Bioresource Technology 174 (2014) 33–41

Contents lists available at ScienceDirect

Bioresource Technology

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

Biodrying of sewage sludge: Kinetics of volatile solids degradation under different initial moisture contents and air-flow rates

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HIGHLIGHTS

- Kinetics of volatile solids (VS) biodegradation in batch biodrying was studied.
- The effect of air flow-rate (AFR) and initial moisture content (Mc) was evaluated.
- Seven kinetic models were analyzed with two statistical indicators.
- Kinetic models proposed simulate VS biodegradation under studied conditions.

ARTICLE INFO

Article history:
Received 29 July 2014
Received in revised form 23 September 2014
Accepted 28 September 2014
Available online 5 October 2014

Keywords:
Biodrying
Sewage sludge
Kinetics
Biodegradation
Initial moisture content

ABSTRACT

This study focuses on the kinetics of the biodegradation of volatile solids (VS) of sewage sludge for biodrying under different initial moisture contents (Mc) and air-flow rates (AFR). For the study, a 3^2 factorial design, whose factors were AFR (1, 2 or 3 L/min kg_{TS}) and initial Mc (59%, 68% and 78% w.b.), was used. Using seven kinetic models and a nonlinear regression method, kinetic parameters were estimated and the models were analyzed with two statistical indicators. Initial Mc of around 68% increases the temperature matrix and VS consumption, with higher moisture removal at lower initial Mc values. Lower AFRs gave higher matrix temperatures and VS consumption, while higher AFRs increased water removal. The kinetic models proposed successfully simulate VS biodegradation, with root mean square error (RMSE) between 0.007929 and 0.02744, and they can be used as a tool for satisfactory prediction of VS in biodrying

1. Introduction

Nowadays the continuous production of large amounts of sewage sludge is becoming a worldwide environmental problem (Zhao et al., 2010). One way to treat this waste is combustion; however, its high moisture content makes direct combustion difficult. In this context, biological drying or simply "biodrying", an alternative pretreatment method aimed at combustion, has been developed in recent years. Biodrying, which is based on a process similar to composting, aims at removing water from biowastes with high water content using the heat generated during the aerobic degradation of organic substances, in addition to forced aeration (Frei et al., 2004; Navaee-Ardeh et al., 2011; Velis et al., 2009; Zhao et al., 2010). In addition, a low biodegradation of its organic content is desire in order to improve its calorific value. In this sense, determination of biodegradation behavior of wastes is important for an optimized design regarding biodrying process parameters such as processing time, reactor size, aeration flow rate (AFR) and initial moisture content (Mc). In this way, the use of a kinetic model that predicts VS biodegradation can be useful in order to determine the degree of biodegradation in the biodrying process.

Despite of the importance of VS biodegradation in the biodrying process, its kinetic has been scarcely studied. Huilinir and Villegas (2014) presented the application of several kinetic models in order to predict the behavior of VS degradation under different AFR. They showed that these models, derived from composting process, can be used for describing VS biodegradation under biodrying conditions. However, its functioning was developed only at different AFR, without taking into account other important factor such as the initial moisture content (Mc). Furthermore, only temperature (T) and Mc were incorporated in the kinetic models. The initial Mc is important because a too high initial Mc limits oxygen transport and obstructs microbial activity, impeding biodrying (Navaee-Ardeh et al., 2011). On the contrary, if initial Mc is too low, microbial activity will be slowed by the lack of moisture,

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http://dx.doi.org/10.1016/j.biortech.2014.09.136
0960-8524/

resulting in reduced drying performance. In addition, it is known that the initial Mc affects other important factors such as the free air space (FAS). The FAS is important in determining the quantity and movement of air through the matrix. Moisture levels should be high enough to assure adequate rates of biological reactions yet not so high that FAS is eliminated, thus reducing the rate of oxygen transfer and, in turn, the rate of biological activity (Yang et al., 2014).

Recently, Yang et al. (2014) studied the effect of initial Mc on the biodrying process. They showed that 50–70 wt% was the optimal initial Mc range for the sludge biodrying process, with VS reduction between 12.3% and 21.2%. Other studies in composting process (Komilis et al., 2011; Liang et al., 2003; Petric et al., 2009; Tremier et al., 2009) also showed the critical importance of initial Mc in the biodegradation process. Therefore, the application of kinetic models for the VS biodegradation under different initial Mc should be studied.

