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Characterization of biomass waste torrefaction under conventional and microwave heating

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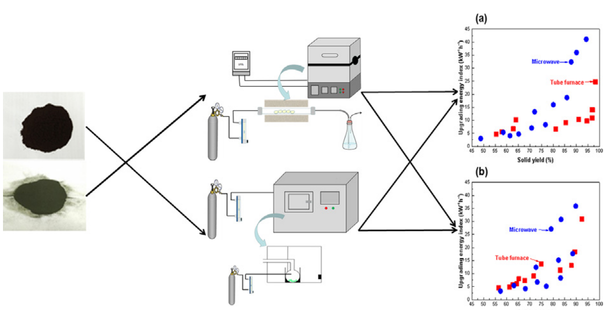
GRAPHICAL ABSTRACT



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ABSTRACT

To evaluate the potential of microwave heating for biomass torrefaction, the torrefaction performances and energy utilization of coffee grounds and microalga residue, under conventional and microwave heating were investigated and compared with each other. For the two biomass samples, the dehydrogenation of the coffee grounds was more sensitive to torrefaction severity, whereas the microalga residue consumed more energy under the same torrefaction conditions. Microwave heating under lower torrefaction severity had a higher energy efficiency. As regard to the lower solid yields or higher torrefaction severity, the energy efficiency of microwave heating was close to that of conventional heating, irrespective of the feedstocks. This revealed the comparable energy consumption state between the two heating modes. Accordingly, it is concluded that microwave torrefaction is more efficient for biomass upgrading and densification than conventional torrefaction.

1. Introduction

Torrefaction is a biomass mild pyrolysis technology in which biomass is thermally pretreated at 200–300 °C in an inert and atmospheric pressure environment (Chen et al., 2015d). Cellulose, hemicellulose, and lignin in lignocellulosic biomass (Chen et al., 2012; Rousset et al., 2011) as well as carbohydrate, protein, and lipid in algal biomass are decomposed after torrefaction; meanwhile, moisture and volatiles in biomass are driven off (Chen et al., 2015c; Kumar et al., 2016). The produced solid has better fuel quality because of its higher calorific value, lower atomic H/C and O/C ratios (Basu et al., 2014; Chen et al., 2015c), better grindability, and improved hydrophobicity (Arias et al.,

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2008; Commandré & Leboeuf, 2015). Torrefaction can also lower the transportation and storage cost of various biomass wastes undergoing densification (Chai & Saffron, 2016; Couhert et al., 2009). In recent years, the advantages of using torrefaction for biomass conversion and utilization have attracted much attention(Chen et al., 2015d; Rizzo et al., 2013).

Nowadays there are mainly two bench-type heating measures for biomass torrefaction, including tube furnace torrefaction (named as conventional torrefaction) and microwave torrefaction (Gronnow et al., 2013). Conventional torrefaction is practiced in a tube furnace with a quartz tube that is powered by electricity. With an adjustable heating rate, the reaction temperature can be controlled precisely (Chen et al., 2015a), but a longer duration is required if severe torrefaction is carried out. In contrast, microwave torrefaction is a biomass upgrading process under heating assisted by electromagnetic irradiation (Chen & Lin, 2013; Huang et al., 2012). Recently, microwave torrefaction has attracted increasing interest among the scientific community that is considered as an alternative method of biomass heating (Bach et al., 2016; Huang et al., 2017c; Oliver, 2008). The increase in scientific efforts to develop microwave heating is attributed to its several advantages: (1) non-contact heating; (2) rapid heating; (3) selective heating; (4) a quick start/stop; (5) a high level of safety and automation; and (6) heating from the body interior of the material (i.e., energy conversion instead of heat transfer). (Patil et al., 2012; Xu et al., 2012). All of these advantages have promoted research into the applications of microwave heating.

The productivity of different types of torrefaction measures are often limited by the low intensity of heat and mass transfer processes, which determines the intensity of the thermal degradation process. From the energy input point of view, it is essential to evaluate whether the torrefaction measures are suitable in order to acquire the optimal torrefaction strategies (Chen et al., 2015b). Up to now, most biomass torrefaction is performed using conventional heating or tube furnaces. However, the use of microwave radiation as a heat source sometimes can be a better attempt because of various advantages such as excellent heat transfer, improved uniformity of heat distribution, better control over the heating process, fast internal heating, higher power densities, the ability of reaching high temperatures at higher heating rates, and less processing time (Chen et al., 2011; Jones et al., 2002; Satpathy et al., 2014). Thus, the unique features of microwave heating can be used to improve the torrefaction process, modify the material selectivity, or even perform reactions that do not occur under conventional thermal heating conditions (Lei et al., 2009; Xu et al., 2012).

Considering biomass torrefaction with microwave heating, Natarajan et al. (2018) used *Prosopis juliflora* as a feedstock for microwave torrefaction, and evaluated the effects of particle size and microwave power on the torrefaction. They concluded that the optimum conditions to attain the maximum energy recovery were 481 W microwave power and 1.9 mm particle size. Huang et al. (2012) performed microwave torrefaction with different power levels using rice straw and pennisetum as feedstocks, and found that the energy density of torrefied biomass was about 14% higher than that of raw biomass. Wang et al. (2012) used rice husk and sugarcane residues as feedstocks, and addressed that microwave torrefaction reduced more O/C ratio of the rice husk in comparison with conventional torrefaction. Emadi et al. (2016) torrefied wheat and barley straw pellets along with microwave heating and using linear low density polyethylene (LLDPE) as a binder. They found that adding LLDPE from 1 wt% up to 10 wt% resulted in an increase in the higher heating values and a decrease in the ash contents of the two types of pellets.

The aforementioned literature suggests that microwave heating is a potential route for biomass torrefaction and fuel upgrading in industry. For example, Bermúdez et al. (2015) paid their attention to the scaling-up of microwave heating processes and studied the variation of the energy expenditure of microwave heating as a function of the scale employed. On the basis of six kinds of microwave-assisted process, they found that the specific energy consumption decreased by 90–95% when the sample amount increased from 5 to 100 g, and it was constant when the sample was above 200 g. Huang et al (2017b) focused on leucaena biochar production by microwave torrefaction and pointed out that microwave torrefaction of leucaena was a promising technique that could be feasible if it was deployed at industrial scale. To date, however, the research concerning the comparison of conventional and microwave torrefaction remains absent, and this comparison plays a pivotal role in evaluating the feasibility of microwave heating for industrial biomass torrefaction. For this reason, this study aims to examine the energy efficiencies of conventional and microwave torrefaction of biomass wastes, and to analyze the solid products characteristics obtained from these torrefaction treatments. To provide a comprehensive study, two different types of biomass, consisting of a lignocellulosic sample (waste coffee grounds) and a microalgal biomass (microalga residue) are explored. In order to compare the characteristics and performance of upgraded fuels acquired from the two torrefaction measures, different torrefaction conditions such as processing time, the power level of microwave heating, and conventional heating temperature are performed.

2. Methodology

2.1. Materials

Two biomass wastes of spent coffee grounds and microalga residue were used as feedstocks for this study. The coffee grounds were obtained from a local coffee shop (Shake coffee, Harbin, China). The microalga residue (*Arthrospira platensis*) was obtained from Fuqing King Dnarmsa Spirulina Co., Ltd (Fuqing, China). The biomass wastes were dried in an oven at 85 °C for 10 h to preliminarily eliminate their surface water; this also provided a basis for the subsequent analysis and experiments. Then the samples were powdered and sieved by a 40 mesh screen where particles with sizes smaller than 0.4 mm were collected for subsequent torrefaction experiments and analysis.

2.2. Experimental apparatus and procedure

The torrefaction system consists of a nitrogen steel cylinder, a rotameter, a reaction unit, and a watt-hour meter. Nitrogen (> 99.99 vol %), controlled by the rotameter, in the cylinder was used for providing an oxygen-free environment during biomass torrefaction. For conventional heating, the reaction unit was composed of a tube furnace and a quartz tube (Zhang et al., 2018). The power supplied to the reaction unit was monitored by the watt-hour meter. For microwave heating, the reaction unit was made up of a microwave furnace, a quartz bottle, and a microwave absorbing medium (E-Supplementary data for this work can be found in e-version of this paper online).

In each experiment, the sample (8 g ± 5%) was loaded into the quartz tube or the quartz bottle. For microwave heating, the amount of the sample was not enough to absorb microwaves sufficiently to reach the desired temperatures, the quartz bottle was thus enveloped by a layer of microwave absorbing medium to improve microwave utilization efficiency and torrefaction condition. The medium was the biochar produced from the kernel of Dimocarpus longan. The biochar showed excellent performance for microwave absorption in our tests, so it was used in this study. A thermocouple was placed at the bottom of the quartz bottle to measure the temperature of the bottle. In order to maintain the non-oxidative environment and remove the volatiles produced during the torrefaction process, nitrogen gas at a flow rate of 100 $mL\,min^{-1}$ was continuously blown into the reaction unit. For conventional heating, three different torrefaction temperatures of 200, 250, and 300 °C, corresponding to light, mild, and severe torrefaction, respectively (Chen et al., 2014b), along with four different torrefaction durations of 15, 30, 45, and 60 min were chosen as the experimental conditions. The linear correlations of power and temperature using the