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Hydrothermal carbonisation of sewage sludge for char production with different waste biomass: Effects of reaction temperature and energy recycling

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A B S T R A C T

Hydrothermal carbonisation (HTC) of sewage sludge (SS) with waste biomass was investigated as a clean and energy-efficient treatment to produce char. The effects of the reaction temperature on the properties, composition, and energy consumption of the obtained char were investigated to evaluate the feasibility of the production process. The results indicate that the dewaterability of char derived from SS with biomass was enhanced by approximately 50% at temperatures exceeding 260 °C. The lowest moisture content of the char was 41.39%, produced from SS with cornstalk at 300 °C and holding time of 60 min. The values of H/C and O/C in char from SS with sawdust, corncob and rape straw at 300 °C dropped to approximately 0.92 and 0.04, respectively, which are close to the values of bituminous coal. SS mixed with corncob was more efficient than other biomass waste during the HTC process. The suggested optimum condition to produce char is 300 °C for 60 min, in which the HHV and energy recovery rate can reach 21.31 MJ/kg and 71.60%, respectively. As regards other types of biomass, a moderate reaction temperature above 260 °C is suggested to produce chars with an energy recovery rate ranging from 47.06% to 71.60%.

1. Introduction

Currently, sewage sludge (SS) as a by-product of municipal waste water treatment, is being generated in significant quantities worldwide. In China, sewage treatment plants produce more than 20 million ton of wet SS annually [1] and this volume is expected to increase in the next few years. In view of the high-moisture and toxic-pollutant contents of SS, traditional treatments and disposal methods, such as landfill, composting, road surfacing, and incineration are problematic [2,3]. Consequently, disposing municipal SS has become a matter of concern in many countries. One approach to ameliorating the situation is to convert SS into char with favourable environmental properties. Hydrothermal carbonisation (HTC) originated in the 1910s to simulate natural coalification and this technology could be adapted for wider use in various fields, such as synthetic composites, char yield, liquefaction, and gasification [4–7]. Whereas liquefaction and gasification require high temperatures, organic waste can be efficiently converted into energy in relatively moderate temperatures (180–350 °C) and autogenous pressures (2–10 MPa) [8–10]. Considering the economic feasibility of this technology, the HTC process is appropriate for waste biomass with high moisture and organic content, such as sewage sludge, algae, municipal solid waste, and various types of biomass [11–13]. During the HTC process, char derived from sewage sludge and other biomass undergoes various physical, chemical, and molecular changes. Some changes, including the yield, volatile contents, heavy metals, pH, microstructure, adsorption, energy density, and element composition are related to variations in the reaction conditions [14–18]. Van Wesenbeeck et al. [11] reported on the hydrothermal carbonisation of SS. They found that char derived

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from SS by the HTC process showed distinct advantages as soil ameliorants because of the retention of most heavy metals, as well as the sequestration of carbon. Similar research was conducted by Berge et al. [13]. This study indicated that the main carbon (49–75%) initially present in municipal waste streams was retained in the solid product, whereas the other carbon was transferred to liquid- (20–37%) and gas-phases (2–11%). Anastasakis and Ross [12] used four types of macro-algae to produce biocrude and solid products. Their energetic analysis indicated that the hydrothermal treatment produced solid char with higher energy output compared with that produced by the traditional treatment. Reza et al. [19] applied anaerobic digestion and the HTC process to produce powder-like chars as solid fuel from wheat straw. The study indicated that the overall bioenergy production increased with the combined process, whereas compared with the HTC process, the high heating value of straw was similar. Danso-Boateng et al. [14] investigated the energetic process of human faecal sludge during HTC. They found that the efficiency of recycled energy was influenced by the variation of the feedstock containing 15–25% solids. Excess energy of 19–21% was obtained with feedstock containing 25% solids. On the other hand, the process of char drying is important because of excessive energy consumption. Recent studies have mentioned that the HTC process could enhance the drying performance of sludge. Zhao et al. [20] compared six conventional semi-theoretical drying models to represent the experimental results and found that the "approximation of diffusion" model was the best model to predict sludge drying. In addition, sludge in subcritical conditions, with NaOH and HCl as additives, has been investigated by Mäkelä et al. [21]. The reaction temperature has a significant effect on the mean moisture diffusivity of hydrochar, However, NaOH and HCl have no significant effect. Previous research has indicated that biomass and SS converted to energy products with the HTC process offer a good prospect.

