran as a binder to prepare of biomass molding fuel in order to reduce energy consumption, increase the relaxation density and improve the mechanical properties of the BMF pellets.

MATERIAL AND METHODS

Experimental equipment

The self-designed single-plunger pelletizer was used as the experimental equipment for this study (Fig. 1).



(a) *(b)*

Fig. 1: Mechanical structure of the single-plunger pelletizer (a), pelletizing mold (b).

1- temperature controller and monitor reducer, 2- eccentric wheel, 3- molding plunger, 4- displacement sensor, 5- pressure sensor thermocouple, 6- hopper, 7- heating coil, 8- cylinder mold, 9- electrical power detector, 10- pressure indicator, 11- displacement indicator, 12- motor, 13- coupling, 14- frequency converter.

As shown in Fig. 1a, the power source part is composed of three-phase asynchronous motor (model YE2-132M-4), reducer (reduction ratio of 6:1) and frequency converter (Siemens Micromaster 440). The transmission system is composed of an eccentric wheel and a molded plunger, and the reducer is connected with the eccentric wheel through a coupling to drive the molded plunger back and forth movement. The feeding system consists of a micro-screw feeder and a storage bin. The biomass raw materials are transported to the storage bin of the forming machine by the micro-screw feeding mechanism in the hopper to ensure uniform feeding during the experiment. The forming system consists of a forming mold (length-diameter ratio 4.2) and the molding plunger. The forming plunger presses the biomass raw material into the storage bin of the forming machine into the forming mold on the coaxial line of the forming plunger, so as to extrude the forming. The auxiliary system consists of a heating coil, a pressure sensor and a displacement sensor. The heating temperature of the coil is changed by adjusting the temperature controller (CHB401) parameters to control the forming temperature. The pressure sensor (LDCZL-ZK) and displacement sensor (KTM-50) are used to measure the axial positive pressure and axial motion displacement of the molded plunger in real time. The forming pressure can be read directly from the pressure indicator. The pelletizing mold used in this experiment is shown in Fig. 1b. The cone angle of the selected mold is 10°, the length of the cone hole segment is 18mm, and the diameter of the cylindrical straight hole is 24 mm. The length-diameter ratio of the pelletizing mold is 4.2.

Experimental materials

Five-year-old and above *Caragana korshinskii* Kom. was used as the raw material in this study. It was grown in Ulanqabu League of Inner Mongolia Autonomous Region, China and harvested in the autumn of 2022, after harvesting was stored for approximately six months in a roofed open-air storage building and then stored for two months in the laboratory of Beijing Forest University. Wheat bran from a flour-milling company located near to the *Caragana korshinskii* Kom. forest was used as a binder. *Caragana korshinskii* Kom. branches and twigs samples dried at ambient temperature were crushed to the grain size below 1.0 mm using a DGSch160/100 crusher (Russia). Wheat bran was ground to a powder with the particle size below 200 μm using Pulverisette 6 planetary mill (Fritsch, Germany). Pulverized wheat bran was mixed with the crushed *Caragana korshinskii* Kom. powder in amounts of 3, 6,9,12 and 15 wt% of the total dry mixture mass. The mixture samples were moistened to 5,10,15,20 and 25 wt% of water content relative to the total mass of moist mixture and mixed using MX-800 mixer (DEXP, China). And the ingredients were thoroughly mixed together and preserved in zip-lock plastic bags at 5°C for 48h before use to avoid water evaporation.

Experimental method

Single factor optimization experiment

The influence of wheat bran content, molding temperature and moisture content on the molding process was studied by changing one factor parameter and fixing the other factors. The procedure of single factor test is as follows. With fixed wheat bran content of 9% and water content of 15%, the effects of different temperatures (20°C, 60°C, 100°C, 140°C, 180°C) on the molding pressure and relaxation density of the molding fuel were studied. The content of fixed wheat bran was 9%, the molding temperature was 60°C, and the influence of different water content (5%, 10%, 15%, 20%, 25%) on the molding pressure and relaxation density of the molding fuel was studied. The fixed water content was 15% and the molding temperature was 60°C. The effects of different wheat bran contents (3%, 6%, 9%, 12%, 15%) on the molding pressure and relaxation density of the molding fuel were studied.

Orthogonal optimization experiment

According to the conditions determined by the single factor test, the three-factor and three-level orthogonal test was designed to further optimize the forming process.

