

COMPARATIVE PROPERTIES OF BAMBOO AND PINE PELLETS

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Abstract. Bamboo is a biomass material that has great potential as a bioenergy resource of the future. To the best of our knowledge, there is a lack of sufficient information concerning bamboo pellets. Bamboo and pine pellets were therefore manufactured using a laboratory pellet mill. This study was carried out to compare and evaluate the properties of bamboo and pine pellets as biomass solid fuels. Bamboo pellets exhibited better combustion properties except for inorganic ash and worse overall physical properties than pine pellets. Most properties of both pellets were improved through carbonization treatment except for bulk and particle density. The properties of all pellets determined in this study met the requirements of Pellet Fuels Institute standards except for bulk density of bamboo pellets, and the gross calorific value also met the minimum requirement for producing commercial pellets of DIN 51731 (>17,500 J/g) (1996). The information from this study is helpful for evaluating properties of bamboo pellets and developing and using bamboo resources.

Keywords: biomass, bioenergy, bamboo, bamboo pellet, pine pellet.

INTRODUCTION

Biomass is the third largest primary energy resource in the world after coal and oil. It provides about 14% of energy consumption.

Especially for developing countries, it can provide about 35% of all energy requirements (Bapat et al 1997). Generally, biomass can be converted into liquid, solid, and gaseous fuels with the help of some physical, chemical, and biological conversion processes (Ravindranath and Hall 1995). Biomass fuels have substantial

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benefits as far as the environment is concerned. It is well known that biomass combustion has the potential to be CO₂-neutral. Potential biomass fuels mainly include wood residues, agricultural residues, industrial residues, municipal solid wastes, wastes from food processing, aquatic plants, and algae animal wastes, and a host of other materials (Demirbas 2004). These raw fuels have several disadvantages such as relatively low heating value per unit volume, difficulty in controlling the rate of burning, large volume or area required for storage, and economic problems associated with transportation and distribution. These are attributed to the low bulk density of biomass materials (Werther et al 2000). Densification is an effective way to increase the bulk density of biomass. Pellets are the main type of densified solid fuel of biomass and are defined as biomass particles formed into cylindrical pellets (Adapa et al 2006).

Wood resources or wood wastes are the most dominant raw materials for biomass pellets excluding agricultural residues. Information on wood pellets has been published worldwide. Biomass pellets, made of forest residues, had higher energy efficiency and were easier to store and transport (Zhou and Zhang 2007). Sawdust was preheated to three different temperatures (100, 115, and 130°C) and was densified into pellets at three different die temperatures (250, 300, and 350°C). A significant amount of energy can be saved by densifying sawdust preheated to 300°C (Sayed and Bhattachary 1992). Biomass materials, including sawdust, rice husks, peanut shells, coconut fibers, and palm fruit fibers, were densified into pellets at modest pressures of 5-7 MPa. Sawdust pellets were found to have better overall handling characteristics (Ooi and Siddiqui 2000). Faizal et al (2010) determined the emissions of organic compounds from incomplete burning of oats using gas chromatography. Telmo and Lousada (2011) determined the calorific values of wood pellets from different wood species. Softwoods had a high calorific value between 19,660 and 20,360 J/g, but hardwoods had a variable interval between 17,631 and

20,809 J/g. The pellets, prepared from mango leaves, eucalyptus leaves, wheat straw, and saw dust, had more heating value than half of the Indian coal, and these can be used as an alternative to coal and fire wood (Susanne and Nilsson 2001).

