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Pre-treatment and utilization of food waste as energy source by bio-drying process

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Abstract

In this study, three different sets of experiments were conducted with the aim of evaluating the effects of initial moisture content and bulking agent on bio-drying efficiency of food waste as well as weight reduction. Results showed that initial moisture content has a significant impact on bio-drying, affecting temperature and water removal rate as well as volatile solid degradation, with higher maximum temperature obtained in Trial 3 (initial moisture content of 44.95 %) and lowest maximum temperature obtained in Trial 1 (initial moisture content of 69.29 %). The bio-drying index indicated that Trial 2 had higher water removal efficiency (72.96 %) with less organics consumption (bio-drying index = 10.1). On the whole, Trial 1, 2 and 3 saw a weight reduction of 54.63 %, 42.56 % and 35.33 % alongside a moisture reduction of 53.26 %, 47.46 % and 64.51 % respectively. This finding suggests that the use of bulking agent has significant effect on the initial moisture content with subsequent impact on bio-drying efficiency which could provide some promising approach to pre-treat organic waste to reduce the moisture content, weight and volume and increase the energy value for solid recovered fuel generation (SRF).

Keywords: bulking agent; bio-drying index; moisture content; water removal efficiency; volatile solid degradation

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1. Introduction

One of the main environmental problems in both developed and developing countries is the vast increase in the quantity of municipal solid waste (MSW) generation due to accelerated urbanization [1]. In an effort to deal with problems of MSW management, a number of technologies such as combustion, incineration, landfilling, pyrolysis and gasification has been researched and developed [2]. However, environmental restrictions/regulations have made the application of some of these technologies increasingly difficult. Thus, research focus over the last 20 years has been drifted toward biological treatment of waste. This approach has become an increasing waste management, as a pre-treatment before landfilling/combustion, option particularly in Europe due to the introduction of the European Union (EU) Landfill Directive (LFD) (99/31/EC) which requires a phased reduction in the amount of biodegradable waste (BW) disposed of to landfill because of its potential to produce landfill gas and leachate [3, 4]. Consequently, emphasis in BW management has shifted from its disposal to the beneficial use of it and its products. One such usage is its conversion to solid recovered fuel (SRF) subsequent to combustion [5]. However, the high moisture content of food waste (FW) reduces its efficiency for energy recovery. As a result, bio-drying as an alternative pre-treatment of waste has been developed in recent years [6–8]. Biological drying (bio-drying), aims at removing water from biowaste by taking advantage of the heat generated from microbial degradation in aid of forced aeration [9, 10]. Even though the concept of bio-drying is similar to composting, the technology tends to pre-treat waste at the lowest possible residence time (7–15 days) to produce a high quality bio-dried material [10, 11]. Whereas composting tends to mineralize substrate with high consumption of volatile solids, bio-drying reduce biodegradation in order to preserve the gross calorific value of the waste matrix. Much of the research on bio-drying has focused on the application of this technology for pre-treating garbage residues and sewage sludge [12, 13] and pulp and paper [14, 15] and MSW [16, 17]. It is obvious bio-drying of FW has not received much attention by researchers due to its high moisture content (MC) and low biomass porosity.

The initial MC is paramount in bio-drying process because it influences the biochemical reactions associated with microbial growth and the biodegradation of organic matter during the process [18]. Bio-drying of FW alone results in high generation of leachate which defeats the purpose of bio-drying as a zero leachate generation technology [17, 19]. To achieve efficient bio-drying, it is imperative to ensure high porosity within the waste matrix during bio-drying i.e. reduction in the initial MC of the substrate. A number of researchers have also used bulking agent (BA) to adjust the initial MC and free air space (FAS) of waste which provides structural support and high porosity as well as allowing easier transport of oxygen through the waste matrix [20, 21]. The objective of this study was to bio-dry FW of high MC in combination with different municipal solid waste including paper and plastic. Additionally, BA was utilized in the bio-drying process with the aim of evaluating the effect of BA on the initial MC of the waste matrix as well as bio-drying efficiency.

