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Comparative Properties of Bamboo and Rice Straw Pellets

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Bamboo is a potential major bio-energy resource. Tests were carried out to compare and evaluate the property of bamboo and rice straw pellets, rice straw being the other main source of biomass solid fuel in China. All physical properties of untreated bamboo pellets (UBP), untreated rice straw pellets (URP), carbonized bamboo pellets (CBP), and carbonized rice straw pellets (CRP) met the requirements of Pellet Fuels Institute Standard Specification for Residential/Commercial Densified including dimension, density, and strength. The inorganic ash (15.94 %) and gross heat value (15375 J/g) of rice straw pellets could not meet the requirement of Pellet Fuels Institute Standard Specification for Residential/Commercial Densified ($\leqslant$ 6.0% for PFI Utility) and the minimum requirement for making commercial pellets of DIN 51731 (>17500 J/g), respectively. Rice straw pellets have been a main type of biomass solid fuel and widely used. Bamboo pellets have better combustion properties compared with rice straw pellets. It is confirmed that bamboo pellets have great potential as biomass solid fuel, especially with respect to development of commercial pellets on an industrial scale in China. The information provided by this research is useful for development and utilization of bamboo resource and pellets.

Keywords: Biomass; Bio-energy; Bamboo; Bamboo pellet; Rice straw pellet

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INTRODUCTION

Hydro, solar, wind, biomass, and ocean thermal energies could substitute for fossil fuels in the future. Among these energy sources, biomass energy is the only carbon-based sustainable energy, and it can be utilized by most people around the world (Faizal *et al.* 2009). Biomass pellets are one form of biomass and are defined as biomass particles formed into cylindrical pellets (Maria *et al.* 2011). There are some advantages of densified fuel pellets exhibiting higher bulk and energy densities, including gains in flow and storage properties, along with lower material waste (Adapa *et al.* 2006). A variety of densification systems have been considered for producing a uniform format feedstock commodity for bioenergy applications, including pellet mill, cuber, screw extruder, briquette press, roller press, tablet press, and agglomerator (Tumuluru *et al.* 2011). In recent years, various pellets have been studied such as those made from tea waste (Ayhan 1999), waste paper and wheat straw mixtures (Demirbas 1999), agricultural residues (Pallav *et al.* 2006), forest residues (Zhou and Zhang 2007), spruce wood sawdust (Demirbas and Sahin-Demirbas 2004), corn stover (Sudhagar *et al.* 2006), spring-harvested reed canary-grass (Susanne and Nilsson 2001), switchgrass (Colley *et al.*

2006), cotton stalk (Abasaeed 1992), peanut hulls (Fasina and Sokhansanj 1993), and poultry litter (Junginger *et al.* 2001).

Agricultural and forest residues represent a major fuel source for potential bio-energy projects in many developing countries (McMullen *et al.* 2004) and some research on agricultural residue pellets has been published worldwide. Purohit *et al.* (2006) made an evaluation on the energetic viability of agricultural residue briquetting compared with the energy embodied in coal in India. Mechanical properties of wheat straw, barley straw, corn stover, and switchgrass, including density, durability, and stability, were determined at different compressive forces, particle sizes, and moisture contents. Corn stover produced the highest pellet density at low pressure during compression. Barley straw had the highest asymptotic modulus among all biomasses. This indicated that barley straw pellets were more rigid than other pellets. Lower moisture stover (5 to 10%) resulted in denser, more stable, and more durable briquettes, compared with higher moisture stover (15%) (Sudhagar *et al.* 2006). Nilsson *et al.* (2011) analyzed the costs and energy requirements for pellet production from agricultural raw materials. The materials were *Salix*, reed canary grass, hemp, straw, screenings, rape-seed meal, rape cake, and distiller's waste. The materials of greatest interest were *Salix* and reed canary grass. They had competitive raw material costs and acceptable fuel properties and could be mixed with sawdust in existing large-scale factories.

China has abundant agricultural residue resources, producing more than 630 million tons of agricultural residues, and amounting to about 20% of total energy consumption in rural areas. Efficient utilization of enormous amounts of agricultural residue is crucial for providing bioenergy, releasing risk of environmental pollution, and increasing farmer income (Chen *et al.* 2009). Rice is the primary food for more than 40% of the Chinese population. At present, most of these residues are burnt *in situ* after harvest. The field burning of rice straw in wide areas not only results in serious environmental issues, but also wastes precious resources. Faced with this situation and the increasingly large market demand for biomass solid fuel during recent years, there has recently been a revival of interest in using rice straw to produce biomass pellets.