The market demand for biomass pellets has greatly increased during recent years. Bamboo is a type of biomass material and is widely cultivated in the west and south of China. Currently, bamboo resources are very abundant covering a total land mass of about 5 M/ha with that of moso bamboo (*Phyllostachys heterocycla*) at about 3 M/ha (Jiang 2002). Bamboo has great potential as a bioenergy resource of the future because of its rapid growth. To date, there is a lack of sufficient information concerning bamboo pellets. In this study, bamboo and pine pellets were therefore manufactured using a laboratory pellet mill with the same parameters. Comparison and evaluation of properties of both pellets were carried out, including bamboo pellets (BP), pine pellets (PP), carbonized bamboo pellets (CBP), and carbonized pine pellets (CPP). The objective of this research was to get an overview of the characteristics of BP and PP, which will be very useful to forecast the potential markets of BP. Data from this study will also be helpful for development and use of bamboo resources.

MATERIALS AND METHODS

Materials

In this study, 4-yr-old Moso bamboos were used. They were taken from a bamboo plantation located in Louisiana. Initial moisture content of the bamboo was about 6.13% and density was about 650 kg/m³. Bamboo materials were cut to 40 mm (longitudinal) × 3-8 mm (radial) × 20-30 mm (tangential). Then, they were broken down into particles using a Wiley mill (Thomas Scientific, Swedesboro, NJ) at the USDA Forest Service, Forest Products Laboratory (FPL). The mixed pine flours stocked at FPL came from American Wood Fibers (Schofield, WI). Bamboo and pine particles

were milled to a particle size of less than 2.0 mm. Five kilograms of both particles were conditioned by adding predetermined amounts of distilled water to the samples (Mahapatra et al 2010), and then the samples were placed in a conditioning room at 27°C and 65% humidity for 48 h to enable uniform moisture distribution. The final moisture contents of bamboo and wood particles were 15.97 and 15.05%, respectively.

Pellet Formation and Carbonization

Both pellets were manufactured with a laboratory pellet mill (L-175) made by Amandus Kahl Co. (Hamburg, Germany). Pellet mill parameters were set to a rotary speed of 235 rpm, die length/depth ratio of 1:6, and die diameter of 6.0 mm. Bamboo and pine particles were continuously fed into the pellet mill and formed into pellets. Pellet temperature was about 70°C after exiting the die because of particle friction. Both pellets were collected and kept in the laboratory at 27°C and 50% humidity for more than one week to stabilize their properties. Then some of them were transferred to separate bags and sealed tightly. Others were dried using a drying oven at 105°C for 8 h. Dried pellets were removed, cooled to room temperature in the desiccator, and weighed using a digital balance (0.0001 resolution). They were returned to the drying oven at 105°C for 2 h and then cooled and weighed. When mass variance of pellets was less than 0.2%, final masses were recorded. Dried pellets were carbonized using a digitally controlled muffle furnace at 220°C for 60 min, which was optimized based on Liu et al (2013). After carbonization, pellets were transferred to separate bags and sealed tightly. The properties of BP, PP, CBP, and CPP were then tested.

Property Tests

Pellet dimensions. The pellets were cylindrical in shape. Length (L) and diameter (d) of each sample were measured using a digital vernier caliper. Individual mass of pellets (m)

was weighed using a precision digital balance (0.0001 resolution).

Mass loss. Individual mass of pellets before and after carbonization was measured using a precision digital balance. The mass loss (MS) was calculated according to the following equation:

$$MS = (M_1 - M_2)/M_1 \times 100\% \quad (1)$$

where MS is the mass loss of individual pellets (%); M_1 is the mass of individual pellets before carbonization (g); and M_2 is the mass of individual pellets after carbonization (g).

Particle density. Particle density (ρ_p) of pellets was determined by weighing the individual pellet and calculating its volume based on its length and diameter as per the following equations.

$$V_p = \pi/4d^2L \quad (2)$$

$$\rho_p = m_p/V_p \quad (3)$$

where V_p is volume of an individual pellet (cm^3); d is diameter of an individual pellet (mm); L is length of an individual pellet (mm); ρ_p is density of an individual pellet (kg/m^3); and m_p is mass of an individual pellet (g).

Bulk density. Bulk density (ρ_b) was calculated as the ratio of the mass of materials to the volume of the container. Pellets were leveled with the top surface of the container and weighed using a digital balance. The container volume was calculated by measuring its length and diameter.

$$\rho_b = m_b/V_b \quad (4)$$

where ρ_b is bulk density (kg/m^3); V_b is volume of container (mm^3); and m_b is total mass of pellets (g).

Pellet fines content. Pellet fines content (P_f) was determined according to PFI (2010).

Pellet absorption. Pellet absorption (P_a) was determined through mass change of samples. Five pellets were dried at 105°C until their mass stabilized, and then the initial mass of samples was weighed using a precision digital balance.

They were then kept in a conditioning room (27°C, 90% humidity) for 24 h. The samples were then weighed again. Pellet absorption was calculated using the following equation:

$$P_a = (m_i - m_f)/m_i \times 100\% \quad (5)$$

where P_a is absorption of samples (%); m_i is initial mass of samples (g); and m_f is final mass of samples (g).

Inorganic ash. Inorganic ash (Ia) of pellets was determined according to ASTM D 1857-2004 Standard Test Method for Fusibility of Coal and Coke Ash (ASTM 2004).

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 pellets was tested using the Parr 1266 Bomb Calorimeter (Parr Instrument Company, Moline, IL). Before testing, the calorimeter was calibrated with tablets of benzoic acid. In this test, about 1 g 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. Five samples were tested for BP and PP.

Combustion rate and heat release rate. Fire time was recorded according to the Parr 1266 Bomb Calorimeter. Based on the mass of the pellets and fire time, the combustion rate (C_r) was calculated using the following equation:

$$C_r = m/t \quad (6)$$

where C_r is average combustion rate (g/s); m is mass of pellets (g); and t is fire time (s).

By knowing the gross calorific value and combustion rate, heat release rate (H_r) could be calculated with the following equation:

$$H_r = G_c \times C_r \quad (7)$$

where H_r is heat release rate (J/s); G_c is gross calorific value (J/g); and C_r is average combustion rate (g/s).

Proximate and Ultimate Analysis

Proximate and ultimate analyses of all pellets were also determined in this research. The determination of moisture and volatile matters was performed according to GB/T 212-2008 (Standard Test Method for Coal; GB/T 2008a). The determination of C, H, and N was performed according to GB/T 476-2008 (Standard Test Method for Hydrogen and Carbon of Coal; GB/T 2008b). The determination of S was performed according to GB/T 217-2007 (Standard Test Method for Sulphur of Coal; GB/T 2007). The determination of chlorine was performed according to ASTM E 776-1987 (R04) (Standard Test Method for Forms of Chlorine in Refuse-Derived Fuel). The determination of heavy metals (sodium, magnesium, aluminum, silicone, potassium, calcium, titanium, iron, zinc) was performed according to standard analysis methods using inductively couple plasma mass spectrometry.

RESULTS AND DISCUSSION

Table 1 shows the physical properties of different pellet types. The mean lengths of BP, PP, CBP, and CPP were 13.89, 13.25, 12.69, and 13.23 mm, respectively. The length of the pellets affects the fuel feeding properties. The shorter the pellets, the easier the continuous flow can be arranged. The mean diameter of pellets slightly varied with values of 6.02, 5.90, 5.80, and 5.81 mm for BP, PP, CBP, and CPP, respectively. An increasing flow trend of pellet dimension was noted compared with carbonized pellets. Pellet diameter and length are important factors with respect to combustion. Experience shows that thinner pellets allow a more uniform combustion rate than thicker ones, especially in small furnaces (Pallav et al 2006). The length and diameter of all pellets met the grade requirements of Pellet Fuels Institute (PFI) premium.

The mass loss of BP (11.35%) was greater than that of PP (2.19%). It is well known that absorbed water is removed and some volatiles are decomposed for biomass materials exposed to a thermal environment. Differences of thermal

Table 1. Physical properties of different pellet types.^a

Pellet types	L (mm)	d (mm)	MS (%)	P _a (%)	ρ _b (kg/m ³)	P _p (kg/m ³)	P _f (%)
BP	13.89 ± 1.13	6.02 ± 0.02		9.60 ± 1.52	540 ± 1	1250 ± 9	0.37 ± 0.012
PP	13.25 ± 0.69	5.90 ± 0.05		11.36 ± 0.45	680 ± 3	1300 ± 2	0.07 ± 0.03
CBP	12.69 ± 2.05	5.80 ± 0.04	11.35 ± 0.54	8.58 ± 0.38	490 ± 1	1160 ± 7	0.23 ± 0.007
CPP	13.23 ± 0.44	5.81 ± 0.02	2.19 ± 0.15	10.45 ± 1.07	640 ± 1	1230 ± 2	0.20 ± 0.016

^a BP, bamboo pellets; PP, pine pellets; CBP, carbonized bamboo pellets; CPP, carbonized pine pellets; L, length; d, diameter; MS, mass loss; P_a, pellet absorption; ρ_b, bulk density; ρ_p, particle density; P_f, pellet fines content.

characteristics for bamboo and pine resulted in variance of mass loss. Thermal characteristics of bamboo and wood were investigated in preliminary research, and bamboo had a lower pyrolysis temperature and greater mass loss compared with wood. Pellet absorption was 9.60, 11.36, 8.58, and 10.45% for BP, PP, CBP, and CPP, respectively. The differences in hydrophilic group levels and hydroxyl groups attributed to this phenomenon. Ohmae et al (2009) found that hydroxyl groups provided absorption sites for water and controlled absorption of samples heated below 250°C. Absorption of water showed a decrease because of a decrease in the number of hydroxyl groups. The absorption decreases of carbonized pellets resulted from destruction of some hydrophilic groups and hydroxyl groups in the carbonization process.

Pellet density is very important in evaluating product properties. Several national standards describe pellet density as a quality indicator of densified fuels (Filbakk et al 2011). Transport, handling efficiency, and storage spaces depend on the bulk density of pellets. Higher bulk density leads to greater transport efficiency and lower storage spaces. In this study, bulk densities and particle densities of pellets were 540, 680, 490, and 640 kg/m³ and 1250, 1300, 1160, and 1230 kg/m³ for BP, PP, CBP, and CPP, respectively. PP had better density properties. Bulk and particle densities decreased when both pellets were carbonized. Bulk density of BP could not meet the grade requirement of PFI utility.

Fines content is also an important factor connected with handling and transporting. Table 1 illustrates the variation in fines content of pellets. Fines content was 0.37, 0.07, 0.23, and

0.20% for BP, PP, CBP, and CPP, respectively. Compared with untreated pellets, fines content of carbonized pellets exhibited improvement. It was confirmed that natural binders or binding types between particles of biomass pellets included attractive forces between solid particles, interfacial forces, capillary pressure, adhesive and cohesive forces, mechanical interlocking behavior, and formation of solid bridges. It was reported that the bonding between particles was created mainly through solid bridges for corn stover and switchgrass pellets. The solid bridges between particles were made by natural binders in the biomass pellets 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. In the carbonization process of pellets, natural binders could be softened to some degree, which resulted in stronger bonding of particles and improved mechanical strength of pellets.

Table 2 shows the combustion properties of BP, PP, CBP, and CPP. The inorganic ash of BP, PP, CBP, and CPP was 1.37, 0.78, 1.43, and 0.88%, respectively. PP had a lower content of inorganic ash compared with BP, and untreated pellets had a lower content of inorganic ash than carbonized pellets. Inorganic ash of PP met the grade requirements of PFI premium, and that of other pellets met the grade requirement of PFI utility. The inorganic ash of biomass pellets depended on the composition of mineral constituents in the source fuel and on the combustion process (Dick et al 2007). The different composition of pine and bamboo attributed to variation in inorganic ash, especially

Table 2. Combustion properties of different pellet types.^a

Pellet types	I _a (%)	G _c (J/g)	C _r (g/s)	H _r (J/s)
BP	1.37 ± 0.08	18,495 ± 230.7	0.156 ± 0.006	2885 ± 204.2
PP	0.78 ± 0.01	18,298 ± 201.8	0.111 ± 0.002	2031 ± 179.9
CBP	1.43 ± 0.14	19,998 ± 173.6	0.188 ± 0.001	3759 ± 244.3
CPP	0.88 ± 0.01	20,188 ± 265.8	0.158 ± 0.002	3189 ± 113.6

^a BP, bamboo pellets; PP, pine pellets; CBP, carbonized bamboo pellets; CPP, carbonized pine pellets; I_a, inorganic ash; G_c, gross calorific value; C_r, combustion rate; H_r, heat release rate.

Table 3. Amount and type of heavy metals in bamboo and pine pellets (mg/kg).

Sample	Sodium	Magnesium	Aluminum	Silicone	Potassium	Calcium	Titanium	Iron	Zinc
Bamboo	242.83	229.46	35.10	358.14	4032.58	965.03	18.07	111.93	20.88
Pine	827.15	234.98	48.89	250.75	1261.39	1160.94	6.74	192.60	25.28

for amounts of heavy metals. Table 3 shows the amounts and types of heavy metals found in ash of BP and PP. The main type of heavy metals, such as sodium (Na), silicone (Si), potassium (K), and calcium (Ca), was similar in the ash of BP and PP. Bamboo had more Si and K and less Na and Ca. Bamboo had a very high content of K, which is undesirable in the use of BP. Combustion is a series of chemical reactions by which some heavy metals can be oxidized to metallic dioxide. It is well known that K₂O exhibits a much lower melting temperature during combustion of biomass. The higher the content of K, the higher the content of K₂O, which affected melting points of ash of BP, resulting in sintering and agglomeration. Agglomeration consists mainly of SiO₂, which has a melting point of 1450°C (Lin et al 1997). The alkali oxides or salts, such as Na and K, can react with Si compounds of the bed material to form eutectic mixtures with melting points of 874 and 764°C, respectively (Demirbas 2004). Pine had a higher content of Na. Chlorine was also found in all pellet types, affecting operation by corrosion in

the combustion application. It is well known that high chlorine and alkali content of biomass fuels is more likely to cause corrosion. Table 4 shows that pine had a higher chlorine content (185.10 ppm) than bamboo (15.46 ppm). However, the chlorine content of CBP was higher than that of CPP. The chlorine content of all pellet types could meet the grade requirement of FPI premium (≤300 ppm). Sintering, agglomeration, and corrosion characteristics of BP and PP will be determined in further research. The removal of small molecules in the carbonization process led to a higher inorganic ash content of carbonized pellets.

The most important parameter to characterize combustibility of a substance is the calorific value, including 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) (Colley et al 2006). In this study, the low heating value was determined for all pellets because it was perhaps the most practical measure of

Table 4. Proximate and ultimate analysis of different pellet types.

Pellet types ^a	Proximate analysis				Ultimate analysis					
	Moisture (%)	Ash (%)	Volatile (%)	G _c ^b (J/g)	Carbon (%)	Hydrogen (%)	Oxygen (difference) (%)	Nitrogen (%)	Sulfur (%)	Chlorine (ppm)
BP	7.60	1.37	81.87	18,495	49.71	6.36	42.50	0.18	0.04	15.46
PP	8.86	0.78	80.34	18,298	49.40	4.60	45.82	1.43	0.02	185.10
CBP	9.36	1.43	69.66	19,998	50.75	5.53	43.72	1.17	0.06	96.77
CPP	7.22	0.88	70.30	20,188	51.18	5.36	43.46	1.07	0.03	74.23

^a BP, bamboo pellets; PP, pine pellets; CBP, carbonized bamboo pellets; CPP, carbonized pine pellets.

