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Hydrothermal carbonization of anaerobically digested sludge for solid fuel production and energy recovery

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HIGHLIGHTS

- The hydrothermal conversion of sewage sludge to solid fuel was achieved.
- Dewaterability and fuel properties of sewage sludge were improved greatly by hydrothermal reactions.
- Formation of the hydrochar from sludge were characterized to be near coal.
- The optimum temperature of hydrothermal carbonization was approximately 220 °C to make alternative energy resource.

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ABSTRACT

The hydrothermal carbonization was investigated to convert anaerobically digested sludge to clean solid fuels. The effects of hydrothermal carbonization were evaluated by varying the reaction temperatures in the range of 180–250 °C. Hydrothermal carbonization increased the heating value though the reduction of the hydrogen and oxygen content of solid fuel in addition to investigating drying performance, and it can do energy saving on treatment processes. Therefore, after the hydrothermal carbonization, the H/C and O/C ratios decreased because of the chemical conversion. These results suggest that the hydrothermal carbonization process is advantageous technology in improving the properties of sewage sludge as an alternative solid fuel product as clean energy by converting the physical and chemical structure of the sludge in addition to also providing other benefits to treat organic and biomass waste.

1. Introduction

A world-wide increase of wastewater treatment plants (WWTPs) has resulted in elevated amounts of wastewater sludge during the past several decades. In Korea, wastewater is currently treated in 347 WWTPs, which generates approximately 10,000 tons of sewage sludge in a day [1]. Sewage sludge produces one of the largest waste material flows for a given municipalities and contains a large amount of biodegradable organic matter, which can be used as a potential energy source [2–4]. Therefore, anaerobic digestion has commonly been employed in the production of biogas; however, the main purpose of the anaerobic digestion has typically been the stabilization for disposal. However, the use of landfills to dispose of sewage sludge, including digested sludge, is prohibited in Korea; thus a cost effective alternative process for the treatment of digested sludge is required.

The thermal treatment process is the most commonly used technology for converting organic matter from digested sludge into an energy resource. Thermal conversion technologies can be classified as carbonization (400–500 °C), pyrolysis (500–600 °C), gasification (600–1000 °C) and combustion (800–1000 °C), and aim to produce carbon-neutral energy from various forms of organic and biomass wastes [5–7]. However, these treatment technologies cannot directly treat sewage sludge as a result of its high moisture content. Consequently, the thermal treatment of sewage sludge requires the removal of water from the sludge, which is often expensive. Therefore, hydrothermal carbonization technology has been developed to circumvent the energy-intensive drying process in the thermal conversion process of high moisture organic feedstock. Previous research on hydrothermal treatment processing concentrated on hydrothermal liquefaction for oil production at 250–380 °C and catalytic hydrothermal gasification for H_2 at 380 °C and 23 MPa. However, these processes exhibit a high energy cost and low energy recovery efficiency as a result of the high temperatures and pressures that are employed. Recently, hydrothermal carbonization (HTC) at moderate temperatures (180–350 °C)

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and pressures (2–10 MPa) has received a great deal of attention as a promising technology for the efficient conversion of wet biomass to useful biocarbons [2–3,8–11].

HTC has been previously employed to convert organic feedstock containing high moisture contents into carbonaceous products (biological char or hydrochar). After hydrothermal conversion, various fuel properties such as the heating value and the amount of aromatic structure in the products were evaluated [8,12]. Therefore, biological char produced from HTC can be incinerated or further utilized in industrial in the form of brown coal. Several forms of biodegradable waste such as cellulose, microalgae, anaerobically digested sludge, municipal solid waste, distiller's grains, and black liquor have been treated using HTC to obtain useful fuels and materials. The application of HTC to municipal wastewater sludge has also been investigated, since HTC is generally suitable for the treatment of any moist or muddy biomass [13–19].

The treatment and disposal of digested sludge using an anaerobic sludge digester can be a costly procedure. However, anaerobically digested sludge can be a suitable feedstock for HTC biological char, because it still contains a high amount of carbon, which corresponds to a high amount of energy. Berge et al. [8] reported that the carbonization of anaerobic digested sludge improved heating values and was directly correlated to carbon content. This technology can be applied to produce a homogeneous solid fuel such as coal, which can be easily dewatered into a powdery fuel with a moisture content of 10% [20–21]. Furthermore, another advantage of HTC is that the moisture content of the sludge can be separated much more efficiently. Therefore, the moisture content of the sludge can be reduced to approximately 20% due to breakdown physical structure [20,22]. However, HTC of anaerobically digested sludge has not been as extensively researched and reported as has lignocellulosic, wastewater sludge and other types of waste biomass.

