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Short communication

Torrefaction of bamboo under nitrogen atmosphere: Influence of temperature and time on the structure and properties of the solid product

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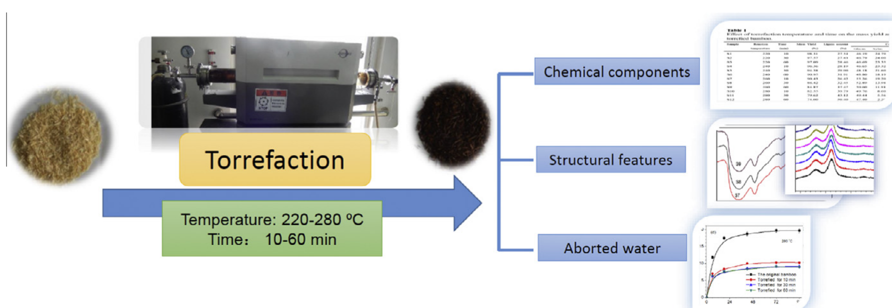
HIGHLIGHTS

- Bamboo was torrefied under nitrogen atmosphere at 220–280 °C for 10–60 min.
- Only 2.20% xylan was detected in the sample torrefied at 280 °C for 60 min.
- The energy yield of the sample after torrefaction was over 90%.
- Bamboo became hydrophobic after torrefaction evidenced by low absorbed moisture.
- Torrefaction produced a good feedstock for the application in burning.

GRAPHICAL ABSTRACT



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ABSTRACT

Torrefaction of bamboo was performed in a horizontal tubular reactor under nitrogen atmosphere at 220, 240, 260, and 280 °C for 10, 30, and 60 min, respectively. It was found that with an increase of the severity of torrefaction, the mass yield and energy yield decreased while the high heating value increased. Due to the release of hydroxyl groups, the torrefied bamboo became more hydrophobic and the maximum content of absorbed moisture was reduced by 53.89%. The elemental components of torrefied bamboo tended to that of coal since carbon content was enriched with the increase of torrefaction severity. The removal of hemicelluloses and the enrichment of lignin produced samples with more uniform quality. This study suggested that torrefaction of bamboo under nitrogen produced a good feedstock for the application in burning.

1. Introduction

Lignocellulose is an important resource for the production of fuels, whereas it is used in low value due to its lower energy density as compared to fossil fuel. To overcome the drawback, many technologies are developed, such as volume reduction, pelletization and torrefaction [1]. Among them, torrefaction is a thermal process which heats lignocellulose at 200–300 °C under inert atmosphere. Bamboo, a promising grassy plant with a high growth rate (matures within 5–7 years) as well as good fuel characteristics [2], has attracted much attentions. Thermogravimetryic analysis suggested that the torrefied samples showed low ignition temperatures and that the torrefaction duration should be lessen 1 h for the preparation of fuels having high heating energy density [3,4]. Bamboo was torrefied by microwaving heating and the caloric

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value increased up to 48% [5]. With respect to fuel characteristics, torrefaction improves physical properties but doses not enhance significantly fouling behavior [6]. Torrefied bamboo can be blended with coal for pulverized coal injection [7]. Torrefaction at 300 °C can transform bamboo into a solid fuel having a proper burnout for blast furnaces [8]. Recently, the liquid fraction was obtained from bamboo (*Bambusa sinospinosa*) torrefaction, and it was found that the heating value of the liquid product was increased after dewatering [9].

From the published literature, it can be found that most studies on bamboo torrefaction focused on the the combustible properties and relatively little attention on the structural modifications during bamboo torrefaction resulted from reaction temperature and time. The objective of the study was to increase our knowledge on bamboo torrefaction from the aspect of the structural features. Bamboo was torrefied in a horizontal tubular reactor at 220–280 °C for 10–60 min under nitrogen atmosphere, and the solid residues obtained were characterized. In addition, the water absorption capacity of the sample was determined. The relationships between the characteristics and application in burning were discussed.

2. Materials and methods

2.1. Raw material

The feedstock used in the present study, culm of bamboo (*Phyllostachys acuta*, Yunnan province, China), was ground and sieved to obtain particles with sizes between 20 and 80 mesh. The bamboo powder was de-waxed with methylbenzene/ethanol (2/1, v/v) for 8 h, treated with water at 80 °C for 6 h to remove starch, and then stored before use. The chemical composition was cellulose 43.78%, hemicelluloses 29.88%, and lignin 27.64%.

