Evaluation Indexes of Poplar Sawdust and Alfalfa Grass Forming Pellets

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An experimental study was conducted to obtain the degree and pattern of influence of the interaction of various test factors on the evaluation indexes of biomass-forming pellets and the optimal combination of test parameters. Poplar sawdust and alfalfa grass were crushed and compressed into pellets, which were used as test samples. The particle size and moisture contents of the biomass raw materials were selected as test factors, and the quality and performance evaluation indexes, such as relaxation density, Shore hardness, water resistance, crush resistance, longitudinal dimensional stability, forming rate, and productivity, were measured for each pellet group. The results showed that for the same biomass raw material, when the particle size range is zero to 1.5 mm and the moisture content is at 15%, the relaxation density, Shore hardness, and forming rate of the formed pellets are the greatest, and the crush resistance, water resistance, and longitudinal dimensional stability are the strongest. When the particle size range is about 4 to 5.5 mm and the moisture content is at 5%, the relaxation density, Shore hardness, and forming rate of the pellets are the smallest, and the crush resistance, water resistance, and longitudinal dimensional stability are the weakest. The best moisture content of the pellets is about 15%.

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Keywords: Forming pellets; Evaluation indexes; Influence pattern; Optimal combination

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INTRODUCTION

At present, traditional energy sources are becoming increasingly scarce, while biomass, with its huge reserves, renewable nature, and non-polluting advantages, is the fourth largest energy source in the world in terms of total energy consumption (Yan *et al*. 2011; Jiao 2020). In compression molding, differences in the chemical composition and physical properties of biomass raw materials will have an impact on the pellet forming effect (Yao *et al*. 2018; Frodeson *et al*. 2019; Sheng *et al*. 2022). Research on dense biomass forming throughout the world has primarily focused on process equipment and parameters, forming pressure, and material moisture content. The analysis of the quality of the formed pellets is primarily focused on macroscopic physical properties such as mechanical strength and relaxation density (Li *et al*. 2015; Li *et al*. 2020; Zhang *et al*. 2020), and research on their quality and performance evaluation indexes are still lacking. Therefore, further thematic studies are still needed on the evaluation indexes of different types of biomass materials.

In this study, the effect of the factors (particle size and moisture content) on the evaluation indexes (relaxation density, Shore hardness, water resistance, crush resistance, longitudinal dimensional stability, forming rate, and productivity) of two types of biomass materials were investigated. Poplar sawdust and alfalfa grass were used as raw materials to obtain the degree and law of the interaction of the test factors on the evaluation indexes of the formed pellets, and to obtain better quality formed pellets (Wang *et al*. 2017; Huang 2022; Yang *et al*. 2022).

Determination of Relaxation Density of Formed Pellets

The relaxation density of the formed pellet is the final density of the biomass raw material after being compressed and formed, and it is one of the important indicators to determine the physical quality and performance of the biomass-formed pellet (Wang *et al*. 2014; Yang *et al*. 2015). After the biomass pellets are extruded and molded, the density starts to decrease, but after 15 days the density tends to stabilize, and the density that tends to stabilize is called the relaxation density. Ten pellets were randomly collected at different locations of the mold holes of the forming machine at different levels of each test factor, and the relaxation density was calculated and averaged according to Eq. 1,

$$\rho = \frac{M}{V} = \frac{4M}{\pi L D^2} \tag{1}$$

where ρ is the density of the formed pellet (g/cm^3); M is the mass of the particle (g); D is the diameter of the particle (cm); L is the length of the particle (cm); and V is the volume of the particle (cm^3).

Determination of Shore Hardness of Formed Pellets

After the biomass pellets were compressed and shaped, 10 pellets with a length of 30 to 50 mm were randomly selected at different levels of each test factor, their hardness values are measured using a Shore hardness tester, and the test data were recorded. The average hardness value of the formed pellet is calculated according to Eq. 2,

$$N = (X_1 + X_2 + X_3 + \ldots\ldots X_{10})/10 \tag{2}$$

where N is the average value of Shore hardness of molded pellet (HD); X_i is the hardness value of individual pellet (HD).