The main purpose of this research was to develop HTC process that can convert anaerobically digested sludge to an alternative fuel while reducing CO_2 emissions. The specific goals of this study were to: (1) investigate the effects of temperature on the filtration and dewatering performances, (2) improve the fuel properties of the hydrothermal product obtained from the anaerobically digested sludge, and (3) determine the optimal reaction temperature of the HTC process.

2. Materials and methods

2.1. Materials

In this study, sewage sludge feed stock were collected from the Il-San municipal WWTP in the Republic of Korea. The sludge was obtained after the anaerobic digestion process for domestic wastewater. The sludge samples were transferred to the laboratory, stored in a plastic box, and at 4 °C prior to experiment. The samples were also shaken well in order to obtain a homogenous mixture.

2.2. Hydrothermal carbonization experiments

Hydrothermal reactor was used to investigate the effects of HTC on the fuel properties and dewatering performance of the sewage sludge. Experiments were performed using a 1000 ml autoclave reactor consisting of a reactor body, a heater, and a steam condenser which was operated under N_2 gas. A 300 ml of sewage sludge feedstock was mixed with an equal amount of water and loaded into the reactor. The operating temperatures and pressures ranged from180 °C to 280 °C and the reaction time was 30 min in the presence of subcritical water. The components within the reactor were vigorously mixed using an agitator rotating at 200 rpm.

2.3. Analytical procedures

2.3.1. Dewaterability test

The dewaterabillity of the sludge was evaluated by measuring the capillary suction time (CST) and the dry matter content (DM_C). The CST was determined using an improvised CST apparatus (model 319 Multi-purpose CST, Triton Electronics Ltd.) with single-radius test and CST paper (size: 7 × 9 cm, quantity: 200 approx., Triton Electronics Ltd.). The DM_C was determined by measuring the sludge samples after centrifuge separation, which was conducted for 10 min at 4000 rpm (Centrifuge MF-80, Hanil Science Industrial Co.).

2.3.2. Properties analysis

The samples prepared powder form that were sieved and the fraction between 177 and 250 μm particle size (80–60 mesh) was used for fuel property analysis. The sewage sludge and its solid products were evaluated using a PerkinElmer 2400 Series II CHN organic elemental analyzer (PerkinElmer, Waltham, MA, USA) to determine the weight percentage of chemical elements. Proximate analysis used to determine the weight percentage of volatile matter, fixed carbon, and ash was conducted using a SHIMADZU D-50 simultaneous TGA/DTA analyzer. In nitrogen, volatile matter is lost at temperatures up to 900 °C, and fixed carbon is burnt in oxygen leaving the ash as a residue following the ASTM procedure. Moisture content determinate were measured by drying samples to constant weight at 105 ± 5 °C in a vacuum oven. Heating values were determined using IKA Calorimeter System C 5000 according to calorimetric standard method of EPA-Method 5050. Results are the average of three experiments performed in triplicate. The samples were subsequently analyzed by the Fourier transform infrared (FTIR) spectroscopy (Nicolet iS 10, SCINCO CO.) in the range of 4000–400 cm^{-1} with each spectrum being generated from the spectral average of least five scans. The FTIR spectra of samples were run on pellet form, using KBr (120 mg, 1 wt%) as reference material. In order to determine the optimum temperature for the hydrothermal treatment process, the energy densification and energy recovery efficiency (ERE) and in the hydrothermal reaction were calculated using Eqs. (1) and (2).

$$\text{Energy densification} = \frac{\text{HHV of product}}{\text{HHV of feedstock}} \tag{1}$$

$$\text{ERE} = \frac{\text{HHV of product} \times \text{mass of dried solid product}}{\text{HHV of feedstock} \times \text{mass of dried feedstock}} \tag{2}$$

3. Results and discussion

3.1. Improvement of the dewaterability

Sewage sludge can be thought of as many particles into flock as a single large particle. The sludge retains a high amount of moisture, which is the primary challenge in isolation the sludge as a solid matrix. This water can be classified as four separate forms of waste with respect to its position within sludge [23]. Free water surrounding the sludge flocks can be easily removed. Interstitial water is held by capillary forces between the sludge particles; when the flocks are broken up, the interstitial water becomes free water and can be easily separated. Surface water is defined as being held by surface forces cannot be easily removed by normal mechanical methods. Finally, some water is chemically bound to the particles and is typically stored within the particles [21,24–25]. This water is defined as bound water and is very difficult to remove. In order to improve the dewaterability of the sludge, the bound water needs to be converted to free water. Kim et al. [20]