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Upgrading fuel quality of moso bamboo via low temperature thermochemical treatments: Dry torrefaction and hydrothermal carbonization

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HIGHLIGHTS

- Fuel potential was enhanced via hydrothermal carbonization and torrefaction.
- Hydrochar performed better than torrefied bamboo produced at the same temperature.
- Hydrophobicity was obtained at higher treating temperature.
- Removal of hemicellulose was the dominant reaction in hydrothermal carbonization.
- 260 °C was determined to be suitable for hydrochar production.

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ABSTRACT

The application of raw bamboo as biomass energy is restricted due to its large particle size, high oxygen content, low energy density and weak water resistance. In order to upgrade the fuel quality of moso bamboo, dry torrefaction (DT) and hydrothermal carbonization (HTC) have been investigated in this study. The physicochemical properties, thermal stability and microstructures of solid products were examined by varying the reaction temperature among 220, 260 and 300 °C. The results showed that increasing temperature reduced the mass yield and energy yield, however, it significantly improved the calorific value of solid products. Through the HTC process, the bamboo hydrochar obtained the calorific value of 28.29 MJ/kg, the energy yield of 59.77% and the fixed carbon content of 63.08% at the temperature of 260 °C, indicating enhanced potential as a solid fuel. In comparison, the grindability (including particle size and bulk density), hydrophobicity, and thermal stability of torrefied bamboo were considerably lower than that of bamboo hydrochar produced at the same temperature. Furthermore, the transformation of chemical bonds demonstrated that hydrolysis, dehydration and decarboxylation took place during the HTC process. The porous structure was only slightly enhanced with increasing reaction temperature, exhibiting variation consistent with that of hydrophobicity.

1. Introduction

In the past few decades, renewable biomass energy has received great attention due to the increasing environmental concerns and energy crisis associated with the exhaustion of conventional fossil fuels. Biomass is advantageous both alone in combustion and co-fired with coal because it is widely available and demonstrates potential for greenhouse gas neutrality [1]. However, low calorific value and poor resistance to moisture absorption make the direct use of biomass less attractive. To overcome these shortages, various types of thermochemical conversions have been attempted [2–5]. Among all the thermochemical treatments, dry torrefaction and hydrothermal carbonization are the two most practical methods with relatively low temperature requirements [6], costing less energy input when compared with slow pyrolysis for biochar, fast pyrolysis for bio-oil, or gasification.

Dry torrefaction (DT), during which processed biomass is heated in an inert atmosphere at temperatures of around 200–300 °C for a residence time of 30 min to a couple hours, is often regarded as a conventional thermochemical pre-treatment and proposed as an alternative to improve the physicochemical

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properties of biomass. Acharya et al. [7] reviewed that torrefaction undergoes devolatilization, depolymerization, and limited carbonization of lignocellulose components and generates a brown to black solid product with 70% mass and 90% energy reserved. Bach and Skreiberg [8] claimed that the improved properties of torrefied biomass, such as relatively superior handling and milling, highlight a beneficial opportunity to co-fire the clean renewable energy source with coal in an effort to relieve the energy crisis and mitigate environmental pollution. Nevertheless, the torrefaction process is unsuitable when disposing feedstocks with high moisture content, and the calorific value of torrefied biomass is still lowly graded. Moreover, the high O/C ratio and volatile content may affect the thermal stability and combustion profile.

Hydrothermal carbonization (HTC), also referred to as wet torrefaction, is often used to prepare a solid product called hydrochar which exhibits reduced O/C ratio, increased calorific value, better grindability and improved hydrophobicity compared with untreated and torrefied biomass [9]. During the HTC process, feedstock is mixed with subcritical water at temperatures of 180–350 °C under an inert atmosphere so that the products are not affected by the high moisture content. Hydrothermal carbonization has the ability to deal with not only extremely wet feedstock such as sewage sludge [10] or sludge from the pulp and paper mill [11], but also forestry processing residues and agricultural wastes [12]. Lynam et al. [13] prepared loblolly pine hydrochar at the temperature range from 200 to 260 °C. A 30% increase in calorific value of hydrochar was found with increasing temperature whereas the mass yield was slightly reduced. In addition, adding both 0.4 g acetic acid and 1 g lithium chloride per g pine resulted in an energy densification ratio of 1.34. Other research included the use of nut husks as feedstock [14]. The fuel properties of hydrochar were found to be most affected by the component weight ratios of the biomass. For example, lignin was the main contribution to the solid fuel yield and the reactivity of cellulose and hemicellulose in different biomass was affected by the biomass species. Moreover, the calorific value of solid fuels prepared at 260 °C, around 25 MJ/kg, were comparable to those of commercial coals. Therefore, the properties of hydrochar may greatly differ depending on the feedstock resource and reaction conditions such as temperature.