Average molding pressure

The mixture of *Caragana korshinskii* Kom. powder and wheat bran powder was fed into the hopper, stirred by a screw set up at the bottom of the hopper to ensure uniform feed occurred in front of the piston. Each experiment with different percentage of wheat bran, molding temperatures and different moisture contents was replicated 3 time. The forming pressure of each experiment can be read directly from the pressure indicator and the average molding pressure was calculated.

The properties of the pellets

The relaxation density of the pellets was calculated by measuring the length and the diameter of each pellet using an electronic caliper and by measuring the mass of the pellet using an electronic balance (Model SF-400A, Suofei electronic balance factory, Jiangsu, China) with a precision of 0.01g. Relaxation density was calculated by:

$$\rho = \frac{4m}{\pi d^2 l} \quad (1)$$

where: ρ is the relaxation density (g/cm^3); m is the mass of the pellet (g); d is the diameter of the pellet (cm); l is the length of the pellet (cm).

The mechanical durability of pellets was calculated by Eq. 2. ISO 17831-1 (2015) standard requires attrition tests conducted with the 0.5 kg test sample placed in a 500 mm long cylindrical box with D=500 mm rotating at 50 rpm for 10 min, where BMF particles collide with each other and the internal surface. The tested sample is sieved with oversize fraction of 3.15 mm taken for weighting.

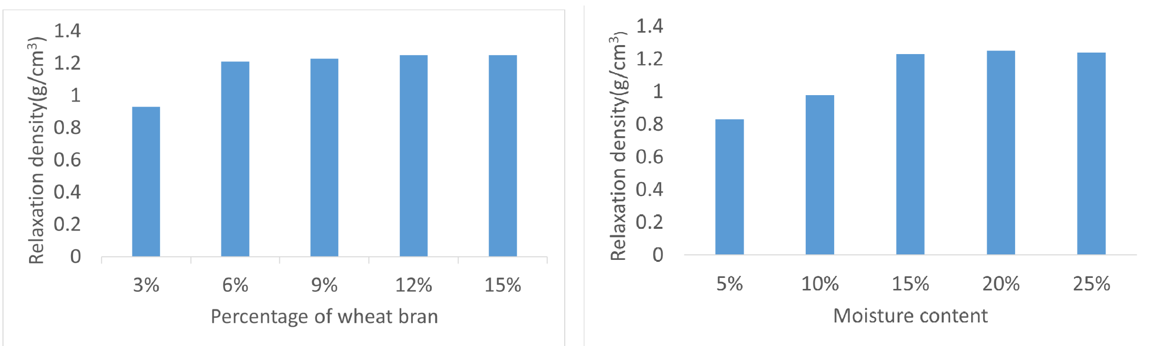
$$DU = \frac{m}{M} \times 100\% \quad (2)$$

where: DU is the mechanical durability of pellets (%); m is the after-test mass of pellet lumps whose sizes are not less than 3.5 mm (kg), M is the total mass of pellet sample taken for testing (kg).

RESULTS AND DISCUSSION

Effect of different wheat bran content on relaxation density

From Fig. 2a, it can be seen that the relaxation density of biomass molding fuels shows a gradual increasing trend with the increase of wheat bran content. This is because wheat bran, as an organic substance, can effectively fill the voids between the fuel particles during the molding process, thus increasing the relaxation density of the finished product. At the same time, an increase in bran content also means a relative decrease in the use of other additives such as binders and water, which also contributes to an increase in the relaxation density of the finished product. However, when the bran content exceeds a certain value, the effect on the relaxation density decreases as the content continues to increase. This may be due to the fact that the interactions between the bran begin to impede the filling effect, resulting in a slower rate of increase in relaxation density. Therefore, in order to improve the quality and performance of biomass molding fuel, the content of wheat bran can be increased appropriately. However, it should be noted that too high bran content may affect other performance indexes of the molded fuels, so it needs to be optimized and adjusted according to the demand in the actual production. Therefore, according to the experimental results, we choose three levels of percentage of wheat bran 6%,9% and 12% for orthogonal tests.



(a) *(b)*

Fig. 2: Effect of different wheat bran content (a) and moisture content (b) on relaxation density.