Regarding the AFR, it is known that this parameter affects the biodrying efficiency. Air-flow is necessary to remove water from the matrix, whose temperature affects temperature of air-flow and subsequently its water holding capacity (Navaee-Ardeh et al., 2006). The effect of AFR on biodrying has been studied recently by several researchers. Zhao et al. (2010) studied the effect of air-flow rate and turning frequency on bio-drying of dewatered sludge, showing that the higher air-flow rate, heat consumed by sensible heat of inlet air and heat utilization efficiency for evaporation was higher than the lower one. Cai et al. (2013) showed that forced aeration controlled the pile temperature and improved evaporation, making it the key factor influencing water loss during the process of sewage sludge bio-drying. Colomer-Mendoza et al. (2013) studied the effect of AFR on the biodrying of gardening wastes, showing that high airflow affects the biodrying process, because the thermofilic phase is avoided, so that the waste is dried only by physical phenomena and not by biodrying. Finally, Sharara et al. (2012) showed that high aeration level was superior in terms of both drying energy and time requirements to the other rates considered. None of these studies worked with different levels of initial Mc, therefore, the effect of both parameters on the VS biodrying kinetic is unknown.

Thus, the main objective of this work was the application of several simple kinetic models for the description of VS biodegradation at different AFR and initial Mc in a laboratory scale bioreactor. A 3^2 factorial design, whose factors were air flow rate AFR and initial Mc, was used in order to test the kinetic models. The measurement of T, Mc and FAS during the assays was incorporated into the model in order to describe VS biodegradation at high air-flow rates and different initial Mc.

2. Methods

2.1. Characteristics of feedstock

Dewatered secondary sludge was obtained from a slaughterhouse wastewater treatment plant in Puente Alto, Santiago, Chile. Sludge was dewatered by screw filter with the addition of organic flocculating agents. Wood shavings of 2.5 mm average diameter were used as bulking agent. The characteristics of the raw materials are presented in Table 1.

2.2. Experimental equipment and process operation

The biodrying experiments were performed in three 64 L cubic reactors (40 cm in height, 40 cm width, 40 cm length) made of acrylic plastic connected to an OPTO22 data acquisition system. Heat losses were reduced by wall insulation provided by a 5 cm layer of polyurethane foam. A perforated baffle with 2-mm mesh was fixed above the bottom to support the material and facilitate aeration. Temperature measuring ports were set in the middle of reactor. A constant and uninterrupted air-flow rate was used in all the assays using a mini-compressor (150 L/min, ACO-012, China) connected to the bottom of the column, while a rotameter (1–10 lpm, Veto, Santiago, Chile; 4–40 lpm, Veto, Santiago, Chile) was used to measure the air flow rate, which was high in order to stimulate the drying effect and not the biodegradation (Adani et al., 2002). In the reactors, temperature was measured each 15 min through a heat-resistant temperature electrode (Pt100, Veto, Chile), placed in the middle of substrate and in the inlet of bioreactor. Pt100 were connected through the acquisition module SNAP PAC OPTO22 (California, USA) on a PC.

The biodrying process was studied through a 3^2 factorial design, whose factors were air flow rate AFR (1, 2 or 3 L/min kg_{TS}) and initial Mc (59%, 68% and 78% w.b.). The AFR levels were chosen based on the work of Huilinir and Villegas (2014), while the initial Mc were chosen according to values reported by Yang et al. (2014) and Petric et al. (2009). Table 2 shows the experimental matrix.

When the matrix temperature was close to the environmental temperature, the reactors were weighed and the matrix was removed from the reactors and loaded again after mixing for 30–60 min, as recommended Zhao et al. (2010). Weight loss was measured using a portable scale, which is directly related to the loss of moisture and VS from the sample. Before the material was loaded again into the bioreactor, three 10-g samples of mixed waste were collected to measure moisture content and volatile solids (VS) of the matrix.

2.3. Analytical methods

The dry matter content was determined by drying the sample at 105 °C for 24 h in an oven (Blue M, Stabil-Therm, model OV-180, USA). The difference between the initial and final weight was the water content or moisture content of the solid. The volatile solids content (VS) was analyzed by heating the sample at 550 °C for 5 h in a muffle furnace.

Carbon content was determined by dividing the volatile fraction by 1.83 (Barrington et al., 2002):

$$C(\%) = \frac{(100 - \%\text{ash})}{1.83} \tag{1.1}$$

Nitrogen content was determined by the total Kjeldahl nitrogen method, using the modified Nessler method (method 8075) with 0.25 g of homogenized material. Digestion was first done using digester Digesdahl Hach (HACH, USA), based on a single total digestion of organic matter with sulfuric acid and hydrogen peroxide. The digested solution was used determining nitrogen using Hach's spectrophotometer DR-3900 (HACH, USA).

Table 1
Characteristics of the raw materials.

Material	Moisture content (% w.b.)	% C	% N	C/N ratio, g C g^{-1} N
Secondary sludge	88.25 ± 8.36	47.08 ± 1.25	6.02 ± 0.45	7.82
Wood shavings for Mc = 59%	9.43 ± 0.78	54.12 ± 0.66	0.26 ± 0.02	208.15
Wood shavings for Mc = 68%	19.53 ± 2.25	51.34 ± 1.23	0.23 ± 0.02	223.22
Wood shavings for Mc = 78%	11.92 ± 1.45	53.60 ± 0.56	0.26 ± 0.03	206.15