One of the characteristics of the HTC process is the application to treating biomass in an aqueous medium [22–24]. In general, SS contains excess water, whereas some types of biomasses could lack water. However, this factor can be neutralised by combining SS and biomass to achieve an optimum condition. Most previous investigations concentrated on the HTC of biomass or SS for soil amendment, the characterisation of char, and the combustion behaviour of biofuel. Energy recycling and economic feasibility of char derived from SS by the HTC process are still not understood properly [12,25]. Moreover, no research has been done on SS blended with biomass in the HTC process. Obviously, the practicability of combining carbonised sludge with biomass is an important factor. Therefore, it is crucial to understand the operating conditions, dewatering properties, thermal performance, and char recovery ratio of the HTC process. Consequently, the focus of the current research is on mass and energy balance of char derived from SS combined with biomass in the HTC process. The effects of the HTC temperature on the yield, dewatering performance, and calorific value of the char, and the energy recovery rate were taken into account to evaluate the waste-to-energy conversion.

2. Materials and methods

2.1. Materials preparation

Dewatered SS, sawdust (SD), corncob (CC), cornstalk (CS), and rape straw (RS) were used in this investigation. Dewatered SS, with a moisture content of 89.32% was collected from a municipal wastewater treatment plant in Changsha, China. The SS sample was dried to constant weight at 105 °C for 24 h, after which it was milled to a size smaller than 0.25 mm and stored in the desiccators. The other samples (SD, CC, CS, and RS) were dried at 40 °C for 24 h and subsequently grounded into solid particles smaller than 1 mm before starting the HTC process.

2.2. Hydrothermal carbonisation process

In the laboratory, the SS and biomass were treated in a 500 ml 316 stainless steel reactor, with an electric heater and auto-stirrer, as described in our previous study [26]. For each run, dried SS and one of the types of waste biomass were mixed with deionized water at a ratio of 1:1:18 and subsequently loaded into the reactor to simulate wet SS after mechanical dewatering. Prior to heating the reactor, it was sealed air tight and filled with nitrogen gas. The homogeneous compound was subjected to three temperature variations, namely, 220 °C, 260 °C, and 300 °C. The reaction time was 60 min, with a heating rate of approximately 4 $°C \cdot min^{-1}$. After treatment, the reactor was allowed to cool down at room temperature. The gas product was collected with an aluminum-foil sample bag. The residual steam was removed thoroughly and separated by filtration. Subsequently, the char was oven-dried at 105 °C for 24 h and pressed to a round cake, with a diameter of 10 mm. In this study, we distinguish the "cakes" by referring to the raw-material-biomass-temperature, e.g. SS-SD-220, which indicates char derived from SS with SD at 220 °C.

2.3. Analytical methods

The char yield and the corresponding approximate equilibrium moisture content were used to characterise the efficiency and the water removability of the HTC production process, respectively. The char yield was calculated by using the ratio of the char weight/dry SS weight determined by Eq. (1), with Eq. (2) showing the approximate equilibrium moisture content of char in the laboratory, as follows:

$$\text{Char yield } (\%) = \frac{M_1}{M_2} \times 100\% \tag{1}$$

$$MC_e = \frac{W_1 - W_2}{W_1} \tag{2}$$

where M_1 is the char weight, M_2 is the dry SS weight. MC_e represents the approximate equilibrium moisture content, and W_1, and W_2 are the char mass (with moisture) and the char dry mass, respectively. The ash contents were calculated by the weight method with muffle furnace. The elemental analyses of the raw materials and chars were conducted by a 2400Series II CHNS Analyzer, (PerkinElmer, USA). The filtrates of the HTC process were collected in a bottle and stored at 4 °C. The total carbon (TC) in the liquid phase was analyzed by a SHIMADZU TOC-VCPH analyzer (SHIMADZU Co., Japan). In the HTC process, heat is consumed by the surface of the batch-type reactor, raw materials, and water. The heat loss of the HTC reactor can be calculated according to the method explained in a previous study [27]. Assuming the room temperature remained at 25 °C and the weight loss was ignored, the energy input equation can be expressed as:

$$\begin{aligned} X_{in} \cdot (H_{g,HT} - H_{l,2\,98}) &= m_w \cdot (H_{l,HT} - H_{l,298}) \\ &+ (m_s \cdot C_p + m_i \cdot C_i + C_{bulk} + 3600 \times h_{bulk} \cdot A \cdot \tau) \cdot (T_H - 298) \end{aligned} \tag{3}$$

$$E_{HT,in} = X_{in} \cdot (H_{g,HT} - H_{l,298}) \tag{4}$$

where m_w, m_s and m_i indicate mass of the water, SS, and the four types of biomass, respectively; H is the enthalpy of the water; C_p,