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Spent coffee ground as a new bulking agent for accelerated biodrying of dewatered sludge

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ABSTRACT

The feasibility of using spent coffee ground (SCG) as a new bulking agent for biodrying of dewatered sludge (DS) was investigated in comparison with two other frequently-used bulking agents, air-dried sludge (AS) and sawdust (SD). Results showed that the moisture contents (MC) of 16-day DS biodrying with AS (Trial A), SCG (Trial B) and SD (Trial C) decreased from 70.14 wt%, 68.25 wt% and 71.63 wt% to 59.12 wt%, 41.35 wt% and 57.69 wt%, respectively. In case of Trial B, the MC rapidly decreased to 46.16 wt% with the highest water removal (70.87%) within 8 days because of the longest high-temperature period (5.8 days). Further studies indicated that the abundant biodegradable volatile solids (BVS) and high dissolved organic matter (DOM) contents in SCG were the main driving forces for water removal. According to pyrosequencing data, *Firmicutes*, most of which were recognized as thermophiles, was rapidly enriched on Day 8 and became the dominant phylum in Trial B. Four thermophilic genera, *Bacillus*, *Ureibacillus*, *Geobacillus* and *Thermobifida*, which can produce thermostable hydrolytic extracellular enzymes, were the most abundant in Trial B, indicating that these thermophilic bacteria evolved during the long high-temperature period enhanced the biodegradation of BVS in SCG. The 8-day biodried product of Trial B was demonstrated to be an excellent solid fuel with low heating value (LHV) of 9284 kJ kg^{-1}, which was 2.1 and 1.8 times those of biodried products with AS and SD, respectively. Thus SCG was found to be an excellent bulking agent accelerating DS biodrying and producing a solid fuel with a high calorific value.

1. Introduction

Due to strict environmental regulations and high costs of disposal, the focus of sewage sludge management is being shifted from traditional disposal to energy recovery (Ma et al., 2016). In wastewater treatment plants (WWTP), thickened sludge is, in general, mechanically-dewatered. However, this dewatered sludge (DS) still contains much water with typical moisture contents (MC) of 80–85 wt% and thus cannot be directly used as a solid fuel (Cai et al., 2016b). Recently, biodrying has been emerged as a pretreatment method for lowering MC of organic wastes. Even so, it does not seem that direct biodrying of DS is technically feasible because not only MC is too high but also biodegradable volatile solids (BVS) content and porosity are low (Zhao et al., 2011). To address these problems, bulking agents are commonly mixed with DS to enhance free air space (FAS) and to adjust the initial MC into optimal ranges. Because it is easy and inexpensive to obtain in large quantities, straw (Zhao et al., 2011), sawdust (SD) (Yang et al., 2014), wheat residues (Li et al., 2015), rice husks (Zhang et al., 2015) and wood shavings (Huiliñir and Villegas, 2015; Villegas and Huiliñir, 2014) have frequently been used as bulking agents for sewage sludge biodrying. However, uses of these bulking agents have resulted in insufficient heat production accompanying low temperature profiles and/or short high-temperature periods. These lignocellulosic bulking agents are sparingly soluble in water and, consequently, concentrations of dissolved organic matters (DOM) contributed by the bulking agents are low. Thus diverse nutrients required for microbial metabolism are not sufficiently provided by these bulking agents (Zhang et al., 2015). It also needs to notice that mixtures of DS and these less-soluble materials are not homogenous (Zhao et al., 2011). Furthermore, lignocellulose is resistant to microbial degradation (Huiliñir and Villegas, 2015; Zhao et al., 2011). Therefore, efforts for finding new bulking agents exhibiting high biodegradation potentials, high DOM contents, appropriate FAS,