Fig. 2b shows that the relaxation density of biomass molding fuels tends to increase with the increase of water content. This is because moisture acts as a binder in the molding process, which helps to tightly bond the particles together, thus increasing the relaxation density of the finished product. However, high moisture content may lead to stresses within the molded fuel, increasing its brittleness and affecting its long-term stability. Therefore, according to the experimental results, we choose three levels of moisture content 15%, 20% and 25% for orthogonal tests. Fig. 3 showed that the relaxation density of biomass molding fuels tended to increase with the increase of molding temperature. This is because at high temperatures, the molecular activity of biomass feedstock is enhanced, which is easy to flow and bond, thus improving the density of the finished product. At the same time, the high temperature also helps to eliminate the internal stress in the biomass feedstock and reduce cracks and defects in the molding process, further improving the density and stability of the finished product. However, excessively high molding temperatures may lead to excessive softening or pyrolysis of the biomass feedstock, affecting its physical structure and thermal stability. Therefore, according to the experimental results, we choose three levels of molding temperature 100°C, 140°C and 180°C for orthogonal tests.

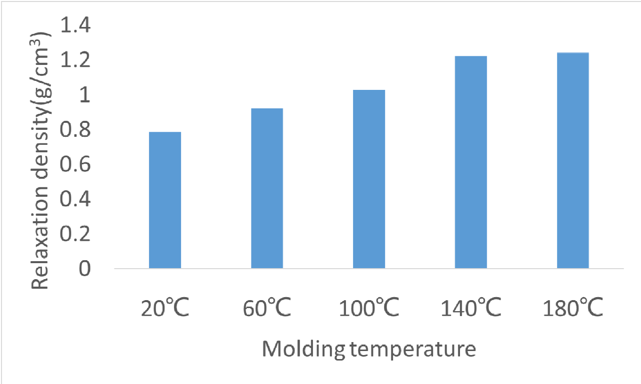


Fig. 3: Effect of different molding temperature on relaxation density.

Orthogonal optimization experiment

According to the results of single factor experiment, the orthogonal experiment of three factors and three levels was designed to further optimize the forming process. The statistical table of the relaxation density and the mechanical durability of the pellets are shown in Tab. 1.

Tab. 1: Results of the orthogonal experiments.

No	Wheat bran content (%)	Moisture content (%)	Temperature (°C)	Empty column	Molding pressure (MPa)	Relaxation density (g/cm^3)	Mechanical durability (%)
1	6	10	100	1	163.9	0.987	96.5
2	6	15	140	2	158.2	1.023	96.6
3	6	20	180	3	157.3	1.086	96.7
4	9	10	140	3	156.3	1.098	96.7
5	9	15	180	1	154.2	1.220	97.4
6	9	20	100	2	159.3	1.113	96.9
7	12	10	180	2	152.3	1.223	97.5
8	12	15	100	3	159.3	1.208	97.2
9	12	20	140	1	154.3	1.211	97.3

Results of orthogonal test and range analysis showed the value of molding temperature has the largest influence on the molding pressure, and the influence of moisture content on the molding pressure is smaller. This is consistent with the results of Zhang et al. (2021), molding temperature is the most significant factor affecting molding pressure P = 0.001727. Range analysis shows that the optimal combination level is 160□, bran content of 12%, raw material moisture content of 10%, molding pressure is the smallest, when the lowest energy consumption. The regression equation between average molding pressure and percentage of wheat bran, moisture content and molding temperature can be written as Eq. 3, and the value of R^2 is 0.9189.

$$P = 174.133-75X-5.3333Y -0.0779Z \tag{3}$$

where: P is the value of average molding pressure, X is the value of percentage of wheat bran, Y is moisture content, Z is the value of molding temperature.

The results of orthogonal test indicate that bran content has the greatest effect on relaxation density, and moisture content has the least effect on relaxation density. This is consistent with the results of the study by Tabakaev et al. (2022), the bran content is the most significant factor affecting the relaxation density (P=0.000595). Range analysis showed that the optimal combination of the level of molding temperature 120°C, bran content of 12%, raw material moisture content of 20%, the relaxation density is large. The regression equation between average relaxation density and percentage of wheat bran, moisture content and molding temperature can be written as Eq. 4, and the value of R^2 is 0.92252.

$$\rho = 1.1773+0.838889X+0.07667Y +0.0001Z \tag{4}$$

where: ρ is the relaxation density (g/cm^3), X is the value of percentage of wheat bran, Y is moisture content, Z is the value of molding temperature.

