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Dewatering and granulation of sewage sludge by biophysical drying and thermo-degradation performance of prepared sludge particles during succedent fast pyrolysis

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ABSTRACT

A novel two-step technology, fast biophysical drying (BPD) coupling with fast pyrolysis (FP), was investigated for moisture removal and energy recovery from sewage sludge. For BPD, combined operations of extreme thermophilic amendment (with accelerated increasing and controllable maintenance of substrate temperature) and enhanced convective evaporation were conducted, both beneficial for moisture removal (moisture content reaching 23.1% for 7 d) and organic preservation. Biophysical-dried sludge (BPDS) was characterized by homogeneous fine-particle morphology and well-developed porous microstructure. The synthesized BPDS particle preserved most organic components (92% volatile matters and 79% HHV of traditional thermal-dried sludge [TTDS]) attributable to the inhibitory effect of BPD adjustment, presenting considerable capacity for subsequent residue-derived energy. For FP, the distribution of products from BPDS pyrolysis indicated that syngas and char yields were higher than those of TTDS. The syngas from BPDS is a type of hydrogen-rich gas composed of 42.6 vol.% H_2 at 900 °C.

1. Introduction

Sewage sludge was identified as "a future waste problem" to resolve. Sewage sludge can also be used as a biomass resource for energy recycling because of the abundant organic compounds in the dried component. The high water content and the low concentration of organic materials in original sewage sludge prohibit the possible utilization of this waste (Fullana et al., 2004), reducing the efficiency of energy recovery. Low energy consumption is expected for the key points of dehydration, disposal, and comprehensive utilization, and high-quality energy recycling was significantly more promising for technological application.

Traditional thermal drying (TTD) treatment is characterized by high energy consumption (Vaxelaire et al., 2000). A hard and relatively impermeable skin layer, formed on the exterior surface of sludge cake because of the reverse direction of heat transfer and moisture migration in TTD processes, would retard further moisture removal (Chen et al., 2004). Moreover, relatively low heating values and the stickiness of sewage sludge result in the technically and economically challenging application of TTD (Navaee-Ardeh et al., 2010).

In contrast, biodrying utilizes biological heat from aerobic reactions, and is one of the best alternatives for reducing the moisture content (MC) of wet organic wastes. The same direction of heat transfer and moisture migration, powered by internal aerobic microorganisms, is characterized by high-energy efficiency, resulting in significant moisture removal. This technique has the potential to raise the dry solid content of sewage sludge to dry solid levels, allowing for subsequent utilization, such as pyrolysis with energy production.

High substrate temperature has a positive correlation with the rate of moisture removal (Navaee-Ardeh et al., 2010). However, biological heat is obtained at the cost of organic substance to some extent. Therefore, aside from the water removal rate, constraining organic consumption should be considered to preserve energy for residue-derived fuels.

Temperature has been approved as an indicator of the accumulation of heat generated metabolically and simultaneously, a determinant of metabolic activity in composting reaction (Tang et al., 2007). In this regard, the maximum biodegradation rates were observed in

Abbreviations: BPD, biophysical drying; BPDS, biophysical-dried sludge; ECE, enhanced convective evaporation; ET, extreme thermophilic; ETE, extreme thermophilic evaporation; FP, fast pyrolysis; HHV, higher heating value; IPB, inoculated pine bark; MC, moisture content; MSS, municipal sewage sludge; PAM, polyacrylamide; TTD, traditional thermal drying; TTDS, traditional thermal-dried sludge.

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the ranges of 45–55 and 52–60 °C, as presented in the investigations of Stentiford (1996) and Macgregor et al. (1981), respectively. When the temperature exceeds 60 °C, the microbiological activity based on the composting decomposition rate of organic matter decreased remarkably (Hassen et al., 2001; Liang et al., 2003).

Consequently, maintenance of higher biodrying temperature is considered an effective operating approach to achieve high moisture removal efficiency coupled with low organic degradation. Furthermore, flocculant polymers in sludge, such as polyacrylamide (PAM), to which the stickiness and hard structure of TTDS is attributable, are broken down with aerobic cultures, especially by extreme thermophiles, which can endure temperatures exceeding 55 °C (Chang et al., 2001; Sheng et al., 2010; Wen et al., 2010). In the present study, fast BPD was conducted and featured by physical amendment, such as temperature feedback adjustment and enhanced convective aeration, which acted in concert with biodrying reaction. The regular-sized inoculated pine bark (IPB) processed by a previous extreme thermophilic (ET) trial was employed in the BPD process for the enhancement of aeration capability and the activity of facultative bacteria.

BPD can be performed as a pretreatment to facilitate the potential coupling of the prior biodrying step with the energy recycling step. Fast pyrolysis (FP) is a promising technology that can produce fuel products, such as syngas and bio-oil, from high solid biomass, including dried sewage sludge, as proposed in recent years (Park et al., 2010; Rulkens, 2008). The pyrolysis conversion to syngases plays an important role for subsequent utilization as fuel or basic chemicals.

