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Effects of carbonization conditions on properties of bamboo pellets

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ABSTRACT

Bamboo is a biomass material and has great potential as a bio-energy resource of the future in China. Bamboo pellets were successfully manufactured using a laboratory pellet mill in preliminary work. This study was therefore carried out to investigate the effect of carbonization conditions (temperature and time) on properties of bamboo pellets and to evaluate product properties. It was concluded that carbonization conditions affected the properties of bamboo pellets. The effects of carbonization temperature on some properties such as unit mass loss, pellet absorption, bulk density, unit density, gross calorific value and combustion rate, were significant at $p = 0.05$. But there were not significant differences between carbonization time and all properties of bamboo pellets. After being carbonized, the properties of bamboo pellets, such as pellet absorption, durability, fine, gross calorific value, combustion rate and heat release rate, were improved. All properties of carbonized pellets meet the requirement of the *Pellet Fuels Institute Standard Specification for Residential/Commercial Densified* and the gross calorific value also meets the minimum requirement for making commercial pellets of DIN 51731 (>17,500 J/g) even though the properties of carbonized pellets, such as bulk density, unit density and inorganic ash, had poor quality compared with untreated pellets. Carbonized bamboo pellets are the proposed new biomass solid fuel and have the potential to be developed as commercial pellets.

1. Introduction

There are several alternative energies which could substitute for fossil fuels in the future, such as hydro, solar, wind, biomass and ocean thermal energy. Among these energy sources, biomass is the only carbon-based sustainable energy and the wide variety of biomass enables it to be utilized by most people around the world [1]. Biomass pellets and briquettes are the main type of bio-energy as they have better flow properties. Densification into pellets could reduce material waste and improve ease of transporting and storage [2]. In recent years, various pellets had been studied, such as tea waste [3], waste paper and wheat straw mixtures [4], agricultural residues [5], forest residues [6], spruce wood saw dust [7], corn stover [8], spring-harvested reed canary-grass [9], switchgrass [10], cotton stalk [11], peanut hulls [12] and poultry litter [13]. Most physical properties of the pellets were significantly affected by variation in moisture contents [14]. The durability of pellets or briquettes depended on abrasion resistance [15]. Faizal et al. studied the physical characteristics of briquettes containing different mixing ratios of empty fruit bunch fiber and mesocarp fiber [16]. Holt et al. manufactured fuel pellets using by-products from two cotton gins [17]. Zimonja and Svihus investigated the influence of cereal starch exposed to various processing techniques on physical pellet quality [18]. Susanne and Calle investigated ash problems of spring-harvested reed canary-grass briquettes during combustion [9]. Maria determined the emissions of organic compounds from incomplete burning of oats using gas chromatography and compared the results to those of softwood pellets [19]. The use of coal-biomass briquettes will effectively reduce the indoor concentration of sulfur dioxide (SO_2) emitted during raw coal combustion. Indoor concentrations of SO_2 emitted from combustion of either coal-biomass briquettes or low-grade coal in households were measured and were found to be less with coal-biomass briquettes [20]. Telmo and Lousada tested the calorific values of wood pellets from different wood species using a Parr 6300 bomb calorimeter. Softwoods had a high calorific value between 19,660.02 and 20,360.45 kJ/kg, but the hardwoods had a ranging interval between 17,631.66 and 20,809.47 kJ/kg [21]. All briquettes prepared from mango leaves, eucalyptus leaves, wheat straw, and saw dust had more heating value than half of the Indian coal and these could be used as an alternative for the coal and fire wood [22].