2. Materials and methods

2.1. Preparation of materials

In the present study, FW (Lactuca sativa) collected from a canteen of University of Kocaeli was the main waste component to be bio-dried, however, due to its high MC; and the high contribution of paper and plastic as component of MSW, these were added in different proportions to initially reduce the moisture component of the FW subsequent to bio-drying. Additionally, pruning waste as BA was added to evaluate its effects on bio-drying process. The raw materials were shredded, FW (15 x 35mm), paper (2 x 14 mm), plastic (5 x 10 mm) and BA of 15mm in diameter. The characteristics of the raw materials are presented in Table 1.

Table 1. Characteristics of the raw materials.

Parameter	Food waste	Paper	Plastic	BA
Moisture content	91.48 ± 0.58	5.40 ± 0.16	0.94 ± 0.05	8.43 ± 0.33
Volatile solids, %	98.51 ± 0.22	78.94 ± 0.20	99.57 ± 0.25	90.62 ± 0.38
Bulk density, kg/m^3	464.18 ± 5.36	100.46 ± 1.01	346.50 ± 3.77	204.14 ± 2.02
Water holding capacity, %	-	43.04	35.77	68.19

2.2. Process operation

Three different trials were set up with different proportions of the raw materials by weight in the bio-drying experiment. The proportion by weight of different component of the waste consisted 75 % FW, 10 % paper, 15 % plastic in Trial 1. In the case of Trial 2, the waste component consisted 64 % FW, 21 % paper, 8 % plastic and 8 % BA. In the third trial, the same materials were used consisting of 38 % FW, 21 % paper, 26 % plastic and 15 % BA. For Trial 1, the reactor was filled with 20 kg of the mixed substrate without BA whereas that of the second and third trials were 39 kg and 32 kg based on the weight proportion of the waste which was thoroughly mixed.

2.3. Experimental equipment and process operation

The bio-drying experiments were performed in an adiabatic reactor of 0.8 m^3 made from a stainless steel with a leachate collection system at the bottom (Fig. 1). The bio-drying reactor consisted of four structural components: a perforated bottom chamber for maintaining uniform supply of air and equipped with a leachate collection port; a middle supporting plate made from a stainless steel sheet perforated with about 8000 holes of 0.5 cm in diameter; an air tight pipe 2 cm in diameter connected to the top side of the reactor for exit air; and a perforated box containing silica gel use to dehumidified the inlet air prior to entering the reactor. A constant and uninterrupted air-flow rate (15 m^3 h^{-1}) was used in all the trials using a whirlpool pump connected to the bottom of the column while an air-flow meter was used to measure the air flow rate. The matrix temperature was monitored with a thermometer sensor inserted in the reactor (5 cm above the bottom of the perforated plate). The weight loss of the matrix was monitored by an electronic balance every 12 hours for 7 days.

2.4. Analytical methods

The MC of the substrate was analyzed following the ASTM–D 3173 standard (105 °C) using moisture analyzer (Precisa, XM 50). It is worth mentioning that, due to the heterogeneous nature of the waste, the weighted average method was employed in determining the initial MC of the mixed waste, since it was impossible to get a typical sample from the heterogonous mixture of the waste, a similar procedure employed by Shuqing et al. [19]. The initial MC of the commingled substrate in the present study was calculated as 69.29 %, 60.43 % and 44.95 % for Trial 1, 2 and 3 respectively. Volatile solids (VS) content was analyzed by heating the sample at 600 °C for 5 h in a muffle furnace. Bulk density defined as the weight per unit volume of material was measured according to ASTM D1895–96 [22]. The water absorption capacity (WAC), also known as water holding capacity (WHC) of the waste sample was determined using a method described by Adhikari et al. [22] and Malinska and Zabochnicka-Swiatek [23].

3. Results and discussion

3.1. Temperature evolution in the waste matrix

The temperature profile of the matrix during the bio-drying is presented in Fig. 2(a). To indicate the temperature differences among the trials, an index, 'temperature integration (TI)', defined as the accumulation of gaps between the matrix and environmental temperatures was employed based on the following equation:

$$TI = \sum_{i=1}^{n} (t_{wi} - t_{ei}) * \Delta t \quad (1)$$

where t_{wi} and t_{ei} is the matrix temperature and ambient temperature at time i respectively; Δt is the time element (12 h) [7]. Fig. 2(b) presents the TI profile during the bio-drying process.