A number of parameters of the pretreated sludge should be considered and are primarily responsible for the subsequent pyrolysis. The size effect exerted by the biomass particle on pyrolysis production has proven that increasing particle size promotes stronger heat transfer resistance, increases temperature gradients inside the particle, and thus decreases dry gas yields (Hernández et al., 2010; Luo et al., 2009). Nitrogenated aromatic compounds have been identified as characteristic compounds in sewage sludge pyrolysis because of their nitrogenous constitution (Fullana et al., 2003), which has a correlation with pyrolysis performance ascribing to the energy efficiency (Kalinci et al., 2010). Consequently, pretreatment processes, such as drying, fragmentation, granulation, and denitrification before pyrolysis, were necessary and can be achieved by the appropriate control of BPD. To the best of our knowledge, the combined technique with modified BPD and FP conducted on original sludge has been given little attention.

In the present study, a novel two-step technology, including BPD and FP, was investigated in a biophysical and a horizontal fixed-bed reactor. Batch BPD pretreatments were performed to evaluate the function of short-term ET spontaneous heating evaporation coupled with enhanced convective evaporation (ECE). The evolution of MC, microstructure, organic matter, and elemental composition were also monitored. Subsequently, a systemic investigation was employed to reveal the role of the properties of the obtained BPDS particle in FP. Thermal decomposition characteristics and hydrogen-rich gas capacity in different temperatures were given a great deal of attention, and the properties of other products were also discussed. The present study provided a novel strategy to achieve efficient volume reduction and energy recycling from sewage sludge with minimal energy consumption.

2. Methods

2.1. BPD

The laboratory biophysical reactor used in this experiment is shown in Fig. 1(A), which primarily consisted of a 159 L adiabatic cylindrical vessel (height 1000 mm, internal diameter 450 mm) made of stainless steel and insulated with 100 mm-thick polyurethane. At the bottom of the cylinder, a perforated plate was utilized for leachate drainage and aeration. A condenser was installed in the exhaust system to collect a fraction of the evaporated liquor before it reached the deodorizer and air pump.

The feedstock of the BPD apparatus was a mixture of municipal sewage sludge (MSS) and the IPB. The MSS (MC = 82.1%) was sampled from the Xiaojiahe Municipal Sewage Treatment Plant in Beijing, China. The IPB (MC = 18.3%, granularity of 10–20 mm) was collected from the products after the ET stage (>65 °C) of the former BPD process, which was separated from the dried sludge by mechanical sieving (Fig. 1(B)). IPB was used as the biophysical amendment and was beneficial for fast BPD because of the ET bacterium inoculation, adjustment of the MC of the substrate, and enhancement of aeration capability and nutrient availability.

The operating parameters are listed in detail: mixture mass proportion (MSS/IPB) is 2:1, filling density is 667 kg m^{-3}, filling height is 0.85 m, and the initial MC of MSS in the mixture is 70.5%. The entire BPD process lasted for 7 d and was primarily composed of two stages, namely, the extreme thermophilic evaporation (ETE) stage (including the start-up phase) and the ECE stage. During the ETE stage (0–4 d), the aeration rate from the bottom, approximately 0.5–1.2 m^3 h^{-1}, was controlled by manual feedback to maintain a high temperature of approximately 65 °C. In this stage, air pumping from the top was used and was beneficial for moisture removal. During the ECE stage (5–7 d), the aeration rate sharply increased to 3 m^3 h^{-1}, which contributed to moisture removal acceleration and organic preservation. Finally, the air-dried sludge (BPDS) was sieved apart from the pine bark for the subsequent pyrolysis process, whereas the screened IPB was reproduced for the next BPD inoculation and recirculation. For comparison, TTD was also performed in an electric oven by heating at 105 °C for 24 h, and the processed sludge sample was labeled as TTDS.

2.2. Monitoring and physical chemistry analysis

Three temperature sensors (PT100, STT-R1) were placed in the center of the substrate at various depths for temperature monitoring and manual feedback control. Sludge samples were collected twice a day during the BPD process. MC, volatile matters, and ash of MSS separated from IPB were determined on a daily basis. The particle strength of dried sludge was measured by a granule intensity apparatus (YHKC-2A, Yinhe Co., Jiangsu, China).

The calorific values of the BPDS and TTDS samples were measured using an oxygen bomb calorimeter (AC-350, China), and the mean value of three measurements was accepted as the result. Elemental analysis (C, H, O, S, and N) was performed using the EAI element analyzer (CE-440, US). Screening analysis with various screening apertures was performed for both BPDS and TTDS. CO_2 concentrations were measured twice each hour by an online CO_2 infrared gas analyzer (GASBOARD-3000, Wuhan cubic optoelectronics Co., China).

2.3. FP

FP experiments were conducted in a horizontal fixed-bed reactor (internal diameter 50 mm, length 1200 mm). Fig. 1(C) shows the schematic diagram of the pyrolysis apparatus.

Typically, 3.0 g BPDS in a porcelain boat was placed on the nonheating end of the quartz tubular. An inert atmosphere was achieved by carrier gas (N_2) sweeping (0.3 L min^{-1}, 30 min) and the experimental temperature was 500–900 °C. Then, the porcelain boat was fed into the heating zone, and the N_2 flow rate was adjusted to 0.03 L min^{-1}. Bio-oil was captured by a tar collector, whereas syngas was bubbled into water for purification and then collected by a gas-collecting bag. The experiment stopped after