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Energy-efficient co-biodrying of dewatered sludge and food waste: Synergistic enhancement and variables investigation

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ABSTRACT

In this study, dewatered sludge (DS) and food waste (FW) were co-biodried by balancing substrate's property and microbial aspect. A series of experiments were conducted to explore the effects of mixing ratio, particle size of bulking agent, air-flow rate and initial moisture content (MC). A synergistic enhancement of co-biodrying of FW and DS was observed in terms of a stable temperature profile and long high-temperature duration. The biodrying index (water removal/VS consumption) indicated that the co-biodrying had a high efficiency for water removal with less organics consumption, especially for DS/FW = 2/2. The small size (<3 mm) of bulking agent and initial MC of 62.68% was preferable for the biodrying process by providing adequate free air space and extra carbon source. A moderate air-flow rate of 0.04 $m^3\,h^{-1}\,kg^{-1}$ showed the best water carrying capacity. This finding suggests that the co-biodrying strategy could be a promising approach to treating different organic wastes with synergistic enhancement.

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1. Introduction

Nowadays, the huge amounts of biowastes are becoming a worldwide environmental problem, of which dewatered sludge (DS) and food waste (FW) are two concerned waste streams. Dewatered sludge is generated from wastewater treatment which is essential in maintaining clean aquatic environments. In China, the amount of dewatered sludge (moisture content, 80%) was more than 30 million tons per year (Feng et al., 2015). Food waste was also abundant and problematic, causing odor and leachate release during its collection and transportation. According to Chinese government statistics, the municipal solid waste (MSW) delivering quantity reached 173 million tons in 2013 (MEP), of which food waste accounted for 50–70% (Li et al., 2009). Due to the strict regulations and high cost of landfill or incineration, the management of these biowastes has shifted from disposal to beneficial utilization (Liang et al., 2003).

Biological treatment is usually regarded as a suitable way for biowastes treatment (Banegas et al., 2007). As for composting, however, the long residence time (30–50 days) (Velis et al., 2009), high process costs (e.g., $200/dry ton) (Liang et al., 2003) and low product value prevent the wider application of this treatment. Anaerobic digestion is another popular method for organic waste treatment, which could reduce the volume and recover the biogas. However, the high investment and further treatment for digestate limited the widely application. Recently, incineration has received worldwide attention as an effective approach to reducing the quantity and toxicity of organic wastes together with energy recovery. However, direct sludge and food waste incineration is not cost-efficient and creates unstable burning due to the high moisture content. For the high-moisture wastes, drying are the prerequisite steps before high efficiency incineration. Direct thermal drying encounters the limits of mass and heat transfer, and thus the high operating cost (e.g. fuel consumption, construction cost) are needed. Therefore, high efficient drying is the key to incinerate the food waste and dewatered sludge.

Biodrying aims at removing water from biowastes by taking advantage of the heat generated from microbial degradation in aid of forced aeration (Frei et al., 2004; Velis et al., 2009), and the dried product was usually used for RDF (refuse derived fuel). It is recognized as a novel and alternative method to treat high-moisture organic wastes due to its relatively short residence time (7–15 days) and high process efficiency (Choi et al., 2001; Velis et al., 2009). With no fossil fuels supplementary and minimal electricity consumption, biodrying presents efficient and economic potential for volume and weight reduction of biowastes (Zhao et al., 2011). Compared with the conventional thermal drying,

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Nomenclature

FW	food waste
DS	dewatered sludge
VS/TS	volatile solid/total solid, dry basis (db)
MC	moisture content, wet basis (wb)
EC	electric conductivity (mS/cm)
C_{dryair}	specific heat of dry air (1.004 kJ kg^{-1} °C^{-1})
C_{solid}	specific heat of solid (1.046 kJ kg^{-1} °C^{-1}) (Yang et al., 2013)
C_{water}	specific heat of water (4.184 kJ kg^{-1} °C^{-1})
C_{watvap}	specific heat of water vapor (1.841 kJ kg^{-1} °C^{-1})
Q_{bio}	biologically generated heat (kJ)
Q_{dryair}	consumed sensible heat of inlet dry air for temperature increase (kJ)
Q_{watvap}	consumed sensible heat of water vapor for temperature increase (kJ)
Q_{evapo}	latent heat of removed water (kJ)
Q_{water}	consumed sensible heat of water in feedstock for temperature increase (kJ)
Q_{solid}	consumed sensible heat of dry solid in feedstock for temperature increase (kJ)
Q_{condu}	conductive heat loss from reactor wall (kJ)
Q_{radi}	radiant heat loss from the top surface of the materials (kJ)
$Q_{turning}$	heat loss by turning (kJ)
P	atmospheric pressure (mm Hg)
p_{vs}	saturated vapor pressure of water (mm Hg)
p_v	vapor pressure of water (mm Hg)
M_{eva}	evaporated water (kg)
M_{air}	mass of dry air (kg)
H_c	heat of combustion
L_{latwat}	latent heat of water evaporation (kJ kg^{-1})
M_{water}	mass of water in materials (kg)
M_{solid}	mass of dry solid in materials (kg)
RH	relative humidity
T_m	matrix temperature (°C)
T_a	ambient temperature (°C)
ω	weight of water vapor on a dry air basis (kg H_2O kg^{-1} -dry air)
a, b, c	Empirical constants in the Antoine expression with values of −2238, 8.896 and 273, respectively (Mason, 2009)

the heat and mass transfer could be overcome by diffusing the air into the organic matrix.

As a novel method, much research has focused on the application of this technology for treating dewatered sludge. Frei et al. (2004) investigated the application of biodrying for efficient sludge combustion, which presented economic advantages for calorific value improvement. The technology was also systematically investigated from design, experiment to modeling, and achieved the best drying effect (Navaee-Ardeh, 2010), which presented great potential for sludge drying in contrast with the other existing drying technologies (Navaee-Ardeh et al., 2006). However, the biomass energy of sludge available for heat generation is limited due to low biodegradable VS (Zhao et al., 2010), as most of the organics is separated by microbial cell membranes and unavailable for biodegradation (Weemaes and Verstraete, 1998). In addition to few available organics, all the disadvantages, such as high moisture content and low biomass porosity, discourage effective aeration and biological energy generation during sludge biodrying (Feng et al., 2015; Zhao et al., 2011).

MSW is characterized by high water and organic content due to the mixture of food waste, which is easily hydrolyzed and acidized, increasing the processing cost and environmental problems. Some researchers focused on the biostabilization of MSW, taking advantage of composting (Adani et al., 2006), biodrying (Adani et al., 2002) or mechanical-biological process (Adani et al., 2004). During these processes, the degradation and heat generation of food waste as the main fraction of MSW contributed to the water removal and biostabilization of MSW (Tambone et al., 2011). Yang et al. (2013) optimized the bioevaporation of highly concentrated organic wastewater, ground FW and glucose solution was added and treated in biodried sludge bed respectively, and the process was proved to be feasible (Yang and Jahng, 2014; Yang et al., 2013). FW presented effective and available biodegradability as a direct carbon resource for microbial metabolism same as glucose.

In this study, FW separated from MSW was introduced to biodrying process of dewatered sludge for providing more biodegradable organics. On the other hand, the abundant microbial consortia in DS could improve the microbial biomass and buffering of volatile acids during degradation process (Demirekler and Anderson, 1998; Fang and Wong, 1999). By the combination of FW and DS, the nutritional properties and moisture distribution would be improved for microbial degradation and evaporation with adequate effective microbes. In addition, the two waste streams generated from urban area could share the facility for co-treatment. Taking all these potential advantages, firstly, the experiments with different proportions of FW and DS were conducted to explore the synergistic effects of co-biodrying. Besides of the temperature profile, moisture removal and VS reduction, the heat balance modeling methodology was adopted to assess the energy efficiency for the co-biodrying of food waste and dewatered sludge with different proportions. Furthermore, in order to identify the key factor, the variables of particle size of bulking agent, air-flow rate and initial moisture content were also investigated by a series of experiments. The obtained results could provide useful information on the application of biodrying technology treating FW and DS.

2. Materials and methods

2.1. Preparation of materials

The corncob was crushed into particle and then screened into three different sizes (<3 mm, 3–6 mm, 6–10 mm). The dewatered sludge (DS) was obtained from a local urban wastewater treatment plant (WWTP) in Dalian, China, whose wastewater treatment capacity is 6.0×10^4 m^3/d using cyclic activated sludge technology (CAST). The food waste (FW) was collected from a canteen of Dalian University of Technology and crushed into <2 mm particles using a food grinder. The physicochemical properties of raw materials are presented in Table 1.

2.2. Experimental equipment

The biodrying process was conducted in a reactor made of polystyrene foam with volumes of 18 L (L × W × H: 380 mm × 270 mm × 220 mm) and wall thickness of 20 mm. Each reactor was filled with about 5 kg of mixed materials. A layer of sponge (thickness of 20 mm) was covered on the top of the mixture to avoid heat loss and vapor condensation. An air pump (ACO-

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