The temperature of the three trials increased rapidly within the first 12 hour period to a maximum of 37 °C, 38 °C and 39 °C in Trial 1, 2 and 3 respectively, indicating a high microbial activity, degradation of organic materials and the concomitant release of metabolic heat in the first 12 hours (Fig. 2(a)) [10]. The rising trend of temperature for Trial 2 and 3, after attaining maximum temperature, was maintained at high level for 24 hours without a valley of low temperature. On the contrary, delay in achieving maximum temperature for Trial 1, which was obtained after 60 hours of bio-drying was probably due to the high MC of the substrate impeding rapid microbial activity. Overall, Trial 2 and 3 conducted with the addition of pruning waste as BA produced the highest temperature, almost 10 °C higher than the ambient temperature, while Trial 1 produced the lowest temperature. These results suggested that the addition of pruning waste as bulking agent had significant impact on the bio-drying process, as reflected by the high temperature in Trial 2 and 3. This is similar to that reported by Tom et al. [17].

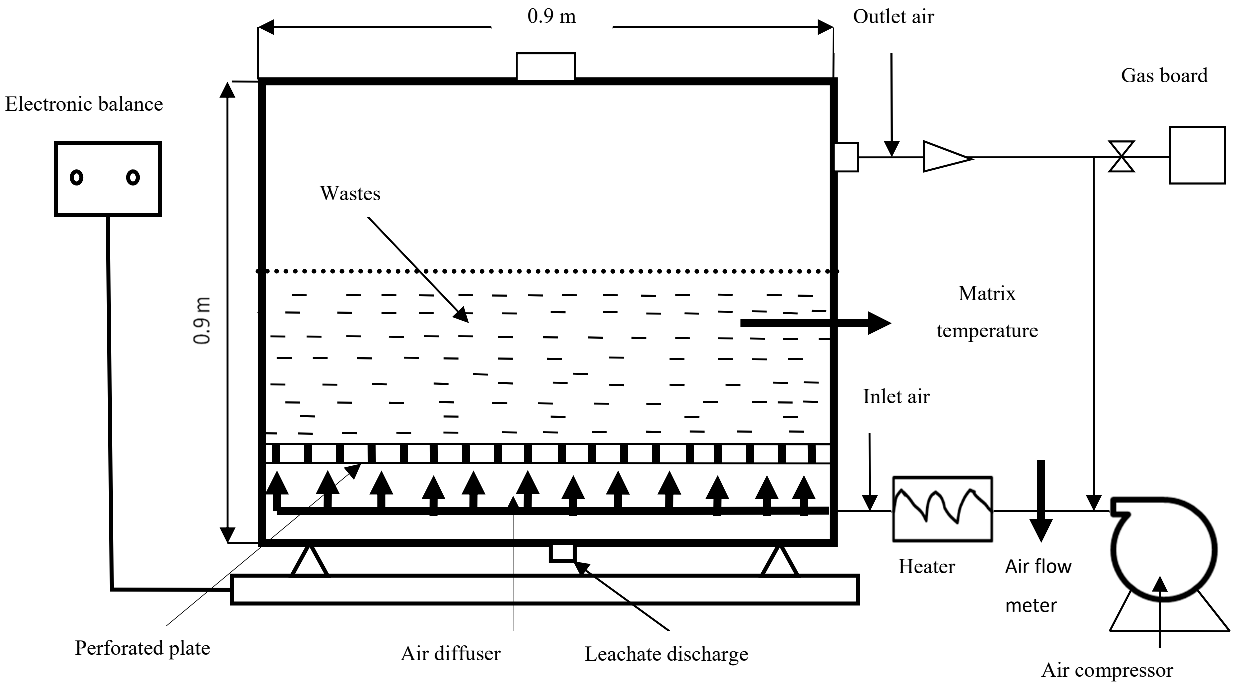
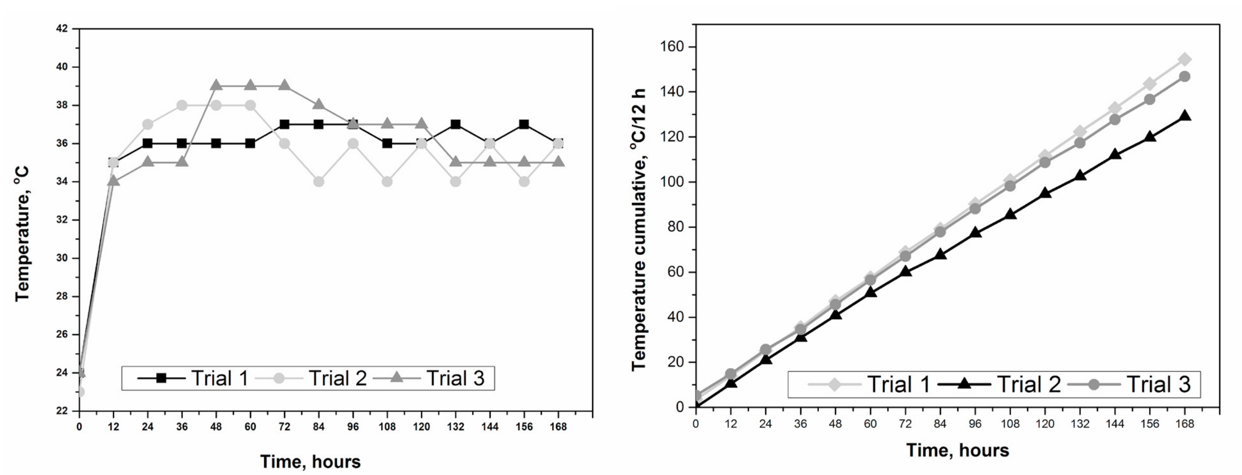