Determination of Water Resistance of Formed Pellets

The water resistance of formed pellet reflects their ability to resist water penetration and determines the storage capacity of the pellets, which is generally achieved by soaking the pellets (Jia 2021). After the biomass pellets were compressed and molded, 10 samples of the pellets with a length of 30 mm were selected at different levels of each test factor, and the mass m_0 of the pellet samples at different levels of each test factor was weighed using an electronic scale. Then the pellets were immersed in water at a distance of 20 mm from the water surface for 30 s and timed with a stopwatch. The water permeability of the molded granules was calculated according to Eq. 3. The test was repeated 10 times for each group and the average value was obtained. The water resistance (K) was calculated using Eq. 3,

$$K = \left(1 - \frac{m_1 - m_0}{m_0}\right) \times 100\% \tag{3}$$

where K is the water resistance of the molded pellet (%); m_1 is the mass of the molded pellet after the 30 s of continuous immersion (g); and m_0 is the mass of the molded pellet after compression molding and cooling to room temperature (g).

Determination of Crush Resistance of Formed Pellets

Crush resistance is a measure of the ability of the formed pellets to resist crushing during transport and storage (Ma 2023). Test samples of 30 to 50 mm in length were collected randomly at different levels of each test factor for 2 kg. The samples were dropped three times from a position 2 m above the ground to a concrete floor and sieved for 3 min with a standard test sieve of 6-mm diameter. The mass m_1 of the formed pellet sample on the sieve was weighed using an electronic scale. The crush resistance of the formed pellets was calculated according to Eq. 4 and each set of tests was repeated 10 times and averaged. The crush resistance was calculated as shown in Eq. 4,

$$S = \frac{m_1}{m} \times 100\% \tag{4}$$

where S is the crush resistance of formed pellets (%); m_1 is the sample mass of pellets on sieve (kg); and m is the total mass of sample taken (kg).

Determination of Longitudinal Dimensional Stability of Formed Pellets

The study showed that the diameter of the molded pellets changed minimally within half a month, almost negligible, indicating that the transverse dimensional stability of the molded pellets was good and could be left out of the study, and only the longitudinal dimensional stability of the pellets should be studied (Kashaninejad *et al*. 2014). After 10 days, samples of formed pellets at different levels of each factor were removed, their lengths were measured, and test data were recorded. The longitudinal dimensional stability of the formed pellets was calculated according to Eq. 5, and the test was repeated 10 times to obtain the mean value.

$$R_L = \left(1 - \frac{|L_i - L_0|}{L_0}\right) \times 100\% \tag{5}$$

In Eq. 5, R_L is the longitudinal dimensional stability of the molded pellet (%); L_i is the length of the molded pellet after 10 days of storage (mm); and L_0 is the length of the molded pellet after compression molding and cooling to room temperature (mm).

Determination of Forming Rate of Formed Pellets

The molding ratio of pellets reflects the percentage of pellets that can be compressed and molded during stable operation of the molding equipment. At the same time, the molding rate of pellets also reflects the degree of molding effect of the molding equipment. At different levels of the test factor, about 2 to 3 kg of pellets were collected at random at different locations in the mold holes of the forming machine, at 5 min intervals, 10 times in total. The collected samples of formed particles were then sequentially sieved using a standard test sieve with a 6-mm diameter. The mass of the formed particles on the sieve was weighed as m_a using an electronic scale and the total mass of the collected particle samples was recorded as m_b, respectively. The forming rate of the formed pellets was calculated according to Eq. 6, and each set of tests was carried out 10 times and averaged,

$$X = \frac{m_a}{m_b} \times 100\% \tag{6}$$

where X is the forming rate of forming pellets (%); m_a is the sample mass of particles on sieve (kg); and m_b is the total mass of sample particles (kg).