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Bamboo is a type of biomass material and has been widely cultivated in the west and south of China. Currently, bamboo resources are very abundant and the total area of bamboo is about five million hectares and that of moso bamboo *(Phyllostachys heterocycla)* is about 3 million hectares in China [23]. Bamboo, like wood, is mainly composited of hemicelluloses, cellulose and lignin. It has great potential as a bio-energy resource of the future in China. To date, no information is available about bamboo pellets. In the preliminary work, bamboo pellets were successfully manufactured using a laboratory pellet mill and all properties of bamboo pellets meet the requirement of the *Pellet Fuels Institute Standard Specification for Residential/Commercial Densified* and gross calorific value of bamboo pellets also meets the minimum requirement for making commercial pellets of DIN 51731 (>17,500 J/g) [1]. Bamboo pellets are the proposed new biomass solid fuel and have the potential to be developed as commercial pellets.

This study was therefore carried out to investigate the effect of carbonization conditions (temperature and time) on properties of bamboo pellets, made in the optimum manufacturing process (moisture content 16% and particle size ≤1.18 mm) based on the preliminary work, and to evaluate properties of carbonized bamboo pellets.

2. Materials and methods

2.1. Materials

Moso Bamboo was used in the study. The initial moisture content of bamboo was about 6.13%, the density was about 0.65 g/cm^3. Bamboo materials were cut off to sample size 40 mm (longitudinal) by 3–8 mm (radial) by 20–30 mm (tangential). Then, they were broken down to particles using wood particle mill at Forestry Products Laboratory of USDA Forest Service. In the preliminary work, the optimum moisture content was 16% for bamboo pellets. So the moisture content of bamboo particles was conditioned by adding predetermined amounts of distilled water onto the samples [14] and placed into the conditioning room with temperature 27 °C, humidity 65% for 48 h to enable moisture to be distributed uniformly.

2.2. Pellet carbonization

1. The bamboo pellets were manufactured using laboratory pellet mill (L-175), made by Amandus Kahl Company of Hamburg Germany. During the manufacturing process, the moisture content of bamboo particles was 16%, and the rotary speed of pellet mill was 280 rpm.
2. The bamboo pellets were collected and kept in the laboratory for more than a week to make properties of bamboo pellet stabilize, such as pellet dimension, density, moisture content et al.
3. Then, bamboo pellets were dried in the drying oven at 105 °C for 8 h. They were removed and cooled in the desiccator to room temperature and the initial mass was determined by a digital balance (0.0001 Resolution). The pellets were returned to the drying oven at 105 °C for 2 h and then cooled and weighed. When mass variance of bamboo pellets was less than 0.2%, the final mass was recorded.
4. The carbonization experiments of bamboo pellets, whose parameters were shown in Table 1, were carried out using a digitally controlled XD-1200N muffle furnace (made by Aremco Products, Inc.). Carbonization process was carried out in the air. After carbonized, they were immediately cooled in the desiccator to room temperature.
5. Then bamboo pellets were transferred to separate Ziploc bags and sealed tightly. And their properties were tested after 7 days to make properties of bamboo pellet stabilize.

Table 1
Carbonization parameters of bamboo pellets.

Experiment no.	Temperature (°C)	Time (min)
1	180	30
2	180	45
3	180	60
4	180	75
5	200	30
6	200	45
7	200	60
8	200	75
9	220	30
10	220	45
11	220	60
12	220	75

2.3. Property test

(1) Unit mass loss (MS)

In order to determine unit mass loss, ten bamboo pellets were randomly selected in each experiment. The unit mass of bamboo pellets before and after carbonization were measured using a precision digital balance (0.0001 Resolution). The MS of bamboo pellets was calculated according the following equation.

$$MS = (M_1 - M_2)/M_1 \tag{1}$$

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

(2) Unit density (ρ_u)

Unit density of bamboo pellets were determined by weighting the individual pellet and calculating its volume based on its length and diameter as per the following equations.