Fig. 4 shows the relationship between relaxation density and mechanical durability of BMF pellets. The relationship between relaxation density and mechanical durbyability is defined by Eq. 5, and the value of R^2 is 0.9307.

$$y = 4.0467x + 92.405 \tag{5}$$

where: y represents mechanical durability, x represents relaxation density.

The mechanical durability is approximately proportional to the relaxation density. That is, the higher the relaxation density of a material, the higher its mechanical durability. This is because more solid material filling the space provides better material continuity and load carrying capacity. When relaxation density is lower, there are more holes and cracks and the structural strength of the biomass fuel pellet is lower. This is mainly because these holes and cracks create stress concentration points when a force is applied, making the biomass fuel pellet more prone to fracture. On the contrary, when the relaxation density of the material increases, the number of holes and cracks decreases and the structure of the biomass fuel pellet is more uniform, which helps to increase its mechanical durability. (Zhang et al. 2021).

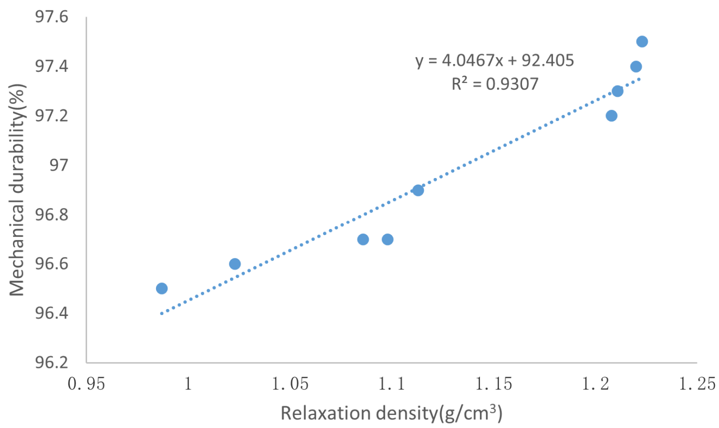


Fig. 4: Relationship between relaxation density and mechanical durability of BMF pellets.

Since the optimal combination of molding process parameters was not included in the orthogonal test combination, in order to check whether the conclusions drawn from the test of the hydraulically-driven single-plunger biomass molding machine are applicable to the plunger-type roll biomass molding machine, it is necessary to carry out experiments to validate the optimal combination of molding process parameters determined.

Using *Caragana korshinskii* Kom. powder as raw material and wheat bran as binder, and adopting the best molding process parameters, i.e., the content of wheat bran is 9%, the water content is 20%, and the molding temperature is 140°C, the resulting MBF pellets have a relaxation density of 1.209 g/cm^3, and a mechanical durability of pellets of 97.2%. ISO 17225-2 (2014) defines the mechanical durability of wood pellets as ≥97.5% (classes A) and ≥96.5% (class B) for industrial use. ISO 17225-6 (2021) for non-wood pellets defines mechanical durability as ≥97.5% (class A) and ≥96.0% (class B). According to ISO 17225-6 (2021) the MBF pellets made from *Caragana korshinskii* Kom. powder and wheat bran are of good quality, and can satisfy the requirements of storage, use and transportation.

CONCLUSIONS

To investigate the effects of molding temperature, moisture content, and percentage of wheat bran on the molding pressure, relaxation density, and mechanical durability of biomass pellets made from wheat bran and *Caragana korshinskii* Kom. powder, a series of single factor and orthogonal experiments were conducted.

The results indicated the molding pressure required for biomass pellets is affected by the molding temperature, moisture content and the percentage of the wheat bran. Optimal conditions for achieving low molding pressure would involve a relative high temperature, high moisture content and a moderate wheat bran content. Meanwhile, the results also showed that the molding temperature had the most significant effect on the relaxation density and durability of the pellets. As the molding temperature increased, the relaxation density and durability of the pellets improved steadily. The moisture content also had a significant effect on the relaxation density and durability of the pellets. As the moisture content increased, the relaxation density and durability decreased. The wheat bran content had a smaller but still significant effect on the relaxation density and durability of the briquettes. As the wheat bran content increased, the relaxation density and durability improved.

Overall, the optimal conditions for producing high-quality biomass pellets with good relaxation density and durability would be a molding temperature of around 140°C, a moisture content of around 15%, and a wheat bran content of around 9%. The results of this study can provide theoretical guidance for the preparation and optimization of biomass forming fuels, which can help promote the sustainable development of biomass energy.

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