Determination of Productivity of Formed Pellets

This experiment was conducted at room temperature and needed to be performed when the molding machine was run for some time to allow the ring mold to reach the molding temperature. At different levels of the test factors, when the molding machine was running steadily, samples of pellets were picked up at the mold hole of the molding machine every 10 min, each time for 5 min, for a total of 3 times. The masses were obtained using an electronic scale and the test data was recorded. The average value was taken as the mass of the formed pellet sample at different levels of each test factor, *m*. The average productivity of the forming machine was calculated according to Eq. 7 (De *et al*. 2020),

$$Q = 3600\frac{m}{t} \tag{7}$$

where Q is the productivity (kg/h); t is the time to pick up the sample (s); and m is the average of the mass of the picked up formed pellets at different levels of each test factor (kg).

EXPERIMENTAL

Materials

Poplar sawdust produced in the year around Hohhot City and alfalfa grass grown mature and naturally dried around Hohhot City were used as test materials. The roots were removed and the impurities were removed from the materials. The test materials were crushed manually using scissors in their natural state, and then crushed finely using a high-powered ordinary hammer mill. The standard test sieve (GB/T6003.1-1997) with mesh diameters of 1.5, 2, 3.5, 4, and 5.5 mm was used to sieve the crushed test materials respectively. Four levels of moisture contents of biomass raw materials were selected as 5%, 10%, 15%, and 20% for testing.

Instruments

The main test equipment used in this work included a ring molding machine with a molding die-hole diameter d_0 of 8 mm (De *et al*. 2020); standard test sieve with 1.5 mm, 2 mm, 3.5 mm, 4 mm, and 5.5 mm sieve pore as per GB/T 6003.1 (2012) (Xinxiang Xiyang Yang Screening Machinery Manufacturing Co., Ltd., Xinxiang, China); JAEIHAENE type electronic scale (accuracy 0.01 g, Ruian Deli Business Electronics Co., Ltd., Ruian, China); Vernier calipers (Wuxi Xigong Gauge Co., Ltd., Wuxi, China); Model LX-D Shore hardness tester (Leqing Eidelberg Instruments Co., Ltd., Leqing, China); and a stopwatch with 0.01 s accuracy.

Parameters Determination

Twenty-four combinations of molded pellets were compressed in a ring molding machine with a mold hole diameter of 8 mm at different levels of each factor, and the relaxation density, Shore hardness, water resistance, crush resistance, longitudinal dimensional stability, forming rate, and productivity were measured for each pellet group.

RESULTS AND DISCUSSION

Parameters of Each Evaluation Index for Poplar Sawdust and Alfalfa Grass Pellets

The test parameters were measured for the molding particles at different levels of each factor, and the average value of each parameter was taken. The results are shown in Tables 1 and 2. The relaxation density of forming pellets is denoted by "ρ", N indicates the Shore hardness of forming pellets, K refers to the water resistance of forming pellets, S point to the crush resistance of forming pellets, R_L indicates the longitudinal dimensional stability of forming pellets, X denotes the forming rate of forming pellets, and Q indicates the productivity of forming pellets.

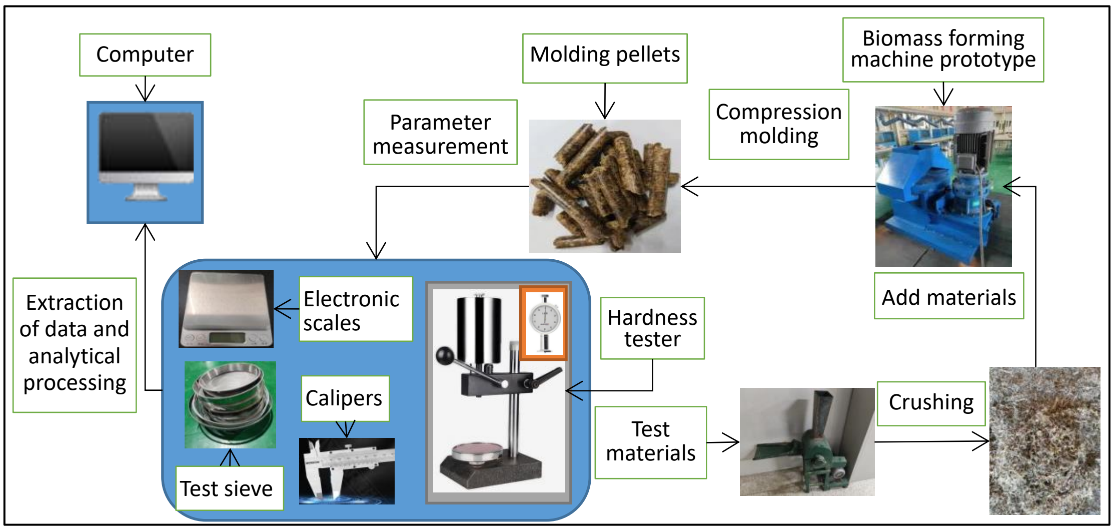


Fig. 1. Pellet-forming test rig and evaluation index measurement system

Table 1. Average Values for Each Evaluation Index Parameter for Poplar Sawdust

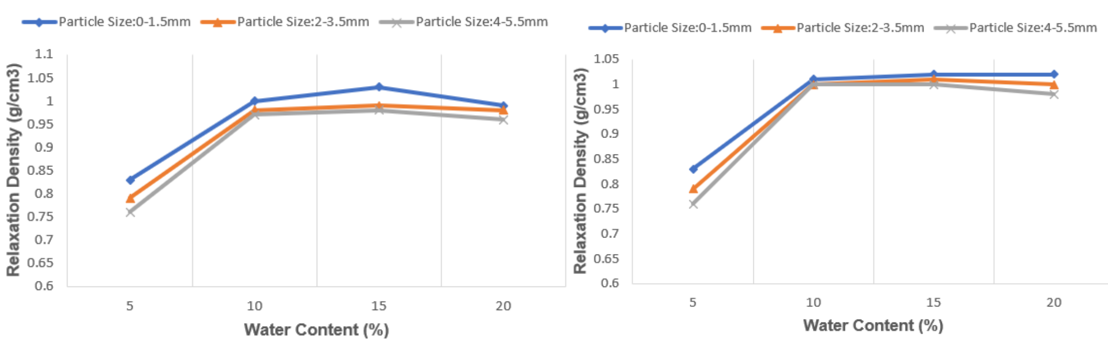
Particle Size Range (mm)	Water Content (%)	P (g/cm^3)	N (HD)	K (%)	S (%)	R_L (%)	X (%)	Q (kg/h)
0-1.5	5	0.83	15.50	72.73	82.01	99.25	79.93	99.43
	10	1.00	43.50	88.07	96.12	99.53	96.41	111.97
	15	1.03	47.75	88.54	96.54	99.67	97.66	117.25
	20	0.99	44.63	88.23	96.01	99.53	96.84	120.98
2-3.5	5	0.79	11.75	67.44	78.37	99.21	74.48	96.52
	10	0.98	38.75	86.23	95.74	99.46	96.62	106.34
	15	0.99	43.25	86.76	96.23	99.52	97.12	114.09
	20	0.98	39.88	86.37	95.87	99.40	96.54	116.09
4-5.5	5	0.76	8.50	61.25	72.69	99.12	67.63	92.17
	10	0.97	34.00	84.47	95.37	99.28	96.28	102.98
	15	0.98	37.25	85.02	95.86	99.40	96.43	104.69
	20	0.96	33.25	84.54	95.42	99.36	96.36	108.51

