Energy 87 (2015) 638–644

Contents lists available at ScienceDirect

Energy

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

Microwave co-pyrolysis of sewage sludge and rice straw

Yu-Fong Huang, Chun-Hao Shih, Pei-Te Chieuh*, Shang-Lien Lo

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

ARTICLE INFO

Article history:
Received 16 July 2014
Received in revised form
5 March 2015
Accepted 8 May 2015
Available online 6 June 2015

Keywords:
Microwave
Co-pyrolysis
Sewage sludge
Rice straw
Biochar

ABSTRACT

This study focused on the co-pyrolysis of sewage sludge and rice straw using microwave heating. The input microwave power level was a critical parameter. Sewage sludge was pyrolyzed without the addition of rice straw at the microwave power levels of 200–300 W, while lower or higher than this range led to only drying or over-heating. The addition of rice straw increased the performance of microwave heating, which allowed a higher maximum temperature. The calorific value of the pyrolyzed biomass increased with the addition of 30–40 wt.% rice straw. A maximum temperature of up to 500 °C was measured for blends containing 20 wt.% rice straw, which could be attributed to the synergetic effect of the addition of rice straw and microwave heating. This high temperature may provide another way of thinking for the thermal treatment of waste sewage sludge. A fixed carbon content of up to 33 wt.% was obtained for blends containing 30–40 wt.% rice straw. The atomic H/C and O/C ratios were very close to those of anthracite coal. Therefore, the pyrolyzed blends should have a high potential to be co-fired with coal or even to replace it.

1. Introduction

The enormous worldwide demand for fossil fuels will soon deplete world energy reserves and cause more severe global climate change than can be imagined. Therefore, it is extremely important to immediately develop reliable and renewable energy to replace fossil fuels. Biomass is an abundant carbon-neutral renewable resource that is used for the production of biofuels and biomaterials [1]. Sewage sludge can be regarded as a biomass resource because of its considerable organic content, and thus energy and resource recovery from sewage sludge is promising [2–4]. Waste sewage sludge could be converted into a valuable biofuel with appropriate processes, which can solve the problem of sewage sludge disposal as well.

Raw biomass has several disadvantages, such as low efficiency, high cost, and high rate of decomposition due to its moisture content, the presence of microorganisms, and the inconvenience of storage in practical applications [5]. Therefore, as-received biomass generally needs to be pretreated before it is stored, transported, and utilized. One pretreatment method of biomass is torrefaction, which is a mild pyrolysis performed at a relatively low heating temperature (200–300 °C) and heating rate (<50 °C/min) [6]. Pyrolysis is a thermal degradation process for organic compounds in the absence of oxygen or air to produce various gaseous components as well as tar and char residues [7]. Significantly more solid residues (named biochar or torrefied biomass) are produced from biomass torrefaction than traditional pyrolysis. The biochar produced by torrefaction has a higher energy density and improved grinding characteristics, hydrophobicity, and homogeneous properties [8]. Additionally, significantly less energy is required to process torrefied biomass, and separate handling facilities are no longer necessary when it is co-fired with coal in existing power stations [9].

It is difficult to recover and utilize energy from several types of biomass (e.g., sewage sludge) because of their compositions and characteristics. However, these problems may be solved by blending several biomass feedstocks for co-pyrolysis. Blends of sewage sludge and another biomass feedstock could provide various advantages, such as enhanced reaction performance and increased calorific values of biochar with less inorganic and toxic content [2]. Several synergistic or coupling effects could occur during the co-pyrolysis of sewage sludge with rice straw to accelerate the release of volatile matter and shorten the processing time [10]. Rice straw is a valuable biomass feedstock because of its abundance [11] and high volatile content [12], and the addition of rice straw to sewage sludge could be workable to improve co-pyrolysis performance due to the synergistic or coupling effects as mentioned above.

* Corresponding author. Tel.: +886 2 3366 2798; fax: +886 2 2392 8830.
E-mail address: ptchueh@ntu.edu.tw (P.-T. Chiueh).

http://dx.doi.org/10.1016/j.energy.2015.05.039
0360-5442/

Compared with conventional heating, microwave heating is environmentally friendly and well-established and reduces energy consumption and reaction time [13]. Besides, microwave heating does not directly contact the heated materials [14]. Microwave heating has been widely used in many applications, including synthesis [15], digestion [16], extraction [17], sample pretreatment [18], and stabilization [19–21]. For large-sized biomass materials (e.g., wood and cornstalk), thermochemical reactions can occur rapidly due to the nature of fast, volumetric, and selective heating using microwave energy [22]. Materials that can absorb microwaves are called dielectrics, so microwave heating is also referred to as dielectric heating [14]. Potential applications of microwave heating are dependent on the dielectric properties of target materials [23].

Pyrolysis induced by microwave heating is one of the promising attempts because of the efficient heating of feedstocks that has been demonstrated using microwave dielectric heating [24]. Therefore, microwave heating has been utilized in various biomass pyrolysis [23,25–35] and torrefaction [36,37] systems. However, there has been no research on the co-torrefaction of biomass blends induced by microwave heating. In a previous work, it was reported that only 150 W microwave power and 10 min processing time were required to produce torrefied lignocellulosic biomass with a 70% mass yield and 80% energy yield, and the energy density of the torrefied biomass was higher than that of raw biomass by 14% [12]. Therefore, microwave torrefaction should be a feasible method to recover energy from biomass waste.