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

$$\rho_u = m_u/V_u \tag{3}$$

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

(3) Bulk density (ρ_b)

Bulk density was calculated as the ratio of pellet mass to container volume. Bamboo pellets were leveled with the top surface of the container and they were weighed using a digital balance (0.001 Resolution). The volume of container was calculated by measuring its length and diameter.

$$\rho_b = m_b/V_b \tag{4}$$

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

(4) Pellet fines (P_f)

Pellet fines were determined using 3.17 mm (1/8 in) wire screen sieve according to *Pellet Fuels Institute Standard Specification for*

Residential/Commercial Densified. Some bamboo pellets were randomly selected and were divided into ten groups. The initial mass of every group sample was weighed using a precision digital balance (0.0001 Resolution). They were placed on a wire screen sieve and tilted from side to side ten times. The final mass was weighed and recorded. The pellet fines were calculated using the following equation:

$$P_f = \left(m_i - m_f\right) \Big/ m_i \times 100\% \tag{5}$$

where, P_f was sample fines (%), m_i was initial mass of samples (g), and m_f was final mass of samples (g).

(5) Pellet durability (P_d)

Pellet durability was determined by mass loss of samples. Some bamboo pellets in each process were randomly selected and weighted using a precision digital balance (0.0001 Resolution). The initial mass was recorded. Then they were 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 recorded. The pellet durability was calculated using the following equation:

$$P_d = 100 - \left(m_i - m_f\right) \Big/ m_i \times 100\% \tag{6}$$

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

(6) Pellet absorption (P_a)

Pellet absorption was determined through mass change of samples. Five bamboo pellets in each process were randomly selected. They were dried at temperature 105 °C until their mass stabilized and then the initial mass of samples was weighed using a precision digital balance (0.0001 Resolution). They were kept in the conditioning room (temperature 27 °C, humidity 90%) for 24 h. Then the final mass of samples was weighed and recorded. The pellet absorption was calculated using the following equation:

$$P_a = \left(m_i - m_f\right) \Big/ m_i \times 100\% \tag{7}$$

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

(7) Inorganic ash (I_a)

Inorganic ash of bamboo pellets was determined based on percent of inorganic material in the bamboo pellets.

1. Five empty crucibles were ignited in the muffle furnace at 600 °C for 2 h, were cooled in the desiccator and were weighed using a precision digital balance (0.0001 Resolution).
2. A 2 g bamboo pellet sample was placed in each crucible, weighed together, and then placed in the drying oven at 105 °C. After 2 h, they were removed, were cooled in the desiccator to room temperature and were weighed.
3. The crucibles were returned to the drying oven at 105 °C for 2 h and were cooled and weighed. When weight variance of the crucible was less than 0.2%, the final weight was recorded.
4. The crucibles were again placed in the muffle furnace at 600 °C and were ignited until all the carbon was eliminated.
5. The crucibles were removed from the muffle furnace and were cooled in the desiccator and weighed using a precision digital balance (0.0001 Resolution).
6. Inorganic ash content was calculated based on the following equation.

$$I_a = (W_1/W_2) \times 100\% \tag{8}$$

where, I_a was inorganic ash content, (%); W_1 was weight of inorganic ash, (g); and W_2 was weight of oven-dry bamboo pellets, (g).

(8) Gross calorific value (G_c)

The gross calorific value was the amount of energy per unit mass released upon complete combustion. The calorific value of bamboo pellets was tested using *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 26,465 J/g. In this test, about 1 g bamboo pellets was introduced into the calorimeter, 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 other combustion aid was used and five samples were tested at each condition.

(9) Combustion rate (C_r) and heat release rate (H_r)

The fire time was recorded according to *PARR 1266 Bomb Calorimeter*. It was time for complete combustion of bamboo pellets. Based on the mass of bamboo pellets and fire time, the combustion rate could be calculated by using following equation.

$$C_r = m/t \tag{9}$$

where, C_r was the combustion rate, (g/s); m was the mass of bamboo pellets, (g); t was fire time in every test, (s).