Table 2. Average Values for Each Evaluation Index Parameter for Alfalfa Grass

Particle Size Range (mm)	Water Content (%)	P (g/cm^3)	N (HD)	K (%)	S (%)	R_L (%)	X (%)	Q (kg/h)
0 to 1.5	5	0.83	23.00	65.87	84.12	99.12	77.71	107.34
	10	1.01	37.63	85.93	96.74	99.43	96.93	119.98
	15	1.02	42.00	86.42	97.12	99.46	97.81	123.67
	20	1.02	38.50	86.07	96.63	99.46	97.13	127.08
2 to 3.5	5	0.79	19.88	61.02	82.37	99.00	72.46	101.23
	10	1.00	30.13	84.05	96.31	99.38	96.71	113.27
	15	1.01	36.25	84.73	96.71	99.42	97.12	118.67
	20	1.00	30.88	84.16	96.23	99.39	96.42	122.97
4 to 5.5	5	0.76	17.88	56.25	78.69	98.98	68.93	97.69
	10	1.00	25.88	82.57	95.71	99.20	96.32	110.75
	15	1.00	29.88	83.06	96.27	99.30	96.67	115.79
	20	0.98	25.75	82.69	95.87	99.35	96.21	119.69

Analysis of the Effect of Particle Size and Moisture Content on the Evaluation Indexes of Poplar Sawdust and Alfalfa Grass

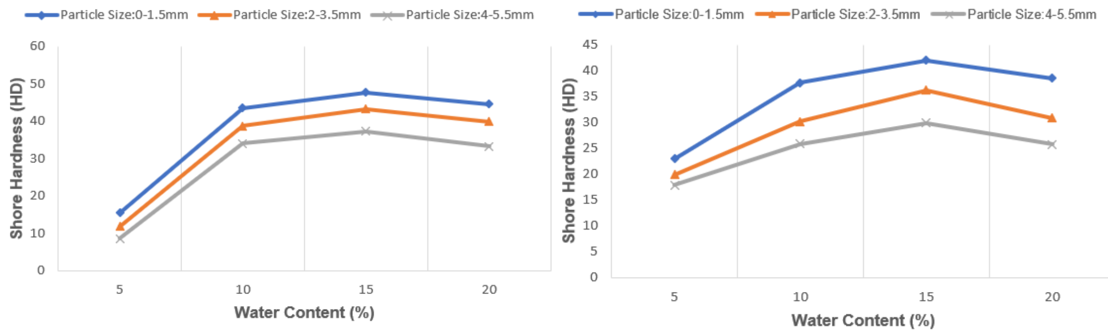
Figures 2(a) and (b) show the effect of particle size and moisture content on the relaxation densities of poplar sawdust and alfalfa grass materials, respectively. The relaxation density of formed pellets was greatest when the particle size of the raw material was within the range of zero to 1.5 mm at a certain moisture content, and it reached the minimum value when the particle size of the raw material increased to 4 to 5.5 mm. The relaxation density of formed pellets was greatest when the moisture content of the raw material was at 15% at a certain particle size. For the same biomass raw material, the relaxation density of the pellets was greatest when the particle size range was zero to 1.5 mm and the moisture content was 15%. The relaxation density of the pellets was the smallest when the particle size range was between 4 and 5.5 mm and the moisture content was 5%.



(a) (b)

Fig. 2. The effect of particle size and moisture content on the relaxation density pattern