Moso bamboo, an abundant natural cellulosic resource, has gained much attention in the comprehensive utilization of biomass over the past years due to its easy propagation, fast growth and regeneration, and high productivity as well as its rapid maturity [15]. It is widely used to produce furniture, veneers and flooring, but a significant amount of bamboo processing residues was treated as waste. Thus, the application of bamboo processing residues for bioenergy production is worth exploring. In order to dispose these solid waste residues, some researchers have evaluated moso bamboo residues directly as biofuel, but the energy density and the fuel quality is generally low for direct burning of moso bamboo. Some other researchers have prepared bamboo biochar by slow pyrolysis, but the mass yield is always lower than 30% and energy cost is high [16–18]. It is necessary to find an environmentally friendly and efficient method to upgrade fuel quality of moso bamboo. However, only a few researchers have studied hydrothermal carbonization on bamboo biomass [19]. Even fewer have examined the comparative assessment of moso bamboo for producing energy dense fuel via DT and HTC treatment.

The main objectives of this study are to (1) upgrade fuel quality of the torrefied product and hydrochar obtained from moso bamboo by investigating the effect of reaction temperature on energy characteristics, such as calorific value, proximate analysis, hydrophobicity, and thermal degradation stability, (2) clarify the relationship between fuel quality and chemical structure as well as pore structure, (3) and compare the performance of these two kinds of solid biofuels to identify the better option for energy application.

2. Materials and methods

2.1. Materials

Moso bamboo (*Phyllostachys pubescens*) particles were supplied by China National Bamboo Research Center in Hangzhou. The raw moso bamboo was harvested in Anji, Zhejiang Province of China. The samples were ground into particles of 200–400 μm using a turbine grinder (XWDJ-130, Zhejiang Xinshiji grinder machine Co. Ltd, China) and the moisture content was measured to be 8%.

2.2. Samples preparation

The torrefaction of bamboo particles was carried out in a bench-scale fixed bed reactor, which was designed and fabricated by Bioenergy and Biomaterials Lab at Zhejiang University. The reactor consists of a stainless steel container with an inner diameter of 120 mm and a height of 330 mm. For each run, 100 g of moso bamboo particles was placed inside the reactor. The reactor was indirectly heated by electric heater at set temperatures of 220, 260 and 300 °C for 1 h, respectively. After the desired isothermal period, the sample was cooled down naturally to room temperature. The solid torrefied bamboo was collected in a sealed transparent plastic bag and stored in an airtight container at room temperature until analysis.

Hydrothermal carbonization of bamboo particles was carried out in a cylindrical stainless steel reactor (4848, Parr Instrument Company, USA) with a working volume of 2 L. A weight of 100 g bamboo particles combined with 1 L purified water was fed into the reactor, which was then closely tightened. The reactor was held at the desired temperature of 220, 260 and 300 °C for 1 h, respectively. Temperature and pressure inside the reactor were measured and adjusted by the controller connected with a thermocouple and a pressure sensor. After treatment, the mixture inside the reactor was filtered by a vacuum pump (SHB-IIIA, Shanghai Yukang Science Teaching Instrument Equipment Co. Ltd), and then the hydrochar was dried at 105 °C until its weight reached a constant value.

The samples were marked as BP for bamboo particle, DT220, DT260, DT300 for dry torrefied bamboo, and HTC220, HTC260, HTC300 for bamboo hydrochar at their respective temperatures.

2.3. Properties characterization

Proximate analysis of the samples was conducted using ASTM E1756-08 to determine the moisture content, ASTM E872-82 for volatile content, and ASTM D1102-84 for ash content. The fixed carbon content was calculated by mass balance. The calorific value of the samples was measured using an Oxygen Bomb Calorimeter (5E-AC, Changsha Kaiyuan Instruments Co., Ltd, China).

The mass yield (M_Y) and energy yield (E_Y) of solid products were calculated as follows:

$$M_Y(\%) = m_{.SP}/m_{.BP} \times 100 \quad (1)$$

$$E_Y(\%) = M_Y \times cv_{.SP}/cv_{.BP} \quad (2)$$

where $m_{.SP}$ and $cv_{.SP}$ are the mass and calorific value of solid products, $m_{.BP}$ and $cv_{.BP}$ are the mass and calorific value of bamboo particles, and $cv_{.SP}/cv_{.BP}$ is energy density of the solid products.

The bulk density was determined using a Bulk Density Tester (Buld-005, Hangzhou Tonfus Corporation, China). The particle size distribution was determined using a Laser Particle Size Analyzer