Fig. 1. Schematic diagram of the bio-reactor for bio-drying.



(a) (b)

Fig. 2. (a) Temperature evolution at the centre of the matrix during bio-drying; (b) temperature integration (TI) for the three trials.

The TI in this study followed the sequence of Trial 1 > Trial 3 > Trial 2 (Fig. 2(b)), indicating that the absence of BA in Trial 1 led to higher TI, since TI was related to the heat generated by aerobic degradation. Compared with Trial 3, Trial 1 had lower TI values in the first 24 hours and then higher values from 36th hour on, while Trial 2 had the lowest values during the entire experiment. The total TI was larger in trial without BA (Trial 1) than trials with BA by 16.5 % (Trial 2) and 4.9 % (Trial 3). This suggests that the high proportion of FW in the waste matrix contributed to higher heat generation in the matrix.

3.2. Effect of initial MC on bio-drying

The initial MC of the FW was reduced by 24.26, 33.94 and 50.86 % for Trial 1, 2 and 3 respectively, based on the weighted average MC of each additional material before bio-drying [24]. This suggests that the amount of BA had a significant impact on the initial MC as seen in Trial 2 and 3. After the bio-drying process, the MC decreased in all the trials, but in varying degrees. Maximum reduction occurred in Trial 3 with MC decreasing from 44.95 % to 20.31 %, while the lowest reduction occurred in Trial 2 with a reduction of 48.65 % (60.43 % to 31.03 %). Therefore, low initial MC can results in higher MC reduction. Correspondingly, the water removal ratios of the trials followed the sequential order of Trial 1 > Trial 3 > Trial 2. This suggests that the high proportion of FW in the waste matrix improved the water removal rate. This corroborates the findings of Ma et al. [24], who worked on co-bio-drying of dewatered sewage sludge and FW; and concluded that water removal rate was enhanced upon the addition of FW. The moisture level in Trial 2 was suitable for microbial activity ensuring good porosity of the matrix for air transport through the matrix and vapour removal as well minimum VS degradation. Consequently, waste matrix of initial MC 60.43 % in this experiment presented the highest efficiency for organic utilization of FW bio-drying with less proportion of BA. In summary, optimum MC for bio-drying represented a trade-off between the moisture requirements of the microbes and their simultaneous need for adequate oxygen transport through the matrix. The high initial MC in Trial 1 limited oxygen transport impeding microbial activity for enhanced bio-drying. Additionally, the lack of MC in Trial 3 (initial MC of 44.95 %) slowed microbial activity, which results reduced bio-drying performance. In effect, by balancing the above criteria (the amount of FW and bulking agent), the initial MC of 60.43 % was thought to be the best among the examined conditions.