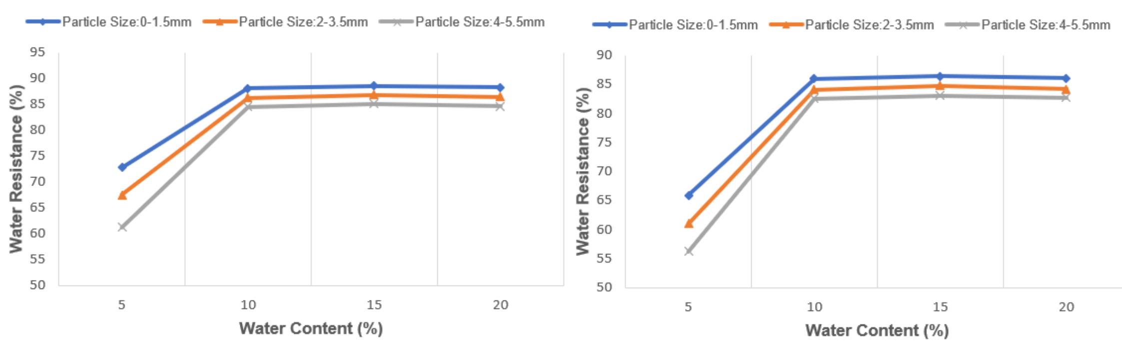
Figures 3(a) and (b) show the effect of particle size and moisture content on the Shore hardness of poplar sawdust and alfalfa grass, respectively. The Shore hardness of formed pellets was greatest when the particle size of the raw material was within the range of zero to 1.5 mm at a certain moisture content, and reached the minimum value when the particle size of the raw material increased to 4 to 5.5 mm. The Shore hardness of formed pellets was greatest when the moisture content of the raw material was at 15% at a certain particle size. For the same biomass raw materials, the Shore hardness of the pellets was greatest when the particle size range was between zero to 1.5 mm and the moisture content is at 15%. The Shore hardness of the pellets was the smallest when the particle size range was 4 to 5.5 mm and the moisture content was 5%.



(a) **(b)**

Fig. 3. The effect of particle size and moisture content on the Shore hardness pattern

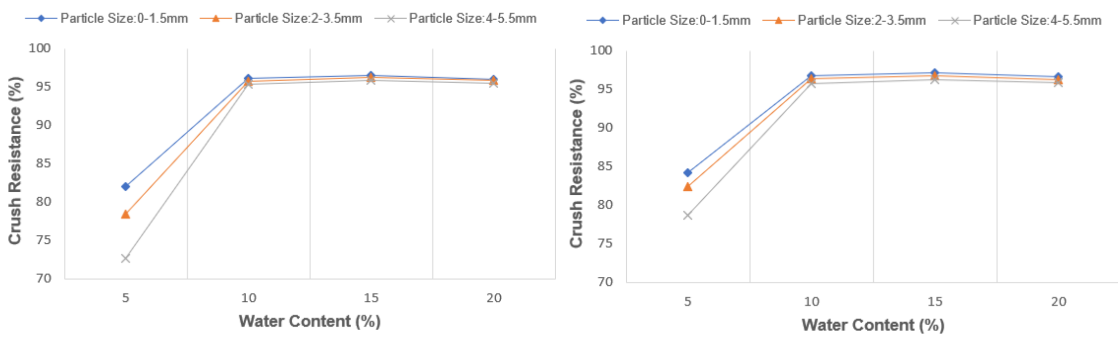
Figures 4(a) and (b) show the effect of particle size and moisture content on the water resistance of formed pellets. The water resistance of pellets was strongest when the particle size of the raw material was within the range of zero to 1.5 mm at a certain moisture content, and reached the weakest value when the particle size of the raw material increased to 4-5.5 mm. The water resistance of formed pellets was strongest when the moisture content of the raw material was 15% at a certain particle size. For the same biomass, the water resistance of the pellets showed the same trend as for hardness; strongest when the particle size range is 0 to 1.5 mm and at 15% moisture content; weakest when the particle size range is 4 to 5.5 mm and at 5% moisture content.



(a) **(b)**

Fig. 4. The effect of particle size and moisture content on the water resistance pattern

Figures 5(a) and (b) show the effect of particle size and moisture content on the crush resistances. The crush resistance of formed pellets was strongest when the particle size of the raw material was within the range of 0 to 1.5 mm at a certain moisture content, and reached the weakest value when the particle size of the raw material increased to 4 to 5.5 mm. The crush resistance of formed pellets was strongest when the moisture content of the raw material was at 15% level at a certain particle size. For the same biomass raw materials, the crush resistance of the pellets was strongest when the particle size range was 0 to 1.5 mm and the moisture content is at 15%. It was weakest when the particle size range was 4 to 5.5 mm and the moisture content was 5%. The above shows that too low moisture content will result in very weak water resistance. In fact, too low a moisture content can cause the pellets to fail to form (Jiang *et al*. 2006).

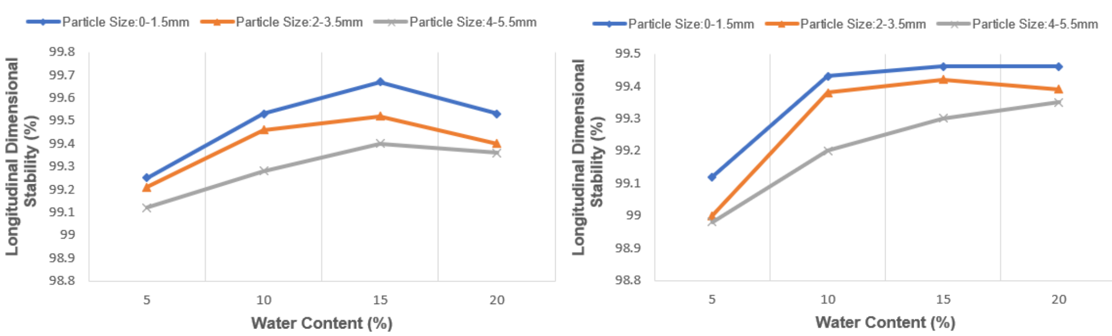


(a) **(b)**

Fig. 5. The effect of particle size and moisture content on the crush resistance pattern

Figures 6(a) and (b) show the effect of particle size and moisture content on the longitudinal dimensional stability of the biomass pellets. The longitudinal dimensional stability of formed pellets was strongest when the particle size of the raw material was within the range of 0 to 1.5 mm at a certain moisture content, and it reached the weakest value when the particle size of the raw material increased to 4 to 5.5 mm. The longitudinal dimensional stability of formed pellets was strongest when the moisture content of the raw material was 15% at a certain particle size.

For the same biomass raw materials, the longitudinal dimensional stability of the pellets was strongest when the particle size range was 0 to 1.5 mm and the moisture content was 15%. It was weakest when the particle size range was 4 to 5.5 mm and the moisture content was 5%.



(a) **(b)**

Fig. 6. The effect of particle size and moisture content on the longitudinal dimensional stability pattern

Figures 7(a) and (b) show the effect of particle size and moisture content on the forming rate of pellets. The forming rate was greatest when the particle size of the raw material was within the range of 0 to 1.5 mm at a certain moisture content, and it reached the minimum value when the particle size of the raw material increased to 4 to 5.5 mm; The forming rate of formed pellets was greatest when the moisture content of the raw material was 15% at a certain particle size.

For the same biomass raw materials, the forming rate of the pellets was greatest when the particle size range was 0 to 1.5 mm and the moisture content was 15%. It was smallest when the particle size range was 4 to 5.5 mm and the moisture content was 5%.