Bamboo is a type of biomass material that is widely cultivated in the west and south of China. Currently, the bamboo resource is very abundant. The total area of bamboo is about five million hectares and that of moso bamboo (*Phyllostachys heterocycla*) is about three million hectares in China (Jiang 2002). Bamboo, like wood or agricultural residue, is mainly composed of hemicelluloses, cellulose, and lignin. It has great potential as a bio-energy resource of the future. To date, no information has been available regarding bamboo pellets.

In preliminary work, bamboo pellets were successfully manufactured using a laboratory pellet mill to investigate the feasibility of exploring bamboo pellets and evaluate its energy properties, where all properties met the requirements of Pellet Fuels Institute Standard Specification for Residential/Commercial Densified and the gross calorific value also met the minimum requirements of commercial pellets of DIN 51731 (>17500 J/g) (Faizal *et al.* 2009). The results of this preliminary research confirmed that bamboo pellets have the potential to be developed for commercial production in China. Rice straw pellets have been a main type of biomass solid fuel and are widely used. This study was therefore carried out to compare and evaluate the properties of bamboo and rice straw pellets, including untreated bamboo pellets (UBP), untreated rice straw pellets (URP), carbonized bamboo pellets (CBP), and carbonized rice straw pellets (CRP). Data from such research may help development and utilization of bamboo resource and pellets.

MATERIALS AND METHODS

Materials

Moso bamboo, of 4 years age, was used in this study. They were taken from a bamboo plantation located in Louisiana, USA. The initial moisture content of the bamboo was about 6.13±0.25% and the density was about 0.65±0.14 g/cm^3. Bamboo materials were cut off to a sample size 40 mm (longitudinal) by 3-8 mm (radial) by 20-30 mm (tangential).

Rice straw was obtained from California, USA. It was approximately 1 m tall at harvest and cut above the water line, leaving the lower third as stubble in the field. This rice was also harvested with a conventional straw walker combine rather than a rotary device, which optimizes straw quality by retaining much longer sections of stalks for bailing. The initial moisture content of the straw was about 8.15±0.37%.

The bamboo and rice straw were broken down into particles using a wood particle mill at the USDA Forest Service Forest Products Laboratory. The bamboo and rice straw were milled to a particle size of less than 2.0 mm based on preliminary work. Five kilograms of both particles were conditioned by adding predetermined amounts of distilled water to the samples (Mahapatra *et al.* 2010). Then they were transferred to separate Ziploc bags and sealed tightly. Finally, they were placed into a conditioning room with temperature 27 °C and humidity 65% for 48 h to enable uniform moisture distribution. The final moisture contents of bamboo and rice straw particles were 15.97% and 15.56%, respectively.

Pellet formation and carbonization

1. The pellets were manufactured using laboratory pellet mill (L-175), made by Amandus Kahl Co. of Hamburg, Germany.
2. The pellets were collected and kept in the laboratory for more than a week to allow the properties of the bamboo pellets to stabilize, such as pellet dimension, density, moisture content, *etc*. Then, some of the pellets were transferred to separate Ziploc bags and sealed tightly.
3. Others were dried in a drying oven at 105 °C for 8 h. They were removed, cooled to room temperature in a desiccator, and weighed using a digital balance.
4. They were then returned to the drying oven at 105 °C for 2 h and were cooled and weighed. When mass variance of pellets was less than 0.2%, the final masses were recorded.
5. The pellet carbonization experiments were carried out using a digitally controlled muffle furnace to improve some properties of both pellets, especially gross calorific value. The carbonization processes were carried out at a temperature of 220 °C for 60 min, which was optimized based on previous bamboo pellet research (Liu *et al.*, 2012).
6. After carbonization, pellets were transferred to separate Ziploc bags and sealed tightly.
7. The properties of UWP, URP, CBP, and CRP were then tested.

Property Tests

The properties of pellets were selected and determined based on *Pellet Fuels Institute Standard Specification for Residential/Commercial Densified.*

(1) Pellet dimensions

The pellets were cylindrical in the shape. In order to determine dimensions and unit mass, 10 bamboo pellets were randomly selected in each experiment. The length (*L*) and diameter (*d*) of each sample was measured using a digital vernier caliper. The mass of bamboo pellets (*m*) was weighed using a precision digital balance.

(2) Unit density

Unit density (ρ_u) of bamboo and rice straw pellets was determined by weighing the individual pellet and calculating its volume based on its length and diameter as per the following equations,

$$V_u = \pi/4 d^2 L \tag{1}$$

$$\rho_u = m_u/V_u \tag{2}$$

where V_u is the volume of an individual pellet (cm^3), *d* is the diameter of an individual pellet (mm), *L* is the length of an individual pellet (mm), ρ_u is the density of an individual pellet (g/cm^3), and m_u is the mass of an individual pellet (g).

(3) Bulk density

Bulk densities (ρ_b) were calculated as the ratio of the material mass to the container volume. The bamboo and rice straw pellets were leveled to the top surface of the container and were weighed using a digital balance. The container volume was calculated by measuring its length and diameter,

$$\rho_b = m_b/V_b \tag{3}$$

where ρ_b is the bulk density (g/cm^3), V_b is the volume of container (cm^3), and m_b is the total mass of pellets (g).

(4) Pellet fines content

Pellet fines content (P_f) was determined based on Pellet Fuels Institute Standard Specification for Residential/Commercial Densified.

(5) Pellet durability

Pellet durability (P_d) was determined by mass loss of samples. Some bamboo and rice straw pellets were randomly selected and weighed using a precision digital balance (0.0001 Resolution). The initial mass was recorded. They were then put into a vibrating sieve with screen size 3.17 mm (1/8 in). After 10 min, they were weighed again and the final mass was recorded. Pellet durability was calculated using the following equation,

$$P_d = 100 - (m_i - m_f)/m_i \times 100\% \tag{4}$$

where P_d is pellet durability (%), m_i is initial mass of samples (g), and m_f is final mass of samples (g).

(6) Inorganic ash

Inorganic ash (I_a) of bamboo and rice straw pellets was determined based on ASTM D 1857 Standard Test Method for Fusibility of Coal and Coke Ash.

(7) Gross calorific value

The gross calorific value (G_c) is the amount of energy per unit mass released upon complete combustion. The calorific value of bamboo pellets was tested using the PARR 1266 Bomb Calorimeter. Before testing gross calorific value of bamboo pellets, the calorimeter was calibrated with tablets of benzoic acid whose calorific value was 26465 J/g. In this test, about 1 g bamboo and rice straw pellets were introduced into the bomb, which was charged slowly with pure oxygen (>99.95 vol. %, quality 3.5) to a pressure of 3.0±0.2 MPa without displacing the original air. No aid to combustion was used and five samples were tested.

RESULTS AND DISCUSSION

Physical Properties of Pellets

Table 1 shows the physical properties of different pellet types. The data presented were the mean of measurements made on fifteen pellets. The differences were simply estimated by average response values between the high and low codes of bamboo and rice straw pellets.

(1) Pellet dimensions

The mean lengths of UBP, URP, CBP, and CRP were 13.89±0.13 mm, 13.20±0.69 mm, 12.69±0.25 mm, and 12.82±0.49 mm, respectively. The length of the pellets affected the fuel feeding properties. The shorter the pellets, the easier the continuous flow can be arranged (Demirbas 1999). The mean diameter of pellets varied slightly with values of 6.02±0.02 mm, 5.99±0.05 mm, 5.80±0.03 mm, and 5.87±0.01 mm for UBP, URP, CBP, and CRP, respectively. A decreasing flow trend based on pellet dimension was noted when comparing carbonized pellets with untreated pellets. The dimensions of all pellet types met the requirement of Pellet Fuel Institute Standard Specification for Residential/Commercial Densified. Dimension change of pellets could be due to water migration from pellets and the disruption of formed bonds during the pelletization process (Mahapatra *et al.* 2010). The pellet dimensions, both diameter and length, were important factors with respect to combustion. Experience illustrates that thinner pellets allow a more uniform combustion rate than thicker ones, especially in small furnaces (Demirbas 1999).

(2) Pellet density

Pellet density is very important in evaluating product properties. Several national standards describe particle density of pellets and briquettes as a quality indicator of densified fuels (Tore *et al.* 2011). The maximum output for a large-scale biomass bulk terminal is set at 40 tons per annum, both solid and liquid biomass, which implies that substantial storage facilities, spaces, and handling systems are required (Wu *et al.* 2011).

Transport, handling efficiency, and storage space requirements depend on the bulk density of pellets. Higher bulk density leads to greater transport efficiency and lower storage space requirements. Fasina (2008) reported a four-fold reduction of storage space due to the pelletization of peanut hulls. Adequate storage spaces are necessary in order to safely keep a large supply of feedstock on hand. In this research, the mean bulk density and unit density values of pellets were 0.54 ± 0.02 g/cm^3, 0.64 ± 0.03 g/cm^3, 0.49 ± 0.01 g/cm^3, 0.59 ± 0.01 g/cm^3, and 1.25 ± 0.04 g/cm^3, 1.35 ± 0.02 g/cm^3, 1.16 ± 0.05 g/cm^3, and 1.28 ± 0.04 g/cm^3 for UBP, URP, CBP, and CRP, respectively. The bulk density and unit density of rice straw pellets were greater than that of bamboo pellets, and both density values decreased for carbonized pellets compared to untreated pellets.

(3) Pellet strength

Pellet strength is also an important factor connected to handling and transporting. In this research, pellet strength includes the two parameters of durability and fines content. Table 1 illustrates the change in durability and fines content of carbonized pellets. Pellet durability values were $94.21\pm0.14\%$, $98.73\pm0.18\%$, $97.80\pm0.27\%$, and $99.17\pm0.23\%$ for UBP, URP, CBP, and CRP, respectively. For pellet fines content, the values were $0.37\pm0.01\%$, $0.27\pm0.02\%$, $0.23\pm0.01\%$, and $0.18\pm0.01\%$. Compared to untreated pellets, the strength properties of carbonized pellets exhibited improvement. To compression-form different materials requires natural binders or binding type particles, in addition to attractive forces between solid particles, interfacial forces, capillary pressure, adhesive and cohesive forces, mechanical interlocking behavior, and formation of solid bridges. The bonding between particles is created mainly through solid bridges for corn stover and switchgrass pellets or briquettes. The solid bridges between particles are made by natural binders in the biomass expressed during the densification process (Nalladurai and Morey 2010). Activating (softening) of the natural binders at temperatures approaching the glass transition range is important to create durable particle-particle bonding. Hemicelluloses, lignin, and protein are essentially amorphous polymers in the bamboo components. Lignin has a glass transition in the temperature range of 60 to 200 °C, depending on the moisture content and measuring technology (Salmen 1984, 1990). Olsson and Salmen (1997) showed that the α_1 transition of moist wood usually occurs between 60 °C and 95 °C, due to the glass-rubber transition of lignin. Hemicelluloses have a glass transition between -23 °C and 200 °C, depending on the moisture content (Dick *et al.* 2007). In the carbonization process of pellets, natural binders can be softened within certain temperature intervals, which results in stronger bonding of material particles and improved strength properties of bamboo and rice straw pellets.

Table 1. Physical Properties of Different Pellet Types

Pellet types	L (mm)	d (mm)	ρ_b (g/cm^3)	ρ_u (g/cm^3)	P_d (%)	P_f (%)
UBP	13.9±0.13	6.02±0.02	0.54±0.02	1.25±0.04	94.21±0.14	0.37±0.01
URP	13.2±0.69	5.99±0.05	0.64±0.03	1.35±0.02	98.73±0.18	0.27±0.02
CBP	12.7±0.25	5.80±0.03	0.49±0.01	1.16±0.05	97.80±0.27	0.23±0.01
CRP	12.8±0.49	5.87±0.01	0.59±0.01	1.28±0.04	99.17±0.23	0.18±0.01

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The Combustion Properties of Bamboo Pellets

Figure 1 shows the combustion properties of UBP, UWP, CBP, and CWP. The data presented are the mean of measurements made on 15 pellets. The differences were simply estimated by average response values between the high and low codes of bamboo and rice straw pellets.

(1) Inorganic ash of pellets

The inorganic ash of biomass pellets depends on the composition of mineral constituents in the source fuel and on the combustion process (Masahiro *et al.* 2004). The inorganic ash content of untreated pellets was lower than that of carbonized pellets, and the inorganic ash content of bamboo pellets was lower than that of rice straw pellets. The inorganic ash values of UBP, URP, CBP, and CRP were 1.37±0.08%, 15.94±0.47%, 1.43±0.14%, and 16.69±0.13%, respectively. The different compositions of rice straw and bamboo were the main reason for differences in inorganic ash. It was confirmed that the main ash-forming elements of biomass materials included Na, Mg, Si, Al, Fe, Ca, Na, K, Zn, and Ti (Werkelin *et al.* 2011). The difference in inorganic ash content of bamboo and rice straw pellets was due to these element variations, which are shown in Table 2. The removal of small molecules in the carbonization process led to a higher inorganic ash content of both pellets compared with untreated pellets. The inorganic ash of rice straw pellets (15.94%) could not meet the requirement of Pellet Fuels Institute Standard Specification for Residential/Commercial Densified (≤6.0% for PFI Utility).