In order to investigate the effect of BA on the porosity of the waste matrix, the free air space (FAS), also known as air filled porosity (AFP) was employed. The FAS is important in determining the quantity and movement of air through the waste matrix. This parameter depends on the structural properties of the waste matrix, such as its bulk density as well as its water content. The FAS was calculated by Eq. (2) [21, 25, 26]:

$$FAS(\%) = 1 - BD\left[\left(\frac{1-TS}{\rho_w}\right) + \left(\frac{TS \times VS}{\rho_{vs}}\right) + TS\left(\frac{1-VS}{\rho_{ash}}\right)\right] \quad (2)$$

where BD is the bulk density on a wet basis (kg m^{-3}); , ρ_w, ρ_{vs} and ρ_{ash} are the density of water, volatile fraction and inorganic fraction (ash), respectively. ρ_{vs} and ρ_{ash} were assumed to be 2.5 x 103 and 1.6 x 103 kg m^{-3}, respectively [25, 27]. Generally, the amount of FAS decreases with increasing MC and BD. On the contrary, organics degradation decreases the FAS due to the collapse of the waste matrix. The initial FAS of Trial 1, 2 and 3 were 70.68, 54.52 and 74.12 %, respectively. At the end of the bio-drying process, the FAS increased by 25.15, 22.53 and 5.85 % respectively. The increase in FAS in all the trials can be explained by the fact that the influence of water removal was larger than that of VS degradation; water removal rate was highest in Trial 1 and 3 compared to Trial 2 with least biodegradation occurring in Trial 2.

3.3. Weight and volume

Weight reduction is a significant parameter affecting solid waste handling and transportation as well as storage. The weight and volume loss during bio-drying is presented in Fig. 3. Final weight loss rates after 7 days of bio-drying were 54.63 %, 42.56 % and 35.33 %, with an average weight reduction of 1.68 kg, 2.37 kg and 1.51 kg per day for Trial 1, 2 and 3 respectively. On the contrary, the final volume loss rates were 62.50 %, 39.02 % and 47.72 % respectively. The highest weight and volume loss was in Trial 1 with highest daily average weight reduction in Trial 2.

This finding suggests that the VS consumption of Trial 1 was more easily degraded, resulting in enhanced volume loss of materials as compared to Trial 2. Theoretically, plastic did not take part in the reaction and thus the mass of plastic did not obviously change. Additionally, the lowest volume and weight reduction in waste matrix with BA was possibly attributed to the non-biodegradability of the BA, maintaining the same structure after the bio-drying process. Neglecting the MC, weight and VS reduction in Trial 1 (without BA); weight loss is directly proportion to VS degradation in Trial 2 and 3, which agrees with some results in literature.

With regards to bulk density, the final bulk density of bio-dried material impacts on the energy density of the product intended for energy generation. The BD is closely related with the MC i.e., as moisture content increases, BD increases. In this study, the bulk density of the initial waste matrix was in the order of Trial 2 > Trial 1 > Trial 3; decreasing by 60.62, 27.01 and 16.76 % for Trial 1, 2 and 3 respectively. The proportion of the different waste in the waste matrix had a significant impact on the variation of BD as the BD of Trial 2 (initial MC of 60.43 %) was higher than that of Trial 1 (initial MC of 69.29 %). The amount of food waste in Trial 2 (25 kg) was higher than that of Trial 1 by 10 kg, even though in percentage wise, the proportion of food waste in Trial 1 was 11 % more than Trial 2 in the total waste mix. Although the finding in this study contradicts the concept that BD increases when MC increases [22], it must be noted that the MC in this study was calculated based weighted average.

