Bioresource Technology 117 (2012) 13–19

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Moisture variation associated with water input and evaporation during sewage sludge bio-drying

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ARTICLE INFO

Article history:
Received 14 February 2012
Received in revised form 29 March 2012
Accepted 29 March 2012
Available online 4 April 2012

Keywords:
Sewage sludge
Bio-drying
Moisture content
Water evaporation
Water generation

ABSTRACT

The variation of moisture during sewage sludge bio-drying was investigated. *In situ* measurements were conducted to monitor the bulk moisture and water vapor, while the moisture content, water generation, water evaporation and aeration water input of the bio-drying bulk were calculated based on the water mass balance. The moisture in the sewage sludge bio-drying material decreased from 66% to 54% in response to control technology for bio-drying. During the temperature increasing and thermophilic phases of sewage sludge bio-drying, the moisture content, water generation and water evaporation of the bulk initially increased and then decreased. The peak water generation and evaporation occurred during the thermophilic phase. During the bio-drying, water evaporation was much greater than water generation, and aeration facilitated the water evaporation.

1. Introduction

The moisture content (MC) of dewatered sewage sludge is about 80%, which causes a series of problems in terms of sludge treatment and disposal; therefore, reducing sludge moisture is important to the reduction of sludge volume and quantity (Zhao et al., 2010). Sludge bio-drying is an economical and energy-saving method of simplifying thermophilic aerobic fermentation that utilizes the biological energy produced by microbial fermentation to activate bound water and evaporate moisture (Navaee-Ardeh et al., 2010), resulting in rapid reduction of the moisture in the bio-drying material (Zhang et al., 2008). The main drying mechanism in bio-drying is convective evaporation, which utilizes heat produced from the biodegradation of organic matter and is facilitated by mechanically controlled aeration (Navaee-Ardeh et al., 2006). The process by which the moisture of the bio-drying material is reduced is as follows: water molecules evaporate from the surface of the material into the air, after which the evaporated water (vapor) is transported and removed by airflow (Velis et al., 2009). Air convection and molecular diffusion are the primary approaches to the removal of water from bio-drying material (Frei et al., 2004).

Moisture is a critical parameter involved in bio-drying technology that influences the complex biochemical reactions associated with microbial growth and the biodegradation of organic matter that occurs during the process (Ryckeboer et al., 2003). In addition, maximizing the removal of moisture present in bio-drying bulk is a crucial pre-treatment step that is beneficial to sludge treatment and disposal (Velis et al., 2009).

The water mass balance of bio-drying bulk indicates that variations in bulk moisture are associated with water input and water output. Water input includes: (1) water generation (WG), which is water produced by microbial metabolism during organic matter decomposition (Sole-Mauri et al., 2007; Zhang et al., 2010); and (2) aeration water input (AWI), which is moisture added to the bulk during forced aeration. In a study conducted by Chen (2010), the airflow from the air chamber under the bulk removed moisture from the bottom of the bulk and no leachate was collected; therefore, it is assumed that no leachate is produced during drying of the bulk. As a result, the water is removed by water evaporation (WE) during bio-drying. WE is achieved *via* the evaporation of free water and primarily removed by air convection (Velis et al., 2009). Accordingly, the water output is actually the water evaporated from the bulk material. In addition, the apparent moisture reduction (AMR) is defined as the difference between two MC values measured at different times. During bio-drying, the degree of drying depends on the ratio of water output to water input (Richard, 2004).

Investigation of the WG and WE during sludge bio-drying is beneficial to improving the efficiency of moisture reduction and contributes to reduction of the sludge volume. However, recent studies have focused on the MC of the bulk itself, and few studies have investigated the water mass balance. Accordingly, the water input and evaporation during sludge bio-drying is not fully

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0960-8524/$ - see front matter © 2012 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.biortech.2012.03.092

Nomenclature

$M_{H_2O,t}$	total moisture of the bio-drying bulk on day t (kg)
M_0	initial weight of the bio-drying bulk on day 1 (kg)
MC_0	moisture content of the bio-drying material on day 1 (%)
VS_0	volatile solids content of the bio-drying material on day 1 (%)
MC_t	moisture content of the bio-drying material on day t (%)
VS_t	volatile solids content of the bio-drying material on day t (%)
ρ_0	density of the bio-drying bulk on day 1 (kg m^{-3})
V	volume of the bio-drying bulk on day 1 (m^3)
e	vapor flux above the bulk surface (kg m^{-2} s^{-1})
q_e	specific humidity of the airflow above the bulk surface (kg water kg^{-1} air)
u_e	vertical air velocity of the airflow above the bulk surface (m s^{-1})
ρ_e	density of the air above the bulk surface (kg m^{-3})
M_{water}	molecular mass of water (g mol^{-1})
M_{air}	molecular mass of air (g mol^{-1})
T	temperature of air (°C)
β	relative humidity of air (%)
E	water evaporation of the bulk (kg)
M_i	water vapor input per second (kg s^{-1})
ρ_i	density of forced air (kg m^{-3})
Q_i	volume of forced air (m^3 s^{-1})
q_i	specific humidity of air forced into the bulk (kg water kg^{-1} air)
I	aeration water input of the bulk (kg)
$\Delta M_{H_2O,a}$	apparent moisture reduction of the bulk (kg)
$M_{H_2O,t-1}$	total moisture of the bulk on day t-1 (kg)
$\Delta M_{H_2O,g}$	water generation of the bulk (kg)