^b G_c, gross calorific value.

energy content. The gross calorific values were 18,495, 18,298, 19,998, and 20,188 J/g for BP, PP, CBP, and CPP, respectively. BP had a higher gross calorific value. It was confirmed that biomass compositions affected gross calorific value. Carbon (C), hydrogen (H), and oxygen (O) are the main components of biomass materials. C and H are oxidized during combustion by exothermic reactions and therefore affect the gross calorific value of the fuel. The gross calorific value is related to the oxidation state of the natural fuels in which carbon atoms generally dominate and overshadow small variations in hydrogen content (Demirbas 2004). Tillman (1978) found a linear relationship between gross calorific value and carbon content. Furthermore, moisture is also an important factor that affects the gross calorific value of biomass (wet basis). Energy is consumed to evaporate moisture contained within pellets during the combustion process. Table 4 shows that BP had a higher C content (49.71%) and a lower moisture content (7.60%) compared with PP, resulting in its higher gross calorific value. The gross calorific value increased after all pellets were carbonized. The gross calorific value of CPP was also higher than that of CBP. The different compositions and thermal characteristics of bamboo and pine led to the variance of gross calorific value. The C content of both pellets increased when they were carbonized. CPP had a higher C content and a lower moisture content compared with CBP. The gross heat value of all pellets also met the minimum requirement for making commercial pellets of DIN 51731 ($>17,500$ J/g) (Junginger et al 2001).

There was a slightly higher combustion rate of BP. Compared with pine, bamboo was characterized by higher contents of volatile matters (Table 4). This indicated that bamboo was easier to ignite and burn. The slight variance of combustion rate was also caused by the difference of porous structure for BP, PP, CBP, and CPP. Particle density of PP (1300 kg/m^3) was greater than that of BP (1250 kg/m^3), indicating the inner pores of PP were less than those of BP. The organically bound O provides a part

of the O necessary for the combustion process; additional O must be supplied by air injection (Oberberger and Thek 2004). The more porous structure in the BP was helpful for better air circulation and more oxygen supply during the combustion process. Carbonization significantly influenced pore size distribution by expanding the porous structure and creating more macropores than micropores (Masahiro et al 2004). This explained that combustion rate of carbonized pellets was higher than that of untreated pellets. The combustion rates of BP, PP, CBP, and CPP were 0.156, 0.111, 0.188, and 0.158 g/s, respectively. Differences in the heat release rates of BP, PP, CBP, and CPP were also found. The main factors were variation in gross calorific value and combustion rate for different types of pellets. The heat release rate values were 2885, 2031, 3759, and 3189 J/s for BP, PP, CBP, and CPP, respectively. The other important properties related to the combustion of BP and PP were the contents of sulfur, nitrogen (N), and chlorine, which could lead to the formation of gaseous pollutants such as SO_2 , NO_x or N_2O , and HCl. Table 4 shows that pine had a higher content of N and Cl, which maybe resulted in more gaseous pollutants of PP.

CONCLUSIONS

Compared with PP, BP exhibited high-quality combustion properties except for inorganic ash, such as a higher gross calorific value, a higher combustion rate, a higher heat release rate, and lower gaseous pollutants. However, it also had low quality physical properties, such as a lower bulk density and a higher fines content. Most properties of both pellet types were improved after carbonization except for bulk density and particle density.

The properties of all pellet types met the grade requirements of PFI utility except for bulk density of BP, and the gross calorific value also met the minimum requirement for making commercial pellets of DIN 51731 ($>17,500$ J/g) (1996). BP, like wood pellets, will be proposed as biomass solid fuel and have

the potential to be developed as commercial pellets on an industrial scale if the bulk density is improved.

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