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Nomenclature

a, b, c	Dimensionless constants in the Antoine expression, with values of 2,238, 8.896 and 273, respectively (Mason, 2009)
AS	Air-dried sludge
BI	Biodrying index
C_{dryair}	Specific heat of dry air (1.004 kJ kg^{-1} °C^{-1}) (Haug, 1993)
C_{solid}	Specific heat of the solids (1.046 kJ kg^{-1} °C^{-1} for sludge, 2.2 kJ kg^{-1} °C^{-1} for spent coffee ground and sawdust) (Guo et al., 2013, Haug, 1993)
C_{water}	Specific heat of water (4.184 kJ kg^{-1} °C^{-1}) (Haug, 1993)
C_{watvap}	Specific heat of water vapor (1.841 kJ kg^{-1} °C^{-1}) (Haug, 1993)
DOM	Dissolved organic matter
DS	Dewatered sludge
H_{f}	Heat content of the biodrying matrix after biodrying (kJ kg^{-1})
H_{i}	Heat content of the biodrying matrix before biodrying (kJ kg^{-1})
HHV	High heating value (kJ)
L_{latwat}	Latent heat of water evaporation (kJ kg^{-1})
LHV	Low heating value (kJ)
M_{air}	Molar mass of air (29 g mol^{-1})
$M_{\mathrm{H_2O}}$	Molar mass of water (18 g mol^{-1})
MC	Moisture content (wt%)
MC_{f}	Moisture content of the biodrying matrix after biodrying (wt%)
MC_{i}	Moisture content of the biodrying matrix before biodrying (wt%)
m_{air}	Mass of dry air (kg)
m_{eva}	Mass of evaporated water (kg)
m_{f}	Mass of biodrying matrix after biodrying (kg)
$m_{\mathrm{H_2O}}$	Water removal (kg)
m_{i}	Mass of biodrying matrix before biodrying (kg)
m_{solid}	Mass of dry solid in biodrying matrix (kg)
m_{water}	Mass of water in biodrying matrix (kg)
m_{VS}	VS consumption (kg)
P	Atmospheric pressure (mm Hg)
p_{vs}	Saturated vapor pressure of water (mm Hg)
p_{v}	Vapor pressure of water (mm Hg)
Q_{bio}	Biologically generated heat (kJ)
Q_{condu}	Heat loss by conduction (kJ)
Q_{dryair}	Consumed sensible heat by inlet dry air (kJ)
Q_{evapo}	Consumed latent heat by evaporated water (kJ)
Q_{loss}	Sum of heat loss by conduction, radiation and turning (kJ)
Q_{radi}	Heat loss by radiation (kJ)
Q_{solid}	Consumed sensible heat by dry solid (kJ)
Q_{water}	Consumed sensible heat by water (kJ)
Q_{watvap}	Consumed sensible heat by water vapor (kJ)
RH	Relative humidity (%)
SCG	Spent coffee ground
SD	Sawdust
T_{a}	Ambient temperature (°C)
T_{m}	Temperature of the biodrying matrix (°C)
TC	Temperature cumulation (Zhao et al., 2010)
ΔT_{m}	Temperature change of the biodrying matrix in a time element (°C)
Δt	Time element (d)
VS_{f}	Volatile solid content of biodrying matrix after biodrying (dry basis, %)
VS_{i}	Volatile solid content of biodrying matrix before biodrying (dry basis, %)
ω	The weight of water vapor on a dry air basis (kg H_2O kg^{-1} dry air)

and good degrees of homogeneity have been continued. Zhao et al. (2011) reported that straw performed better than SD as a bulking agent for DS biodrying because of its high biodegradation potential in the aerobic process. However, the final MC was high (50–55 wt%) despite that the biodrying continued as long as for two weeks. Yang et al. (2014) achieved high water removal (55.1%) by using air-dried sludge (AS) as a bulking agent. However, the preparation of AS is time-consuming (at least 2 weeks in ambient atmosphere), which brings difficulties for large-scale DS biodrying (Yang and Jahng, 2015; Yang et al., 2014). Besides, the AS contains 20–50 wt% of inorganic materials such as sand and metal oxides (Han et al., 2015; Huang et al., 2015), which may cause problems in process operation and produce low-energy biodried products.

Spent coffee ground (SCG) is a solid residue generated during the production of espresso or hydro-soluble coffees (Murthy and Naidu, 2012). According to the International Coffee Organization (ICO), around 9.1 million tons of coffee bean were consumed in 2016 (ICO, 2017). Generally, 550–670 kg of SCG are produced from 1 ton of coffee bean (Park et al., 2016), therefore over 5.8 million tons of SCG are generated every year. Although SCG is abundant in nutrients, it is barely used for feeding domestic animals because polyphenols, tannins and caffeine are contained in it (Ulloa Rojas et al., 2003). Therefore, most of SCG has been discarded as a valueless waste without any treatment because efficient methods to handle the enormous amount have not been available (Park et al., 2016). Recently, several attempts have been made to compost (Hachicha et al., 2012; Sánchez et al., 1999) and co-compost with SCG for horticultural use without phytotoxic effects of direct application of SCG to soils (Hardgrove and Livesley, 2016; Santos et al., 2017). In addition, it was found that SCG accelerated process rates and augmented microorganisms in composting (Emmanuel et al., 2017; Zhang and Sun, 2017). Besides, SCG was also used as a feedstock for production of various biofuels by anaerobic digestion (Kim et al., 2017), biodiesel *trans*-esterification (Park et al., 2016), combustion (Chen et al., 2017), and pyrolysis (Li et al., 2014). Attention is being increasingly paid to SCG management to meet its ever-increasing production, nonetheless, few studies have focused on SCG as a bulking agent for biodrying. Considering its availability, biodegradability and high calorific value (21 MJ kg^{-1}) (Chen et al., 2017), SCG is thought to be a good candidate for a bulking agent in biodrying targeting solid fuel production.

In this study, the feasibility of using SCG as a bulking agent for DS biodrying was investigated, and its performance was compared with two other bulking agents, AS and SD. Temperature, CO_2 concentration in exit gas, water removal, VS consumption and DOM variations were monitored. For further comparison, mass and heat balances of DS biodrying with these three bulking agents were established. Additionally, bacterial communities developed during biodrying were analyzed by pyrosequencing. High heating value (HHV) and low heating value (LHV) were also measured in order to examine the fuel characteristics of biodried products. Based on these investigations, it was concluded that SCG was an excellent bulking agent for DS biodrying.