By knowing the gross calorific value and combustion rate, the heat release rate could be calculated by using following equation [1].

$$H_r = G_c \times C_r \tag{10}$$

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

3. Results and discussions

3.1. Effects of carbonization temperature on properties of bamboo pellets

(1) The physical properties of bamboo pellets

Table 2 illustrates the effects of carbonization temperature on the physical properties of bamboo pellets. The data presented were the mean of measurements made on 30 pellets. As shown in Table 2, the mass loss of bamboo pellets increased as carbonization temperature increased and the values were 2.12%, 3.31% and 7.45% at 180 °C, 200 °C and 220 °C respectively. Treusch et al. [24] and Kwon et al. [25] found the dimensional changes and mass loss were influenced by carbonization temperature for wood-based materials. The mass loss was due to removal of absorbed water and degradation of small molecules in the bamboo materials. The value of pellet absorption was 9.99%, 9.20% and 8.66% respectively, and absorption of all carbonized pellets was lower than that of untreated pellets (10.90%). The absorption decrease of carbonized pellets resulted from the destruction of some hydrophilic groups, such as hydroxyl groups, in the carbonization process. Ohmae et al. [26] found that hydroxyl groups provided absorption sites for water and controlled absorption of samples heated below 250 °C using fourier transform infrared (FTIR). A comparison of the absorption of

Table 2
Physical properties of bamboo pellets with different carbonization temperatures.

Temperature (°C)	MS ± COV (%)	P_a ± COV (%)	ρ_b ± COV (g/cm^3)	ρ_u ± COV (g/cm^3)	P_d ± COV (%)	P_f ± COV (%)
Control		10.90 ± 0.05	0.56 ± 0.005	1.25 ± 0.03	94.80 ± 0.003	0.30 ± 0.06
180	2.12 ± 0.25	9.99 ± 0.08	0.53 ± 0.004	1.11 ± 0.04	97.06 ± 0.003	0.28 ± 0.05
200	3.31 ± 0.08	9.20 ± 0.09	0.51 ± 0.002	1.11 ± 0.02	97.44 ± 0.0024	0.24 ± 0.05
220	7.45 ± 0.12	8.66 ± 0.06	0.49 ± 0.002	1.10 ± 0.04	97.85 ± 0.0018	0.22 ± 0.06

COV means coefficients of variation.

water decreased because of a reduction in the number of hydroxyl groups.

The density of pellets was very important in evaluating product properties. Several national standards describe the particle density of pellets and briquettes as a quality indicator of densified fuels [27]. The maximum throughout for such a large-scale biomass bulk terminal was set at 40 tons per annum, both solid and liquid biomass, which implied that substantial storage facilities and spaces and handing systems were required [28]. Transport efficiency and amount of storage space also depended on the bulk density of pellets. The greater was the bulk density, the higher transport efficiency and the smaller amount of storage space. Fasina [29] reported a four-fold reduction of storage space due to the pelletization of peanut hulls. The bulk density and unit density of carbonized pellets slightly ranged and the values were 0.53 g/cm^3, 0.51 g/cm^3, 0.49 g/cm^3 and 1.11 g/cm^3, 1.11 g/cm^3, 1.10 g/cm^3 at 180 °C, 200 °C and 220 °C, respectively. The bulk density of bamboo pellets slightly decreased with carbonization temperature increase.

The strength of pellets was also an important factor connected with handling and transporting. In the research, the strength of pellets included two parameters, durability and fines. Table 2 illustrates the change of durability and fines of carbonized pellets. Pellet durability increased with greater carbonization temperature with values of 97.06%, 97.44% and 97.85% respectively. For pellet fines, the smallest value occurred at 220 °C, the next was 200 °C and the last was 180 °C. Compared with untreated pellets, the strength properties of carbonized pellets were improved. The formation and binding of different materials via compression occurs in several ways including 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 was created mainly through solid bridges for Corn stover and switchgrass pellets or briquettes. The solid bridges between particles were made by natural binders in the biomass expressed during the densification process [30]. Activating (softening) the natural binders using temperature in the range of glass transition was important to make durable particle–particle bonding. Hemicelluloses, lignin and protein were essentially amorphous polymers in the bamboo components. In the carbonization process of bamboo pellets, natural binders could be softened at some temperature interval, which resulted in stronger bonding of bamboo particles and improved strength properties of bamboo pellets.

Some physical properties of carbonized pellets, including mass loss, pellet absorption, unit density, bulk density, durability and fines, were determined. The carbonization temperature affected these physical properties and analysis of variance results (Table 3) showed that the effects were significantly different at $p = 0.05$ for mass loss, pellet absorption, unit density and bulk density.

(2) The combustion properties of bamboo pellets

Table 4 illustrates the effects of carbonization temperature on combustion properties of bamboo pellets. The data presented were the mean of measurements made on 15 pellets. The inorganic ash of biomass pellets depended on mineral composition of source fuel and on the combustion process [31]. As shown in Table 4, the inorganic ash of untreated pellets was lower than that of carbonized pellets. The inorganic ash of carbonized pellets increased with the carbonization temperature increase, and the values were 1.28%, 1.35% and 1.40% at 180 °C, 200 °C and 220 °C, respectively. The removal of absorbed water and degradation of small molecules (mass loss) led to the difference of inorganic ash of bamboo pellets at different carbonization temperatures. The gross calorific value was 19,434 J/g, 19,482 J/g and 19,711 J/g for carbonized pellets treated at 180 °C, 200 °C and 220 °C. The gross calorific value increased after bamboo pellets were carbonized. There was no significant difference of combustion rate of bamboo pellets. The slight variance of combustion rate was due to differences of porosity and structure for bamboo pellets with different carbonization temperatures. An increase of carbonization temperature significantly influenced the pore size distribution by expanding the porous structure and creating more macropores than micropores [32]. The greater number of pores and the larger pore size in the bamboo pellets, the better the air circulation. Due to better air circulation through the air gap of pellets, the combustion rate of pellets increased [1]. In this research, the combustion rate of bamboo pellets carbonized at 220 °C was fastest, the next was 200 °C and the last was 180 °C. It was also found that the heat release rate of bamboo pellets was also increased with carbonization temperature increase. The main reason was that gross calorific value and combustion rate increased with carbonization temperature increase. The value of heat release rate were respectively 3186 J/s, 3314 J/s and 3437 J/s for bamboo pellets at 180 °C, 200 °C and 220 °C.

In summary, the carbonization temperature affected combustion properties of bamboo pellets, inorganic ash, gross calorific value, combustion rate and heat release rate, and analysis of

Table 3
Analysis of variance.

Physical properties	Variance	SS	df	MS	F value	P-value	F crit
MS	Interior-group	626.34	2	313.17	107.68	$2.981E-27$	3.07
	Inter-group	340.27	117	2.91			
	Total	966.60	119				
P_a	Interior-group	55.07	2	27.53	13.32	$1.793E-05$	3.16
	Inter-group	117.83	57	2.067			
	Total	172.89	59				
ρ_b	Interior-group	0.019	2	0.009	76.74	$5.106E-22$	3.07
	Inter-group	0.014	117	0.0001			
	Total	0.033	119				
ρ_u	Interior-group	0.30	2	0.15	4.30	0.0158	3.07
	Inter-group	3.93	114	0.03			
	Total	4.23	116				

Table 4
Combustion properties of bamboo pellets with different carbonization temperatures.

Temperature (°C)	I_a ± COV (%)	G_c ± COV (J/g)	C_r ± COV (g/s)	H_r ± S.D. (J/s)
Control	1.04 ± 0.08	19,011 ± 0.008	0.159 ± 0.006	3143 ± 0.03
180	1.28 ± 0.009	19,434 ± 0.005	0.164 ± 0.012	3186 ± 0.03
200	1.35 ± 0.07	19,482 ± 0.016	0.174 ± 0.011	3314 ± 0.04
220	1.40 ± 0.05	19,711 ± 0.007	0.176 ± 0.006	3437 ± 0.04

variance results (Table 5) showed that the effects were significantly different at $p = 0.05$ for gross calorific value and combustion rate.

3.2. Effects of carbonization time on properties of bamboo pellets

(1) The physical properties of bamboo pellets

Table 6 illustrates the effects of carbonization time on the physical properties of bamboo pellets. The data presented were the mean of measurements made on 40 pellets. As shown in Table 6, the mass loss of bamboo pellets increased as carbonization time increased with values of 4.10%, 4.34%, 4.45% and 4.53% at 30 min, 45 min, 60 min and 75 min respectively. The mass loss was due to removal of absorbed water and degradation of small molecules. The experimental results showed that the mass loss of bamboo pellets was more readily affected by carbonization temperature rather than carbonization time because bamboo pellets with different carbonization time exhibited a lower mass loss value. The value of pellet absorption was 10.12%, 9.96%, 9.90% and 9.56% respectively, and absorption of carbonized pellets was lower than that of untreated pellets (10.90%). The water absorption capacities of heated bamboo differed and the decrease in water absorption capacity extended up to 2 h. The physical structure of internal pellets was also changed in the carbonization process. Both functional groups and physical structure contributed to the water absorption changes upon carbonization time [26]. The absorption decrease of carbonized pellets resulted from a reduction in the number of hydroxyl groups, which were the main absorption sites of water.

The mean bulk density and unit density of carbonized pellets varied slightly and the values ranged from 0.527 g/cm^3, 0.519 g/cm^3, 0.509 g/cm^3, 0.512 g/cm^3 and 1.12 g/cm^3, 1.09 g/cm^3, 1.02 g/cm^3, 1.05 g/cm^3 at 30 min, 45 min, 60 min and 75 min, respectively. The bulk density and unit density are an important factor connected with handling and transporting of bamboo pellets. The unit density and bulk density of bamboo pellets meet the requirement of *Pellet Fuels Institute Standard Specification for Residential/Commercial Densified* even though they decreased with carbonization time increase.

Pellet durability increased with carbonization time increases and the values were respectively 97.29%, 97.45%, 97.77% and 97.30%. For pellet fines, however, the smallest value occurred at 60 min, the next was 45 min and 75 min, the last was 30 min. Compared with untreated pellets, the strength properties of carbonized pellets was improved. Softening the natural binders using temperature in the range of glass transition was important to producing durable particle–particle bonding. The strength of carbonized pellets increased when carbonization time was increased up to 60 min, after which it decreased with further heat treatment. In the carbonization process of bamboo pellets, natural binders could be softened within some temperature intervals for certain times, which resulted in stronger bonding of bamboo particles and improved strength properties of pellets. But if carbonization time was too long, some bonding of bamboo particle is destroyed due to heating, which leads to the decrease of pellet strength.

The carbonization time affected these physical properties, but analysis of variance results showed that there were no significant differences at $p = 0.05$ between carbonization time and these physical properties of bamboo pellets.

(2) The combustion properties of bamboo pellets

Table 7 illustrates the effects of carbonization time on combustion properties of bamboo pellets. The data presented were the mean of measurements made on 20 pellets. The inorganic ash of untreated pellets was lower than that of carbonized pellets. The inorganic ash of carbonized pellets increased with the carbonization time increase, and the values were 1.29%, 1.32%, 1.36% and 1.40% at 30 min, 45 min, 60 min and 75 min, respectively. The mass loss increased with carbonization time increase, which led to the variance of inorganic ash of bamboo pellets. The gross calorific value was 195,11 J/g, 19,539 J/g, 19,539 J/g and 19,580 J/g for carbonized pellets at 30 min, 45 min, 60 min and 75 min. The gross calorific value increased after bamboo pellets were carbonized. The carbonization treatment changed the composition of bamboo, which resulted in the variance of gross calorific value of bamboo pellets. The gross calorific value of carbonized pellets met the minimum requirement for making commercial pellets (>17,500 J/g), as stated by DIN 51,731 [1]. There was no significant difference of combustion rate of bamboo pellets and the values ranged between 0.161 g/s and 0.171 g/s. The slight variance of

Table 5
Analysis of variance.

Combustion properties	Variance	SS	df	MS	F value	P-value	F crit
Gc	Interior-group	526,679.36	2	263,339.68	13.72	4.599$E-05$	3.28
	Inter-group	633,205.27	33	19,188.038			
	Total	1,159,884.6	35				
Cr	Interior-group	0.0018	2	0.00093	5.00	0.0126482	3.28
	Inter-group	0.0061	33	0.00019			
	Total	0.0079	35				

Table 6
Physical properties of bamboo pellets with different carbonization times.

Time (min)	MS ± COV (%)	P_a ± COV (%)	ρ_b ± COV (g/cm^3)	ρ_u ± COV (g/cm^3)	P_d ± COV (%)	P_f ± COV (%)
Control		10.90 ± 0.05	0.563 ± 0.05	1.25 ± 0.03	94.84 ± 0.0003	0.30 ± 0.03
30	4.10 ± 0.18	10.12 ± 0.21	0.527 ± 0.06	1.12 ± 0.02	97.29 ± 0.0002	0.26 ± 0.01
45	4.34 ± 0.11	9.96 ± 0.37	0.519 ± 0.04	1.09 ± 0.03	97.45 ± 0.0015	0.24 ± 0.05
60	4.45 ± 0.15	9.90 ± 0.31	0.509 ± 0.04	1.01 ± 0.05	97.77 ± 0.0066	0.21 ± 0.09
75	4.53 ± 0.09	9.56 ± 0.34	0.512 ± 0.06	1.05 ± 0.04	97.30 ± 0.0023	0.24 ± 0.19

Table 7
Combustion properties of bamboo pellets with different carbonization times.

Time (min)	$I_a \pm$ COV (%)	$G_c \pm$ COV (J/g)	$C_r \pm$ COV (g/s)	$H_r \pm$ COV (J/s)
Control	1.04 ± 0.08	19,011 ± 0.008	0.174 ± 0.006	3314 ± 0.03
30	1.29 ± 0.04	19,511 ± 0.023	0.170 ± 0.012	3330 ± 0.02
45	1.32 ± 0.10	19,539 ± 0.023	0.164 ± 0.018	3201 ± 0.03
60	1.36 ± 0.16	19,539 ± 0.025	0.161 ± 0.373	3147 ± 0.03
75	1.40 ± 0.03	19,580 ± 0.021	0.171 ± 0.023	3345 ± 0.02

combustion rate was due to the difference of composition and porous structure for bamboo pellets with different carbonization time. It was also found that the heat release rate of bamboo pellets was changed with carbonization time increase. The value of heat release rate was respectively 3330 J/s, 3201 J/s, 3147 J/s and 3345 J/s for carbonized pellets at 30 min, 45 min, 60 min and 75 min.

In summary, the carbonization time affected combustion properties of bamboo pellets even though there were no significant difference at $p = 0.05$ between carbonization time and these combustion properties of bamboo pellets according to analysis of variance method.

4. Conclusions

It can be concluded from this research that carbonization conditions (temperature and time) affect the properties of bamboo pellets. The effects of carbonization temperature on some properties such as mass loss, pellet absorption, bulk density, unit density, gross calorific value and combustion rate, were significant at $p = 0.05$. But there were not significant differences between carbonization time and all properties of bamboo pellets.

After being carbonized, the properties of bamboo pellets, such as pellet absorption, durability, fines, gross calorific value, combustion rate and heat release rate, were improved. All properties of carbonized pellets met the requirement of *Pellet Fuels Institute Standard Specification for Residential/Commercial Densified* and the gross calorific value also met the minimum requirement for making commercial pellets of DIN 51,731 (>17,500 J/g) even though the properties of carbonized pellets, such as bulk density, unit density and inorganic ash, exhibited poor quality compared with untreated pellets. Carbonized bamboo pellets are the proposed new biomass solid fuel and have the potential to be developed as commercial pellets.

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