2.2. Torrefaction of bamboo under nitrogen atmosphere

Torrefaction of the sample was conducted in a horizontal tubular reactor (SK-G08123K, Tianjin Zhonghuan Experimental Furnace Co. Ltd., China). The experiments were conducted at 220, 240, 260 and 280 °C for 10, 30, and 60 min respectively, producing 12 torrefied bamboo samples (S1 to S12, as shown in Table 1), respectively. In a typical run (for the preparation of the sample S11), 10 g (dry weight) of bamboo (S0) was put into a zirconium oxide boat (length: 60 mm, width: 51 mm, and height: 32 mm) which was placed into a quartz tube. Nitrogen flow (rate 100 mL/min) was used to maintain an inert atmosphere and remove volatile products from the system. The furnace was heated to reach 280 (±1) °C and the temperature was kept for 30 min. After the torrefaction, the furnace was cooled below 100 °C and the boat was pulled out and the torrefied solid was collected and weighted.

2.3. Characterization of the sample

The weight of the torrefied solid was determined by gravity method. Mass and energy yields, chemical components, elemental components, HHV, and water absorption capacity were measured according to a previous report [10]. All the measurements were conducted by triplicate the average values of the results were reported. FTIR spectra were collected in a Thermo Scientific Nicolet iN10 FTIR Microscope (Thermo Nicolet Corporation, Madison, US) which was equipped with an MCT detector cooled by liquid nitrogen. The data of X-ray diffractograms were collected on an X-ray diffractometer (XRD-6000, Shimidzu, Japan). SEM images of the samples were acquired using a scanning electron microscope (S-3400 N, 224 HITACHI, Japan) operating at 10 kV. The samples were coated with gold–palladium in a sputter coater (E-1010, HITACHI, Japan) before observation.

3. Results and discussion

3.1. Component variation

The mass yield and chemical components of the solid residue obtained are listed in Table 1. The mass yield gradually decreased with the increase of temperature and time. As expected, the lowest mass yield of 74.60% was obtained under the severest torrefaction conditions of 280 °C and 60 min whereas the highest mass yield of 98.31% was obtained under the mild conditions of 220 °C and 10 min. The mass lose was relatively low as compared to the previous report of *Miscanthus* × *giganteus* in which the torrefaction at 270 °C for 30 min resulted in a low mass yield of 65.3% [11]. Both the original and torrefied bamboo samples contained cellulose, hemicelluloses, and lignin. However, the amount of each component in the torrefied samples was different to that of the original bamboo depending on the reaction conditions. For the same torrefaction time, there was a slight increase of the cellulose content with the increase of torrefaction temperature from 220 to 260 °C and a reduction with the further increase of temperature to 280 °C; whereas a constant reduction of hemicelluloses (represented by xylan, arabinan and galactan) was observed as the torrefaction severity increased. The samples obtained from the torrefaction over 260 °C for 30 and 60 min showed a marked variation of the chemical components as compared to the original bamboo. For sample S12 (torrefied at 280 for 60 min), there was only 2.20% xylan but araban and galactan were not detected. This was mainly due to the fact that hemicelluloses were the most unstable component. In addition, the content of lignin increased as the reaction temperature and time increased.

The elemental components, HHV, and energy yield of the torrefied samples were analyzed and the results are listed in Table 2.

Table 1
Effect of torrefaction temperature and time on the mass yield and chemical components of torrefied bamboo.

Sample	Reaction temperature (°C)	Time (min)	Mass yield (%)	Lignin content (%)	Carbohydrate content (%)				
					Glucan	Xylan	Arabinan	Galactan	Total sugar
S1	220	10	98.31	27.34	46.19	24.79	1.14	0.35	72.46
S2	220	30	97.57	27.43	46.79	24.00	1.22	0.31	72.31
S3	220	60	97.09	28.46	46.69	23.35	1.10	0.32	71.46
S4	240	10	96.36	28.19	46.65	23.32	1.05	0.32	71.25
S5	240	30	94.58	29.00	48.18	21.60	0.81	0.29	70.89
S6	240	60	90.95	31.91	48.80	18.19	0.58	0.17	67.75
S7	260	10	90.43	26.42	53.26	19.20	0.61	0.18	73.25
S8	260	30	86.42	32.45	52.89	13.98	0.37	0.00	67.23
S9	260	60	84.87	37.47	50.60	11.91	0.28	0.00	62.79
S10	280	10	82.55	39.79	49.76	8.60	0.00	0.00	58.36
S11	280	30	79.62	43.12	49.44	5.56	0.00	0.00	55.00
S12	280	60	74.60	50.40	47.40	2.20	0.00	0.00	49.43