Additionally, in practical sense, a decrease in weight of a material corresponds to a decrease in density; as density is proportional to the mass of a material. This was corroborated in this study as the weight loss followed a sequential order of Trial 1 > Trial 2 > Trial 3. It must be noted that the weight of the FW had no significant impact on the weight of the waste matrix after bio-drying as the weight seems almost weightless, with the plastic and BA maintaining the same structure and weight. However, the paper absorbs the leachate and stick with each other and with the waste, thereby increasing in slight weight after bio-drying. This finding showed a very promising development towards fulfilling the objective of weight and volume reduction with regards to waste management.

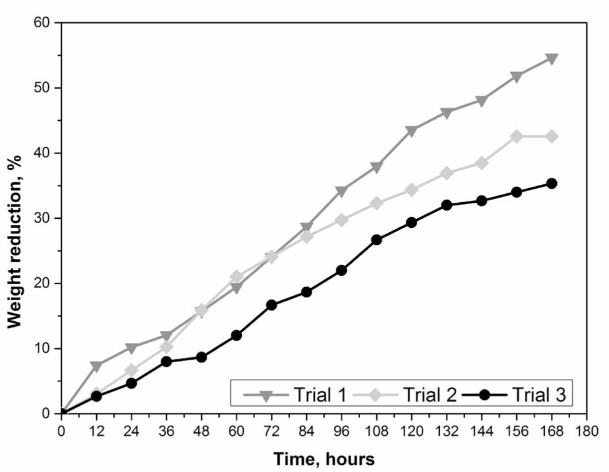


Fig. 3. Weight loss rate during bio-drying.

3.4. Bio-drying performance

To indicate the effect of each material used on bio-drying performance, the water absorption capacity (WAC) and removal rate of the materials were investigated. As indicated in Fig. 4, the BA showed the highest WAC among the three materials with plastic as the lowest, and the WACs of BA, paper and plastic were 68.2 %, 43.0 % and 35.8 % respectively. However, with regards to water loss rate, the plastic was fast dried to constant weight in less than 40 min with less water absorbed as compared to the BA, indicating a better drying efficiency. The water loss rate of paper was the slowest, which was disadvantageous for bio-drying process.

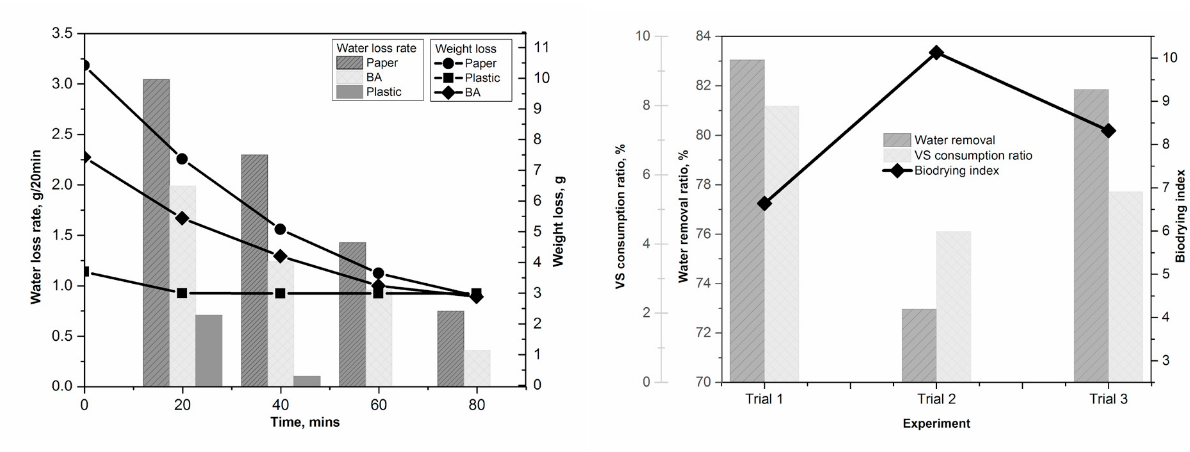
To quantitatively evaluate bio-drying performance of each trial, the bio-drying index (BI) (Eq. (3)), which is defined as the ratio of water removal to VS consumption, was applied [7].

