Waste Management 80 (2018) 327–338

Contents lists available at ScienceDirect

Waste Management

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

Thermally assisted bio-drying of food waste: Synergistic enhancement and energetic evaluation

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ARTICLE INFO

Article history:
Received 4 June 2018
Revised 31 August 2018
Accepted 12 September 2018

Keywords:
Food waste
Staged heating acclimation
Synergistic enhancement
Thermally assisted bio-drying

ABSTRACT

Recently, bio-drying is becoming a promising method to treat the slurry-type food waste together with recovering refused derived fuels (RDFs). In practice, however, conventional process frequently encountered low temperature and inefficient drying performance due to the low microbial activity and organics degradability. In order to improve bio-drying performance, in this study, an externally thermal assistant strategy was proposed to increase water evaporation and stimulate microbial degradability. Based on this idea, a series of experiments were conducted to establish, evaluate and optimize the thermally assisted bio-drying system. It was found that staged heating acclimation was an effective strategy to obtain a superior thermophilic inoculum with high metabolic activity and microbial consortia. In thermally assisted bio-drying process, an extremely high metabolic activity [cumulative OUR, 38.98 mg/(g TS·h)] was obtained, which was greatly higher than that of conventional bio-drying [19.74 mg/(g TS·h)]. Furthermore, thermally assisted bio-drying exhibited a high water-evaporation capacity as thermal drying (157.9 g *vs.* 147.8 g), which was 3-fold higher than conventional bio-drying. Heat balance calculation indicated that externally supplying a small fraction (12.94%) of thermal energy triggered conventional bio-drying, thus greatly promoting water removal with high energy utilization efficiency as conventional bio-drying (Q_{evapo} 60.30% *vs.* 64.62%). In addition, the increased air-flow rates greatly accelerated water removal with high bio-energy efficiencies, especially at 0.8 $L \cdot min^{-1} \cdot kg^{-1}$. The drying effect after 4 days was close to that of 20 days in conventional bio-drying. This research suggests that thermally assisted bio-drying is a promising approach to upgrade conventional bio-drying with high efficiency and low energy cost.

1. Introduction

Among many types of solid wastes, food waste (FW) is one of the most concerned wastes, accounting for 51–66% of municipal solid waste (MSW, 215 million tons in 2017) in China (MEP, 2018; Zhang et al., 2018c). Besides, FW was reported to be responsible for the unpleasant odour and greenhouse gases emission and leachate release during MSW landfill, and it also brought about the inefficient combustion in MSW incineration (Tai et al., 2011). Meanwhile, FW was characterized by high organic matter content [volatile solid/total solid (VS/TS), 80–97%] (Chang and Chen, 2010), and it has great potential as a renewable energy source (Pham et al., 2015). Anaerobic digestion was usually regarded as a suitable way for food waste treatment with biogas production (De Gioannis et al., 2017), however, the high capital cost and further digestate treatment limited its wide application (Pham et al., 2015). As for thermochemical recovery, the high moisture content (74–90%) in FW was a main barrier (Chang and Chen, 2010), the dewatering and drying is the prerequisite for achieving energy recovery. So far, thermal drying was still a main method for FW drying. For instance, food residues were dried under high temperature for eliminating pathogens and removing water (Lin et al., 2013). Household FW was proposed to be dried by thermal heat on site for further utilization (Sotiropoulos et al., 2016). However, conventional drying methods, e.g., fluidized bed drying, convective drying, were less effective with high energy consumption due to the limitation of mass and heat transfer for slurry-type wastes (Bianchini et al., 2015; Rulkens, 2008). Therefore, more effective and economical drying technology for this huge amount of FW is still a challenge.

Derived from composting, bio-drying technology was developed recently and more studies are undergoing in this technology (Velis et al., 2009). Although microbial degradation was essential in both composting and bio-drying technologies, the different products

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https://doi.org/10.1016/j.wasman.2018.09.023
0956-053X/

can be obtained by different control strategies. Composting aims at producing a safe, stabilized and nutrient enriched soil fertilizer with humic substance formation during microbial metabolism (Sharholy et al., 2008). However, removing the excessive water in biowaste is the principal target of bio-drying, by which the solid fuel with high energy content was obtained (Shao et al., 2010; Tom et al., 2016). It took advantage of heat generated from microbial degradation of organics for evaporating water with aid of forced aeration (Velis et al., 2009). Air flow was also an important factor for bio-drying. With high air-flow rate together with high temperature, water vapor was continuously taken out of matrix (Adani et al., 2002; Sugni et al., 2005). After removing excessive moisture, the remaining solid waste could be used as a refuse derived fuel (RDF), which is a carbon-neutral and renewable energy alternative to fossil fuel source (Hao et al., 2018a; Zhang et al., 2009a). Attributed to the rich degradable organics in FW, abundant bio-heat was generated for water removal in MSW bio-drying (Velis et al., 2009; Zhang et al., 2008). FW also presented favorable bio-drying performance with high temperature evolutions and energy efficiency (Ma et al., 2016; Zhang et al., 2018a). Therefore, bio-drying is considered to be a prospective and profitable method for FW treatment with minimal energy consumption and RDF recovery.

Bio-drying process is strongly dependent on microbial activity. High microbial activity helps to generate huge amounts of heat, which increases matrix temperature and the high temperature (> 50 °C) was effective to promote water evaporation (Velis et al., 2009; Zhao et al., 2011). In aspect of microbial metabolism, during thermophilic phase, high temperature promoted the degradability of readily biodegradable and lignocellulosic bulking materials by enriching the thermophiles, e.g. *Acinetobacter*, *Bacillus* and *Ascomycota*, and stimulating their enzymes activities (Cai et al., 2016; Zhang et al., 2018b). The high temperature profile together with the appropriate air-flow rate would accelerate the water removal from bio-drying matrix (Adani et al., 2002; Sugni et al., 2005). For example, the thermophilic composting could speed up organics degradation, which greatly shortened composting cycle and promoted the humic substance formation (Bernal et al., 2009; Hosseini and Aziz, 2013). The humic substances (alkali-extractable organic molecules) were considered as a major reservoir of organic carbon, which were important to soil ecology, fertility and structure, and beneficial for plant growth (Adani et al., 2006; Kleber and Johnson, 2010; Lehmann and Kleber, 2015). However, excessively high (>60 °C) temperatures significantly slowed or even stoped the organics degradation (Liang et al., 2003; Velis et al., 2009). Therefore, the moderately high temperatures (50–60 °C) were desirable conditions, which not only promoted water evaporation, but also stimulated microbial degradation in bio-drying process.

Air-flow rate is another important factor for bio-drying performance. The quality of water removed from matrix is determined by air humidity and aeration rate. During bio-drying process, some heat is brought out together with water vapor by air flow, which will decrease the matrix temperature. In practice, in order to achieve high temperature for longer duration of time, the air-flow rate was usually maintained at lower levels (Adani et al., 2002). However, low air supply could not efficiently remove water vapor, but led to low bio-drying efficiency. In addition, low air supply could be a limiting factor for aerobic respiration, and sometimes could cause anaerobic condition and affect aerobic metabolism. In conventional bio-drying, air-flow rate was controlled at a moderate value, which compromised between temperature and water removal, and consequently the metabolic capability and drying performance in bio-drying process could not be intensified simultaneously. For example, in the late stage of conventional bio-drying, relatively low moisture content (<50%) in the matrix slowed down microbial activity and exhaustion of readily degradable organics limited microbial degradation (Yang et al., 2014). These consequently led to the low-temperature phase with low drying performance. Therefore, in previous studies, the final moisture content was around 45% even with prolonged the residence times (>15 d) (Hao et al., 2018b; Velis et al., 2009; Zhao et al., 2010), which were not low enough for spontaneous combustion (moisture content <30%) and efficient energy recovery (Fu et al., 2005). Therefore, slightly reducing the interdependence of matrix temperature and air-flow rate, enhancing both of them simultaneously might be the key to greatly improve bio-drying performance.

During bio-drying, microbial activity was affected by many factors, e.g., available biodegradable organics, microbial species, and other environmental factors (Navaee-Ardeh et al., 2010; Velis et al., 2009). At initial hydrolytic stage, lag phenomenon was frequently noticed (Ma et al., 2016; Zhang et al., 2009b), which was also noted in FW composting, resulting from initial organics acids accumulation (Cheung et al., 2010). Attributed to the high degradability of thermophiles, high-temperature phase achieved most of organics degradation and water removal (Cai et al., 2016), and along with the decrease of moisture content and readily degradable organics, microbial degradation slowed down with low temperature profile and inefficient water removal in cooling phase (Yang et al., 2014). Without external control, the unfavorable phenomena further negatively affected microbial activity, thus leading to the low efficiency and long operating period. Therefore, maintaining comfortable conditions for microorganisms, especially relatively constant temperature, might be another key for high-efficiency bio-drying process.

In order to guarantee water removal and accelerate bio-heat generation, thermal assistance by sustaining the matrix at high temperatures might be a solution for bio-drying. The external thermal supply could flexibly adjust the temperature fluctuation and maintain matrix temperatures at high levels, which will stimulate microbial metabolism and ensure high water evaporation efficiency. In this line, some researches indicated that thermal control was helpful for composting (Nakasaki et al., 2013). For example, thermophilic composting was conducted in MSW or cattle manure treatments by thermal assistance at 40–50 °C to promote the organics degradation and stabilization of products (Hosseini and Aziz, 2013; Xiao et al., 2009). As for bio-drying, the external thermal supply is expected to be a triggering force to enhance drying performance. Ideally, it is desirable that most heat for water evaporation comes from biogenic heat other than external heat. Therefore, it is necessary to systematically evaluate the thermally assisted bio-drying process in terms of water removal, energy efficiency and microbial activity.

In this study, a thermally assisted bio-drying system was established and its performance was evaluated and optimized. Specifically, in order to establish the robust thermally assisted bio-drying system, different acclimation strategies were examined to obtain the highly active inocula. Then, the thermally assisted bio-drying system inoculated by different inocula was compared with conventional bio-drying and thermal drying in terms of temperature profile, microbial activity, water removal and energy efficiency. Finally, in order to further optimize thermally assisted bio-drying process, air-flow rates and operating periods were regulated. These results could provide some useful information for practical thermally assisted bio-drying application.

2. Materials and methods

2.1. Preparation of materials

Food waste used in this study was collected from a canteen of Dalian University of Technology. It was mainly composed of rice,