In this study, the co-pyrolysis of sewage sludge and rice straw using a single-mode microwave device was investigated to evaluate the performance of microwave heating and energy recovery. The compositions and characteristics of sewage sludge, rice straw, and their blends were also studied.

2. Materials and methods

2.1. Materials

The dry sewage sludge cake used in this study was obtained from the Dihua sewage treatment plant in Taipei, Taiwan. The moisture content of the as-received sewage sludge was approximately 85 wt.%. The sewage sludge was air dried for several months and then dried in an oven for three days. The rice straw was gathered on-site in Chiayi, Taiwan. After drying, the sewage sludge was grinded in a mortar. The rice straw was smashed and sieved using a 50-mesh screen. The characteristics of the raw sewage sludge and rice straw samples are listed in Table 1. Both of the biomass feedstocks contained a high content of volatiles. The volatile content of the rice straw was higher than that of the sewage sludge by approximately 20 wt.%, whereas the ash content in the rice straw was lower than that of the sewage sludge by approximately the same magnitude. Consequently, it is not surprising that the calorific value of rice straw was significantly higher than that of the sewage sludge. In this study, the calorific value of the sewage sludge was compared with values presented in the literature. The obtained value was similar to 16.45 MJ/kg [38] and significantly higher than 9.69 MJ/kg [5]. Both of the biomass feedstocks were predominately composed of carbon. The content of oxygen and nitrogen in the sewage sludge was higher than that of the rice straw by 8.64 and 7.28 wt.%, respectively. Sulfur was not detected in either the two biomass feedstocks.

Table 1
Characteristics of the raw sewage sludge and rice straw samples.

Biomass	Sewage sludge	Rice straw
Moisture (wt.%)	11.79 ± 3.82	10.14 ± 0.34
Proximate analysis (wt.%)[a]		
Volatiles	62.11 ± 1.86	79.71 ± 2.86
Fixed carbon	10.00 ± 0.80	12.32 ± 2.55
Ash	27.89 ± 1.69	7.97 ± 0.63
Ultimate analysis (wt.%)[b]		
C	45.16 ± 0.37	43.64 ± 0.48
H	7.20 ± 0.37	5.32 ± 0.11
N	7.69 ± 0.22	0.41 ± 0.04
O	27.50 ± 0.41	18.86 ± 1.01
S	N.D.	N.D.
Calorific value (MJ/kg)[a]	16.18 ± 0.13	18.40 ± 0.46

[a] Dry basis.
[b] Dry and ash-free basis.

2.2. Experimental procedure

This study used a single-mode (focused) microwave device with a 2.45 GHz frequency. The schematic diagram of the overall microwave pyrolysis set-up can be found elsewhere [36]. The shredded and sieved biomass feedstock was added to a quartz crucible and then placed inside a quartz tube that was located in the pathway of the microwaves. An infrared thermometer was placed at the top of the quartz tube to measure the temperature of the biomass sample. To maintain anoxic conditions, nitrogen gas was purged into the system at a flow rate of 25 mL/min. After sufficient purging was performed to maintain an inert atmosphere, the power supply was turned on and switched to the prescribed microwave power level for 20 min. The reflection microwave power levels were controlled to be as low as possible during the entire experimental period. When the prescribed processing time was reached, the power supply was turned off, the carrier gas purging was stopped, and the tar and gas collectors were removed and sealed. After self-cooling to approximately 100 °C, the solid residues were removed and placed in a desiccator for several hours. All of the experiments were performed at least twice to obtain average values for the results. Because the maximum temperature would exceed 300 °C at higher microwave power levels or under certain conditions, the terms of co-pyrolysis and pyrolyzed biomass were used in the following text. Ultimate, proximate, and thermogravimetric analyses (TGA) were performed, and the weight loss and calorific values of the pyrolyzed biomass were calculated to evaluate reaction performance and determine the optimum operating conditions for the microwave co-pyrolysis of sewage sludge and rice straw.

2.3. Product analysis

Proximate analyses of the raw and pyrolyzed sewage sludge, rice straw, and blends were performed according to the standard test method D7582-12 of the American Society for Testing and Materials (ASTM). The ultimate analyses were performed with a Perkin–Elmer 2400 Elemental Analyzer. The calorific values were determined using a CAL2K ECO calorimeter. All of the samples were tested at least twice to obtain representative analytical results. The surfaces of the biochar were observed by using a JEOL JSM-7600F field emission scanning electron microscope (SEM) with an INCA X-Max Energy Dispersive Spectrometer (EDS). The SEM was operated at an acceleration voltage of 15.0 kV. The SEM images are shown in Fig. 1. The measurements of specific surface areas and micropore and mesopore size distributions were carried out by using a Micromeritics ASAP 2020 Analyzer with pure N2 at 77 K. Before the measurements, the samples were degassed in a vacuum at 373 K. The specific surface areas were calculated by the Brunauer–Emmett–Teller (BET) model, and the pore size distributions were determined by the Barrett–Joyner–Halenda (BJH) model. The microporous properties were calculated by the t-plot method. The