(2) Gross calorific value of pellets

The most important parameter to characterize combustibility of a substance is the calorific value. The number of units of energy produced by the combustion of a unit mass of a fuel is termed the calorific value. The calorific value of biomass can be expressed as follows: higher heating value at constant volume (dry basis), low heating value at constant pressure (dry basis), and low heating value at constant pressure (wet basis or as received) (Chen *et al.* 2009). In this research, the low heating value was used for all pellets because it is perhaps the most practical measure of energy content. Low heating value at constant pressure (wet basis) was used for untreated pellets and low heating value at constant pressure (dry basis) was used for carbonized pellets. The gross calorific values were 18495±71.33 J/g, 15375±99.61 J/g, 19998±36.53 J/g, and 16805±18.58 J/g for UBP, URP, CBP, and CRP, respectively. The different compositions of bamboo and rice straw led to the variance of gross heat value. The gross calorific value of pellets was most affected by the composition of materials (Chen *et al.* 2009). Both pellets after carbonization had a higher gross calorific value when compared with untreated pellets. The removal of moisture and small molecules in the carbonization process resulted in this phenomenon. It is well known that the moisture evaporates and small molecules contained within bamboo and rice straw composition undergo thermal degradation during bamboo or rice straw pellet combustion. Both processes require energy. It is very important information that the gross calorific value of rice straw pellets URP (15375 J/g) and CRP (16805 J/g) could not meet the minimum requirement for making commercial pellets of DIN 51731 (>17500 J/g). This also indicates that the combustion properties of bamboo pellets is better than that of rice straw pellets, and has a greater market potential.
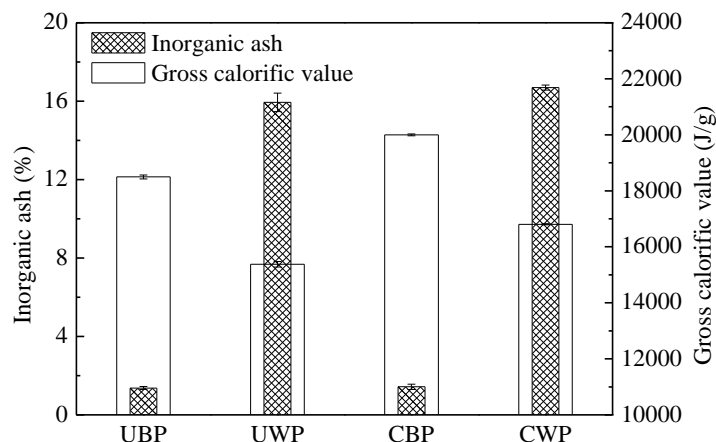
Fig. 1. Combustion properties of different pellet types

Table 2. Ash-forming elements of bamboo and rice straw pellets

Pellet Species	Na (mg/kg)	Mg (mg/kg)	Al (mg/kg)	Si (mg/kg)	K (mg/kg)	Ca (mg/kg)	Ti (mg/kg)	Fe (mg/kg)	Zn (mg/kg)
Bamboo	242.83	229.46	35.09	358.14	4032.58	965.027	18.07	111.93	20.88
Rice straw	718.27	1136.92	51.23	2321.88	11234.3	2407.38	7.02	187.81	45.43

CONCLUSIONS

The properties of UBP, URP, CBP, and CRP, including dimension, density, strength, inorganic ash, and gross calorific value were determined in this research. It can be concluded from this research that all physical properties of UBP, URP, CBP, and CRP met the requirements of Pellet Fuels Institute Standard Specification for Residential/ Commercial Densified. The inorganic ash and gross heat value of rice straw pellets could not meet the requirement of Pellet Fuels Institute Standard Specification for Residential/ Commercial Densified (≤6.0% for PFI Utility) and the minimum requirement for making commercial pellets of DIN 51731 (>17500 J/g), respectively. Most properties of both pellet types were improved through carbonization treatment, except for pellet density. Rice straw pellets have been a main type of biomass solid fuel and are widely used. Bamboo pellets exhibited better combustion properties compared with rice straw pellets. Thus the present results support the use of bamboo pellets as biomass solid fuel, having potential to be developed as a commercial product on an industrial scale in China.

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