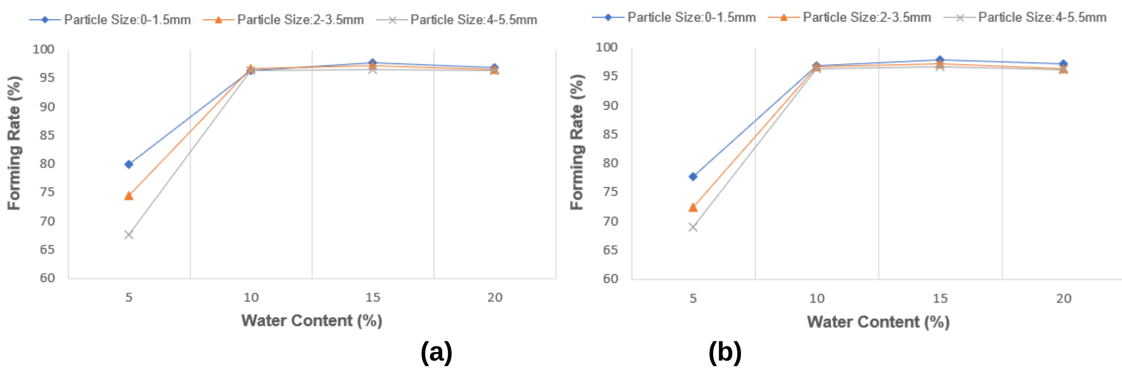


Fig. 7. The effect of particle size and moisture content on the forming rate pattern

Figures 8(a) and (b) show the effect of particle size and moisture content on the productivity of poplar sawdust and alfalfa grass pellets. The productivity of pellets was greatest when the particle size of the raw material was within the range of 0 to 1.5 mm at a certain moisture content, and it reached the minimum value when the particle size of the raw material increased to 4 to 5.5 mm. The productivity of formed pellets was greatest when the moisture content of the raw material was 15% at a certain particle size. For the same biomass raw materials, the productivity of the pellets was greatest when the particle size range was 0 to 1.5 mm and the moisture content was 15%. It was smallest when the particle size range was 4 to 5.5 mm and the moisture content was 5%.

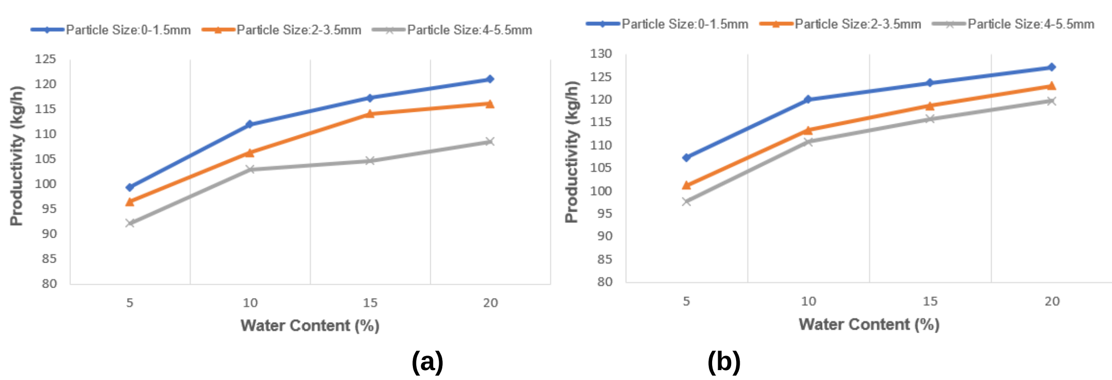


Fig. 8. The effect of particle size and moisture content on the productivity pattern

CONCLUSIONS

1. For biomass raw materials of poplar sawdust and alfalfa grass, when the particle size range was between zero to 1.5 mm and the moisture content was 15%, the relaxation density, Shore hardness, and forming rate of the pellets were the highest, and the water resistance, crush resistance, and longitudinal dimensional stability were the strongest. The productivity of the formed pellets was greatest when the particle size range was 0 to 1.5 mm and the moisture content was 20%.

2. For biomass raw materials studied, when the particle size range was 4 to 5.5 mm and the moisture content was 5%, the relaxation density, Shore hardness, and forming rate of the pellets were the smallest, and the water resistance, crush resistance, and longitudinal dimensional stability were the weakest.
3. For poplar sawdust and alfalfa grass, the trends of both evaluation indicators were almost the same as the particle size and moisture content changed. Both evaluation indicators were at their optimum values, except for productivity, when the particle size was in the range from 0 to 1.5 mm and the moisture content was 15%. When the water content is specified, the smaller the particle size, the better the indicators of the particles. When the particle size is specified, with the increase of water content, the indicators of the particles first increase and then decrease, although less obvious after 10%. The best moisture content of pellets was about 15%.

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