$$BI_t = \frac{WL_t}{OL_t} \tag{3}$$

where BI_t is bio-drying index at time t; WL_t is the water loss rate at time t (g); and OL_t is the VS loss at time t (g). Fig. 5 shows the BI for all the trials. A high BI indicates more water removal with less organics consumed (i.e., less VS consumption) and more energy retained in the final product which is beneficial for utilization as energy source. The VS consumption found in this study were 7.99, 4.36 and 5.51 % in Trial 1, 2 and 3 respectively, which were lower than the values of 12 % and 21 % of initial VS reported by Yang et al. [13]. Villegas and Huilinir [28], working with bio-drying of sewage sludge concluded that the VS consumption depends on initial MC. This is contrary to the findings in this study, where Trial 2 obtained the lowest VS degradation at initial MC of 60.43 % compared to Trial 3 (initial MC of 44.95 %). Notwithstanding the fact that the water removal of Trial 1 (bio-drying without BA) was the highest, the BI was the least (6.64), suggesting that the utilization efficiency of degraded organics was low. Trial 2 and 3 presented a higher BI, suggesting that more water was removed with less organics consumed as well as more energy retained in the bio-dried material. As shown in Fig. 4, Trial 2 (BI = 10.13) presented the highest utilization efficiency of degradable organics for water removal. The BI values obtained in this study are in accord with those reported in literature. However, it must be emphasized that, the type and composition of waste matrix as well as operating parameters used during bio-drying can have a significant influence on the process efficiency.

4. Conclusions

The study demonstrated the potential of bio-drying as a waste management strategy for high moisture FW and its subsequent utilization as an energy source (SRF). Even though the biomass energy of FW available for heat generation is not very high, FW bio-drying with BA can be considered as an effective moisture, volume and weight reduction process. The results found major differences between the effect of the proportion of BA and the other waste in the waste matrix in terms of moisture, VS, weight and volume reduction. Within the range of different proportions of waste matrix studied, low proportion of BA in the waste matrix produced higher bio-drying performance (Trial 2; 64 % food waste, 21 % paper, 8 % plastic and 8 % BA and initial moisture content of 60.43 %), lower matrix temperature and lower VS reduction. Thus, the results demonstrated that bio-drying approach can be used as a pre-treatment for organic waste by rendering the bio-product more suitable for energy utilization in combustion process as well as partially stabilizing the product for storage without emission of odour.



(a) (b)

Fig. 4. (a) Water absorption capacity and weight loss curves of paper, plastic and BA; (b) bio-drying index for the three trials.

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References

[1] Tacoli C. Urbanization, Gender and Urban Poverty: Paid Work and Unpaid Carework in the City. London: International Institute for Environment and Development; 2012.
[2] Marshall R, Farahbakhsh K. Systems approaches to integrated solid waste management in developing countries. Waste Management 2013;33(4):988–1003.
[3] European Commission. Council Directive, 1999/317 EC of 26 April 1999 on the landfill of waste. Official Journal of the European Communities, 1999;L 182 16/07/1999.
[4] Beloborodko A, Romagnoli F, Rosa M, Disanto C, Salimbeni R, Karlsen EN, Reime M, Schwab T, Mortensen J, Ibarra M, Blumberga D. SWOT analysis approach for advancement of waste-to-energy cluster in Latvia. Energy Procedia 2015;72:163–169.
[5] Dace A. Characteristics of mechanically sorted municipal wastes and their suitability for production of refuse derived fuel. Environmental and Climate Technologies 2012:8:18-23.
[6] Adani F, Baido D, Calaterra E, Genevini P. The influence of biomass temperature on biostabilization – biodrying of municipal solid waste. Bioresource Technol. 2002;83:173–179.
[7] Zhang DQ, He PJ, Jin TF, Shao LM. Bio-drying of municipal solid waste with high water content by aeration procedures regulation and inoculation. Bioresour. Technol. 2008;99:8796–8802.
[8] Bezama A, Aguayo P, Konrad O, Navia R, Lorber KE. Investigations on mechanical biological treatment of waste in South America: Towards more sustainable MSW management strategies. Waste Manage. 2007;27(2):228–237.
[9] Zhang DQ, He PJ, Yu LZ, Shao LM. Effect of inoculation time on the bio-drying performance of combined hydrolytic-aerobic process. Bioresour. Technol. 2009;100:1087–1093.
[10] Velis CA, Longhurst PJ, Drew GH, Smith R, Pollard STJ. Biodrying for mechanical-biological treatment of wastes: A review of process science and engineering. Bioresource Technology 2009;100(11):2747–2761.
[11] Choi HL, Richard TL, Ahn HK. Composting high moisture materials: Biodrying poultry manure in a sequentially fed reactor. Compost Science and Utilization 2001;9(4):303–311.
[12] Hansjoerg H, Boeddeker HJ, Gurudas S, Schaefer K, Roth B, Roth J. Process and apparatus for biological drying of residual waste, sewage sludge and/or biomass. European Patent EP1408021. 14-04-2004, European Patent Office, 2004.
[13] Yang B, Zhang L, Jahng D. Importance of initial moisture content and bulking agent for biodrying sewage sludge. Drying Technology 2014;32:135–144.
[14] Frei KM, Cameron D, Jasmin S, Stuart PR. Novel sludge drying process for cost effective on-site sludge management. Pulp Pap. Canada 2006;107:47–53.
[15] Navaee-Ardeh S, Bertrand F, Stuart PR. Emerging biodrying technology for the drying of pulp and paper mixed sludges. Drying Technol. 2006;24:863–878.
[16] Tambone F, Scaglia B, Scotti S, Adani F. Effects of biodrying process on municipal solid waste properties. Bioresource Technology 2011;102(16):7443–7450.
[17] Tom AP, Pawels R, Haridas A. Biodrying process: A sustainable technology for treatment of municipal solid waste with high moisture content. Waste Management 2016;49:64–72.
[18] Ryckeboer J, Mergaert K, Vaes S, Klammer D, De Clercq J, Coosemans H, Insam J, Swings. A survey of bacteria and fungi occurring during composting and self-heating processes. Ann. Microbiol. 2003;53:349–410.
[19] Shuqing Z, Wenxiong H, Ran Y, Song Y. The effect of bio-drying on heating values of municipal solid waste. Advance Materials Research 2014;1010–1012:537–546.
[20] Zhou HB, Ma C, Gao D, Chen TB, Zheng GD, Chen J, Pan TH. Application of a recyclable plastic bulking agent for sewage sludge composting. Bioresour. Technol. 2014;152:329–336.
[21] Iqbal MK, Shafiq T, Ahmed K. Characterization of bulking agents and its effects on physical properties of compost. Bioresour Technol. 2010;101:1913–1919.
[22] Adhikari BK, Barrington S, Martinez J, King S. Characterization of food waste and bulking agents for composting. Waste Manag. 2008;28:795–804.
[23] Malinska K, Zabochnicka-Swiatek M. Selection of bulking agents for composting of sewage sludge. Environment Protection 2013;39:91–102.
[24] Ma J, Zhang L, Li A. Energy-efficient co-biodrying of dewatered sludge and food waste: Synergistic enhancement and variables investigation. Waste Management 2016;56:411–422.
[25] Zhao L, Gu WM, He PJ, Shao LM. Biodegradation potential of bulking agents used in sludge bio-drying and their contribution to bio-generated heat. Water Res. 2011;45(6):2322–2330.
[26] Soares MAR, Quina MJ, Quinta-Ferreira R. Prediction of free air space in initial composting mixtures by a statistical design approach. Journal of Environmental Management 2013;128:75–82.
[27] Ruggieri L, Gea T, Artola A, Sanchez A. Air filled porosity measurements by air pycnometry in the composting process: a review and a correlation analysis. Bioresour. Technol. 2009;100:2655–2666.
[28] Villegas M, Huilinir C. Biodrying of sewage sludge: Kinetics of volatile solids degradation under different initial moisture contents and air-flow rates. Bioresource Technology 2014;174:33–41.