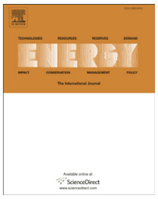
Energy 116 (2016) 1–7

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Co-torrefaction of sewage sludge and leucaena by using microwave heating

Yu-Fong Huang, Hsuan-Te Sung, Pei-Te Chiueh*, Shang-Lien Lo

Graduate Institute of Environmental Engineering, National Taiwan University, 71, Chou-Shan Rd., Taipei 106, Taiwan, ROC

ARTICLE INFO

Article history:
Received 3 June 2016
Received in revised form
20 August 2016
Accepted 17 September 2016

Keywords:
Co-torrefaction
Sewage sludge
Leucaena
Microwave heating
Synergistic effect

ABSTRACT

Microwave co-torrefaction of sewage sludge and leucaena can be a workable technique, because it not only produces biofuels but also solves the problems in waste treatment. When the sewage sludge blending ratio was 25–50 wt% and the microwave power level was 100 W, a synergistic effect was found to influence the mass and energy yields as well as product properties. The relatively small amount of sewage sludge could play a role as a catalyst, since the synergistic effect was hard to be identified at higher sewage sludge blending ratios. Besides, it was difficult to find out the synergistic effect at higher microwave power levels. This could be attributable to the effect of microwave heating which increases with its power level. The elemental compositions of biochar were close to those of anthracite and bituminous coal. The energy return on investment (EROI) of microwave co-torrefaction of the 25/75 (w/w) sewage sludge/leucaena blend at a microwave power level of 100 W in a processing time of 30 min can be approximately 10.1 or 4.7, when the gaseous and liquid products are utilized or not. Therefore, the technique should be energetically and economically feasible.

1. Introduction

Because of heavy dependence on fossil fuels that are non-renewable and cause a great deal of carbon emissions, the use of nuclear energy that may lead to radioactive pollution for hundreds years, and global climate change that is leading to more and more unexpected disasters, the research and development of clean, safe, abundant, and low-cost renewable energy has been so important and urgent. Biomass, one of renewable energy sources, provides various advantages. Biomass is the only source of renewable liquid, gaseous, and solid fuels [1]. The growth of plant biomass removes atmospheric carbon dioxide, which can offset the carbon dioxide emitted by the combustion of biofuels [2]. Biomass is an abundant, carbon-neutral, and renewable resource for the production of biofuels and biomaterials [3], and thus there has been increasing interest in producing biofuels from a range of biomass feedstocks in recent years [4]. Furthermore, most of the municipal and industrial wastes can be regarded as biomass feedstocks. In addition to the advantage of biofuel production, the utilization of the organic wastes can also reduce the cost and environmental impacts from waste treatment and disposal.

Microwaves are located between infrared and radio waves in the electromagnetic spectrum, and they have wavelengths from 1 mm to 1 m, corresponding to frequencies between 300 MHz and 300 GHz [5]. In order to avoid interference with telecommunications and radar transmissions, domestic and industrial microwave ovens generally operate at either 900 MHz or 2.45 GHz [5,6]. Microwave technology has been used in various applications, including organic synthesis [5–8], digestion [9,10], and food heating [11,12]. Microwave heating provides a number of advantages over conventional heating, including higher heating efficiency and power density, better heat transfer and process control, more uniform heat distribution, and faster internal heating [13–16]. Microwave heating can reach high temperatures in a fraction of the time required for conventional heating, and the unique features of microwave heating can be used to improve processes, to modify selectivity, and to perform reactions that do not occur by conventional heating [17,18]. Microwave heating has been used for biomass pyrolysis and torrefaction in several studies [19–29]. The dominant product of microwave pyrolysis can be liquid [20], solid [27], or gases [28], depending on operational parameters such as microwave power level, processing time, biomass characteristics, and the presence of catalysts or microwave absorbers [29].

Raw biomass feedstocks have high moisture content, low energy

---

* Corresponding author.
E-mail address: ptchueh@ntu.edu.tw (P.-T. Chiueh).

http://dx.doi.org/10.1016/j.energy.2016.09.102

densities, and hydrophilic nature, and they are bulkier with poorer handling and transportation characteristics and is more tenacious to make it difficult to comminute into small homogeneous particles, resulting in complicated and expensive storage and transportation [30–33]. In addition, the high oxygen content of biomass would result in a large amount of smoke formation during combustion [33]. All of the drawbacks have given rise to the research and development of new technologies for biomass modification in order to ensure that its utilization as an energy source is environmentally friendly and economically efficient [31,34]. One potentially feasible way is a thermal processing step known as torrefaction [30,34,35]. Torrefaction is a low-temperature (200–300 °C) thermal pretreatment of biomass operated at atmospheric pressure in the absence of oxygen [35–37], so it is also known as mild pyrolysis [30,31,33,38]. In addition to increasing energy density and decreasing moisture and oxygen content, torrefaction offers a great effect on the grindability and reactivity of biomass [31]. Furthermore, biomass becomes hydrophobic after torrefaction, which could be attributable to the formation of nonpolar unsaturated structures [35].

In this study, the co-torrefaction of sewage sludge and leucaena was carried out by using microwave heating. The disposal of sewage sludge would be one of the most complex environmental problems [39,40], whereas the organic fraction of sewage sludge can be regarded as a resource of bioenergy [41,42]. Leucaena is a fast growing plant with high biomass production rate, so it has a high potential for bioenergy production and can be a satisfactory alternative to the use of traditional biomass feedstocks [43,44]. The purpose of this study was to investigate the biochar produced by microwave co-torrefaction of sewage sludge and leucaena. This study also evaluated the energy usage of the technique. The originality of this study was that a synergistic effect between the two very different biomass feedstocks was found to influence the properties of the biochar and the mass and energy yields of microwave co-torrefaction. Consequently, even at relatively low microwave power levels, the performance of microwave co-torrefaction was satisfactory. Besides, it was found that the energy usage benefit of microwave co-torrefaction was high, no matter gas and liquid products were recovered or not.

2. Material and methods

2.1. Materials

Sewage sludge was obtained from the Dihua Sewage Treatment Plant, Taipei, Taiwan. The moisture content of the as-received sewage sludge was approximately 85 wt%. To remove the moisture, the raw sewage sludge was air dried for several months and then dried in an oven (95 °C) for three days. Leucaena wood was provided by the Kenting National Park, Pingtung, Taiwan. Before applying to microwave torrefaction and relevant experiments, sewage sludge and leucaena was dried, shredded, and ground into powder, and then it was sieved by using a 50-mesh screen (0.297 mm opening). The blended samples were obtained by mixing sewage sludge and leucaena at the ratios of 25:75, 50:50, and 75:25, named as SS25%, SS50%, and SS75%, respectively.

2.2. Experimental apparatus

A single-mode (focused) microwave oven was used in this study. This microwave oven operates at a frequency of 2.45 GHz, and its maximum output power is 2000 W. A schematic diagram of the overall microwave heating system can be found elsewhere [45]. Both reaction tube (40 cm length, 5 cm outer diameter) and sample crucible (3 cm height, 4 cm outer diameter) are made of quartz. There was a three-stub tuner in charge of regulating the incident angle of microwaves to make sure that microwave peak is located at the center of reaction zone. At the end of microwave propagation pathway, a short-circuit plunger was set to adjust the wavelength phase of microwaves. During the experiment induced by microwave heating, both three-stub tuner and short-circuit plunger were adjusted to minimize reflected microwave power. The heat caused by the reflected microwave power was absorbed by a water load that was cooled down by a refrigerated circulator. Incident and reflected microwave power was measured by a power meter. The temperature of the biomass sample was measured by a thermocouple and an infrared thermometer. After passing through a condenser, the vapor produced during the experiment was divided into condensable (tar) and non-condensable (gas) parts, and the flow rate of the gaseous product was measured by a digital flow meter.

2.3. Experimental details

In this study, individual and blended biomass samples were heated at microwave power levels of 100, 150, 200, 250, 300, and 350 W. The reaction cavity was purged with pure nitrogen gas at a flow rate of 25 mL/min to maintain its inert atmosphere. After sufficient purging, the power supply of the microwave heating system was turned on and switched to the prescribed microwave power level for 30 min. reflected microwave power was controlled to be as low as possible during the entire experimental period by adjusting the three-stub tuner and the short-circuit plunger. The actual working microwave power level was determined by subtracting the reflected microwave power level from the incident level. At microwave power levels of 100, 200, and 300 W, sewage sludge was heated to approximately 170, 280, and 350 °C, and leucaena was heated to approximately 230, 340, and 390 °C, respectively. When the prescribed processing time was reached, the power supply was turned off, the gas purging was stopped, and the tar and gas collectors were removed and sealed. After self-cooled down to the room temperature, solid residues (biochar) remained in the crucible were removed and then placed in a desiccator for hours. All of the experiments were performed in triplicate at least to obtain average values for the results.

2.4. Analytical methods

Proximate analyses of biomass samples and torrefied products were performed according to the standards D7582-12 and D3172-07a of the American Society for Testing and Materials (ASTM). Ultimate analyses were carried out by using a Perkin–Elmer 2400 II CHNS/O elemental analyzer. Higher heating values (HHV) were measured in a Parr 1341 adiabatic oxygen bomb calorimeter. Each sample (approximately 1 g) was dried at 105 °C in an oven for 24 h prior to heating value analysis. All of the samples were tested in triplicate at least to obtain average values for the results. Thermogravimetric analyses (TGA) were carried out by using a TA Instruments SDT Q600 thermogravimetric analyzer with a nitrogen flow rate of 100 ml/min, and each sample (approximately 10 mg) was heated to 900 °C at a rate of 10 °C/min.

3. Results and discussion

3.1. Characteristics of biomass feedstocks

The general characteristics of air-dried sewage sludge and leucaena samples are listed in Table 1. As can be seen, the moisture contents of the two biomass feedstocks were approximately 9.0 and 10.5 wt%, respectively. The volatile matter content of leucaena