understood. Therefore, this study was conducted to investigate the variations in water input and evaporation of sludge bio-drying bulk in terms of a water mass balance developed *via in situ* moisture and vapor measurement.

2. Methods

2.1. Bio-drying materials

Sewage sludge (SS) was collected from the municipal wastewater treatment plant in Qinhuangdao, China. Sawdust (SD) was acquired from wood-working factories in the same city. Bio-dried product (BP) was obtained from Lvgang Municipal Sewage Sludge Treatment Plant, which is a SS bio-drying plant in Qinghuangdao, China. SD and BP were used as bulking agents for bio-drying. Specifically, these materials were added to three feed bins and then fed into a mixing machine by screw conveyors. The mixing ratio of the three materials was 3:2:1 (SS:BP:SD) based on volume, and this was set by adjusting the rotating speed of the screw conveyors. This ratio was selected based on the initial MC and free air space of bio-drying material that was appropriate for microbial fermentation (Adhikari et al., 2009; Chen et al., 2011). The characteristics of the raw materials and mixture feedstock used in this study are presented in Table 1.

2.2. Experimental procedures

The mixture for bio-drying was loaded into the fermentation compartment and then flattened using a slope trimmer. The process of sludge bio-drying was conducted by CTB (control technology for bio-drying) auto-control based on a combination of temperature and O_2 concentration feedback from temperature sensors and oxygen sensors, which were controlled using Compsoft® 3.0 (GreenTech Environmental Engineering Ltd., Beijing, China) (Chen et al., 2011). Air was forced from the air chamber under the bulk to the top of the bulk by an air blower. The volume of forced air was adjusted according to the bulk temperature and O_2 consumption rate during different bio-drying phases (Chen et al., 2011).

The experimental equipment for SS bio-drying is shown in Fig. 1. An unsealed cylindrical cover made of hydrophobic material was vertically installed into the bulk from top to bottom to minimize the interference caused by external factors. The cylindrical cover had an internal diameter of 1.13 m and a cross-sectional area of 1.0 m^2, and the bio-drying bulk was 1.6 m in height; therefore, the volume of the experimental bulk material was about 1.6 m^3 (1.0 m^2 × 1.6 m). A water vapor sensor was installed along the central axis of the cylindrical cover about 0.5 m above the top of the bulk. A moisture sensor and temperature sensor were inserted into the bulk at a depth of 0.6 m (from top to bottom). An airflow meter was located in the horizontal ventilation duct from the air blower to the air chamber. The period of sludge bio-drying was 20 days and the bio-drying bulk was intermittently aerated using an air blower throughout the study period. In addition, the bulk was turned on days 9, 12, 15 and 18.

2.3. Data acquisition and sample analysis

Bulk temperature was monitored in real time using a PT100 temperature sensor throughout the study period. The MC of the bio-drying material was measured using a moisture sensor based on time domain reflectometry that consisted of a pulse generator (Soilmoisture Equipment Corp., USA) and probes. The MC was determined by *in situ* analysis of 15 replicates at the same time every day. A water vapor sensor composed of an ultrasonic anemometer (Gill Instruments, UK), a temperature sensor and a humidity sensor (Rotronic, Switzerland), was used to log data from three replicates at a 2-s interval. Airflow was measured in real time using a thermal flowmeter (Virvo, USA) and data were logged at a 1-min interval based on three replicates. Additionally, bio-drying material was collected from the bulk daily to measure the volatile solids (VS) content, which was determined by oven-drying of the sample and subsequent incineration in a muffle furnace. The collected bio-drying material was also used to determine the bulk density by the cutting ring method. The VS and bulk density were determined based on five replicates analyzed using the methods described by the US Department of Agriculture and US Composting Council (2001).

2.4. Formulas for data computation

During sludge bio-drying, the WE accounted for the total water output, while the water input consisted of WG and AWI. The difference between the two values of total moisture is the AMR.

2.4.1. Total moisture of bulk

In this study, MC is expressed on a wet weight basis (i.e., weight of moisture/wet weight of sample). Assuming that the change in the weight of the bulk is determined by the degradation of VS and migration of moisture, and that the ash content of the bulk does not change throughout the bio-drying process, the total weight of moisture of the bulk on day t can be obtained from the following formula: