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Biodrying of municipal solid waste with high water content by combined hydrolytic-aerobic technology

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Abstract

The high water content of municipal solid waste (MSW) will reduce the efficiency of mechanical sorting, consequently unfavorable for beneficial utilization. In this study, a combined hydrolytic-aerobic biodrying technology was introduced to remove water from MSW. The total water removals were proved to depend on the ventilation frequency and the temporal span in the hydrolytic stage. The ventilation frequency of 6 times/d was preferable in the hydrolytic stage. The hydrolytic span should not be prolonged more than 4 d. At this optimal scenario, the final water content was 50.5% reduced from the initial water content of 72.0%, presenting a high water removal efficiency up to 78.5%. A positive correlation was observed between the organics losses and the water losses in both hydrolytic and aerobic stages ($R = 0.944$, $p < 0.01$). The evolutions of extracellular enzyme activities were shown to be consistent with the organics losses.

Key words: biodrying; high water content; hydrolysis; aeration; municipal solid waste; extracellular enzyme

Introduction

The acceleration of urbanization has led to an increasing generation of municipal solid waste (MSW) in many developing countries. The MSW, in most of these countries, e.g., China, is comprised of a relatively high proportion of food waste (> 60%) and also an increasing proportion of recyclable materials, such as wasted plastics, paper, glasses, and metals (He, 2002). As to the latter, they can be utilized as resources after mechanical or manual sorting. Unfortunately, mainly due to food waste, the water content of MSW is very high up to 74.5% (He *et al*., 2005). This is severely unfavorable for mechanical sorting since the mixed materials in MSW may adhere together and leachate will be generated during this process. In this case, a biodrying process, removing water by the activities of microbes, is regarded as a good solution to reduce water content of wet organic wastes (Choi *et al*., 2001).

Currently, most studies of biodrying process focus on the aerobic technology, which removes water mainly as vapor by high temperatures and adequate ventilation. Adani *et al*. (2002) and Sugni *et al*. (2005) indicated that the appropriate control of aeration operational parameters (e.g., air-flow rate and direction) and temperatures can achieve a high biodrying efficiency (66.7% of initial water eliminated). However, the principle of the aerobic biodrying technology is to drive evaporation energized by organic matter degradation. When the ratio of water content to biodegradable organics is excessively high, the heat derived from the biodegradation is not enough to make water evaporate. On the other hand, for the putrescible wastes with high water content, more amount of water is constrained by cell wall or membrane and can be released only when the wall or membrane was destructed. In this context, prior to the aerobic biodrying stage, a hydrolytic stage may be supplemented to destruct the cell wall or membrane with a less organics consumption. In this way, more water can be released with certain organics consumed since fewer organics will be lost as CO_2 by hydrolysis than aerobic degradation. Moreover, microaeration in the hydrolytic stage is possible to enhance the partial disintegration and hydrolysis of macromolecular organic compounds (Nguyen *et al*., 2007). Bezama *et al*. (2007) proposed a combined hydrolytic-aerobic process to obtain stabilized materials. In his study, 42% of total leachate is generated during the first hydrolytic stage. The study implies that the water in MSW can be removed by the combined hydrolytic-aerobic process; however, it is targeted at improving waste stability but not at reducing water content. Therefore, the optimal operational parameters in the hydrolytic stage are still unknown for the combined process.

This study investigated the biodrying performance of the scenarios with the same operations during the aerobic stage but with various ventilation frequencies or temporal spans during the hydrolytic stage, so as to optimize the operational parameters of the process. The evolution of

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the extracellular enzyme activities was also monitored to explain biodrying performance from the points of enzymolysis.

1 Materials and methods

1.1 Characteristics of waste feedstock

The MSW feedstock was sampled from a residential area in Shanghai, China. It comprised of 60% (*W/W*, in wet weight) kitchen waste, 23% (*W/W*) paper, 11% (*W/W*) plastics, and 6% (*W/W*) others. The initial water content was 72%. The biochemical compositions of the sampled wastes with plastics removed were 0.42 ± 0.028 g/g TS of amylums, 0.12 ± 0.013 g/g TS of proteins, 0.12 ± 0.009 g/g TS of lipids, 0.15 ± 0.009 g/g TS of celluloses, 0.01 ± 0.001 g/g TS of hemicelluloses, 0.05 ± 0.007 g/g TS of lignoses, and 0.13 ± 0.008 g/g TS of ash.

1.2 Experimental equipment

The trials were performed in the laboratory column reactors, as shown in Fig.1. Made of PVC plastics, each column was 1,200 mm in height and 400 mm in internal diameter. The outer wall of the column was enwrapped with the 100-mm-thick hollow cotton for the thermal insulation. A 100-mm high layer, filled with crockery balls (diameter about 5 mm), was placed at the bottom of each column for the leachate drainage and air distribution. Above the balls, there existed a perforated baffle (2-mm mesh) to support the wastes and to facilitate the aeration. Five sampling ports were set above the baffle at equal intervals of 200 mm. Two layers, straw and cotton, respectively, were covered above the wastes to avoid heat loss and vapor condensation. A whirlpool pump (XGB-8, Penghu Co., Shanghai, China) and a gas-flow meter (LZB-10, Shanghai Instrument Co., Shanghai, China) were used for aeration.

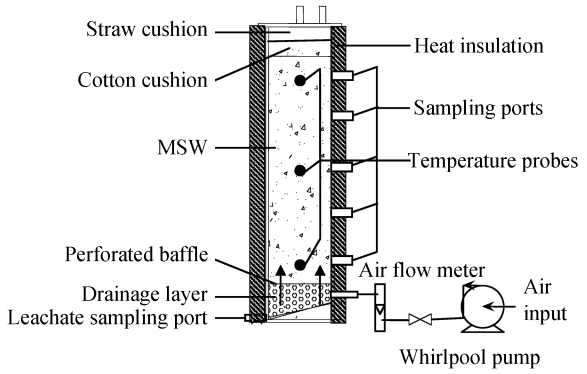

Fig. 1 Schematic representation of the reactor columns in biodrying trials.

1.3 Experimental setup and operation

Five columns were set-up in biodrying experiments and each was filled with 32 kg of the above-mentioned raw MSW at a density of approximately 212 kg/m^3 after remixing adequately. The whole biodrying process lasted for 16 d and was separated into two stages, i.e., the hydrolytic and the aerobic stages. The air-flow rate was fixed at 0.45 m^3 per kg wet wastes per m^2 cross-section area of the reactor per hour (i.e., 0.45 m^3/(kg·m^2·h)) during entire experiment. However, the ventilation frequencies and temporal spans in the hydrolytic stage varied for the different columns. Columns 1, 2, and 3 had the same hydrolytic span of 4 d, where the ventilation frequencies were kept at 2, 6, and 10 times/d of an equal interval within 24 h, separately. Columns 4 and 5 had the hydrolytic span of 6 d and their ventilation frequencies remained at 6 and 10 times/d of an equal interval. Since the operational conditions of the hydrolytic stage were the first concerns in this study, the same operations were taken during the aerobic stage, i.e., the ventilation frequencies of all columns were enhanced to 48 times/d and the fed wastes were turned manually every 2 d.

The detailed operation conditions of five columns are shown in Table 1. For convenience of expression, these columns were named as 2 times/d × 4 d scenario, 6 times/d × 4 d scenario, 10 times/d × 4 d scenario, 6 times/d × 6 d scenario, and 10 times/d × 6 d scenario, respectively, denoting the ventilation frequencies and the temporal spans in the hydrolytic stage.

1.4 Monitoring methods

1.4.1 Experimental monitoring

The processes were monitored everyday for temperature, oxygen (O_2) concentration, and leachate quantity. The temperature was monitored by a thermometer (WMY-01C, Huachen Co., Shanghai, China) with the sensor probes

Table 1 Operation conditions of biodrying trials

Condition	Column 1 (2 times/d × 4 d)	Column 2(6 times/d × 4 d)	Column 3 (10 times/d × 4 d)	Column 4 (6 times/d × 6 d)	Column 5 (10 times/d × 6 d)
Weight (kg)	32	32	32	32	32
Density (kg/m^3)	212	212	212	212	212
Ventilation flow rate* (m^3/(kg·m^2·h))	0.45	0.45	0.45	0.45	0.45
Time in hydrolytic stage (d)	4	4	4	6	6
Ventilation frequency in hydrolytic stage (times/d)	2	6	10	6	10
Ventilation time in hydrolytic stage (min/times)	10	10	10	10	10
Ventilation frequency in aerobic stage (times/d)	48	48	48	48	48
Ventilation time in aerobic stage (min/times)	7	7	7	7	7
Turning frequency in aerobic stage	1 times/2 d	1 times/2 d	1 times/2 d	1 times/2 d	1 times/2 d

* Supplied air quantity (m^3) per kg wet waste per m^2 cross section area of the reactor per hour.

located at the top, middle, and bottom points along the longitudinal axis of the columns as indicated in Fig.1, and the average value was reported. A probe of the O_2 concentration (CYS-1, Xuelian Co., Shanghai, China) was set at the central point along the longitudinal section of the waste body to measure the O_2 concentration. The leachate produced from the column was collected and weighed.

1.4.2 Sampling and analytical methods

During biodrying, the samples of about 300 g fresh wastes were collected from three different depths of each column and then mixed every 2 d. All the samples were reduced into size $\Phi < 2$ mm before analysis. The analysis was carried out in triplicate for each sample. The sampled wastes were determined for water content, volatile solid (VS), and biochemical compositions, as well as extracellular enzyme activities (including amylase, lipase, protease, FPase, i.e., filter paper cellulase, and CMCase i.e., carboxymethyl cellulase).

Physico-chemical analysis

The total organic carbon (TOC) content of the collected leachate was measured using a TC/TN analyzer (multi N/C 3000, Analytikjena, Germany). The water content of the wastes was determined at 70°C for 48 h. VS was analyzed under 550°C to a constant weight. The element carbon was measured by an elemental analyzer (CHNS-900, Leco, USA). The determination of celluloses, hemicelluloses, and lignocelluloses was based on the measurement of neutral detergent fiber, acid detergent fiber, and ash contents of the samples (Faithfull, 2002). For the measurement of amylums, the air-dried solid sample was first digested by the aether, ethanol, and boiled HCl solution (6 mol/L) in sequence, and then titrated with alkaline copper tartrate (Horwitz, 2005). The lipids concentration was determined gravimetrically after Soxlett extraction with petroleum ether (Nielsen, 2002). The protein content was determined based on Kjeldahl nitrogen (KN). The measured KN was multiplied by 6.25 to give the proteins content (APHA *et al*., 1998).

Assay of extracellular enzyme activities

For the determination of extracellular enzyme activities, 15 g of the fresh solid sample was immersed with 15 ml of 0.9% NaCl solution and centrifuged twice at 5,000 ×*g* for 30 min. The supernatant was collected. The pellet was immersed by suspension in 30 ml potassium dihydrogen phosphate buffer (pH 7.2, 0.1 mol/L) for 1 h and then was centrifuged at 5,000×*g* for 30 min to get the supernatant again. Both of the collected supernatants were mixed for the assay of enzyme activities.

The analyses of amylase, CMCase, and FPase activities were based on testing the generation rate of glucoses from enzymolysis under different incubation conditions. The amylase activity was measured using the modified method of Bernfeld (1955). The CMCase activity was determined according to Nakamura and Kitamura (1988). The FPase activity was measured grounded on Ghose (1987). The protease activity was measured according to Lowry *et al*. (1951). The lipase activity was determined based on GMC (1963).

2 Results

2.1 Evolution of temperatures and oxygen contents during biodrying

The temperature was the key parameter for water evaporation and organics degradation during biodrying. The evolution of daily average material and atmosphere temperatures during biodrying is shown in Fig.2. During the hydrolytic stage, the temperatures were higher for the trials with higher ventilation frequencies, i.e., the 10 times/d × 4 d scenario or 10 times/d × 6 d scenario. The temperatures in the aerobic stage were inversely proportional to the ventilation frequencies during the hydrolytic stage. Additionally, the prolonged hydrolytic spans might cause the temperature peaks of biodrying to appear late.

Figure 3 presents the evolution of daily average O_2 concentrations in the free space of columns during biodrying. During the hydrolytic stage, the O_2 concentrations remained at a low level (< 5%, *V/V*) since the air input was greatly lower than required for sufficient aerobic degradation in the hydrolytic stage. During the aerobic stage, the average O_2 concentrations consistently exceeded 10% (*V/V*), suggesting that the aerobic conditions were maintained in this stage. The average O_2 concentration could indicate the organics degradation rate by the aerobic microorganisms under the given ventilation frequency and

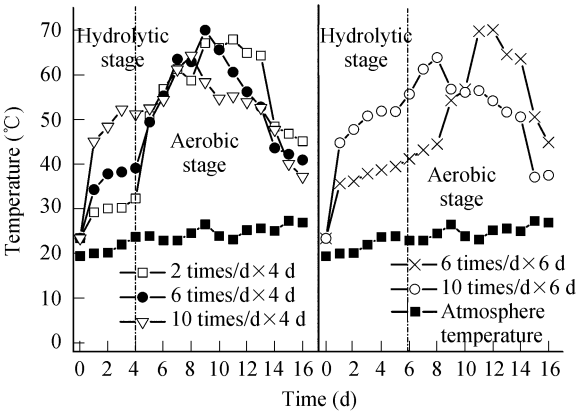

Fig. 2 Temporal evolution of daily average material and atmosphere temperatures during biodrying.

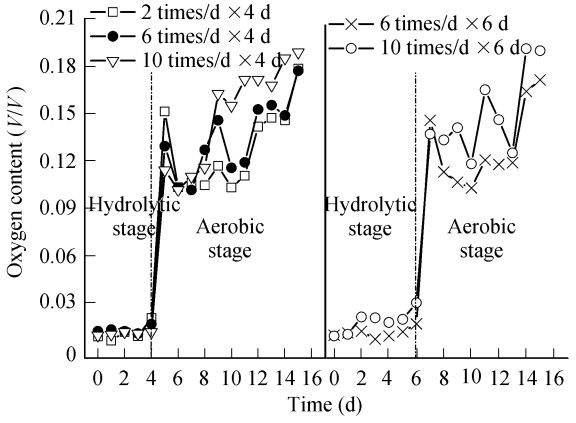

Fig. 3 Temporal evolution of daily average O_2 concentrations in the free space of columns during biodrying.

air-flow rate, to some extent. It was worth mentioning that the higher the ventilation frequencies during the hydrolytic stage were, the higher the O_2 concentrations during the subsequent aerobic stage were. In addition, higher O_2 concentrations might be achieved tardily with prolonged hydrolytic spans.

2.2 Material balance for the combined hydrolytic-aerobic biodrying processes

Material balance for the combined hydrolytic-aerobic biodrying processes is presented in Fig.4 and Table 2. The calculation is listed in the Appendix. During the hydrolytic stage (4 or 6 d), the water was removed mainly as leachate and the amounts of the water removal increased with enhanced ventilation frequencies or prolonged spans. This suggested that the release of the cell-contained water could be strengthened through the destruction of more cell walls or membranes, as indicated by more organics losses during the hydrolytic stage. However, when the ventilation frequencies were kept more than 6 times/d or the spans were kept more than 4 d, the increase of ventilation frequencies or spans were not able to cause the enhancement of leachate generation significantly. During the aerobic stage, the vapor was the main form of water losses energized by the organics degradation. Therefore, the vapor removals were correlated with the behavior of the previous hydrolysis, i.e., the amount of vapor was negatively related to ventilation frequencies or temporal spans during the hydrolytic stage. As a result, the scenario of 6 times/d × 4 d had the optimal performance of water removal and water content reduction. For this optimal scenario, 78.5% of the initial water was removed, wherein 54.7% was in the form of vapor and the other 23.8% was in the form of leachate. Furthermore, its final water content was 50.5% reduced from the initial water content of 72.0%. As a comparison, the final water contents of wastes for 2 times/d × 4 d, 10 times/d × 4 d, 6 times/d × 6 d, and 10 times/d × 6 d scenarios were 61.5%, 54.5%, 58.3%, and 62.4%, respectively.

During the hydrolytic stage, more organics were consumed for the scenarios with the enhanced ventilation frequencies or the prolonged spans. However, an opposite trend was observed during the aerobic stage owing to the substrate limitation. As a result, the total organics losses followed a decreasing sequence: 10 times/d × 6 d scenario > 6 times/d × 6 d scenario = 10 times/d × 4 d scenario > 6 times/d × 4 d scenario > 2 times/d × 4 d scenario. Obviously, the degradation rate corresponded to the temperature. Therefore, the temperature played an important role in improving organics degradation when concerning the wastes that mainly consisted of easily degradable components. Furthermore, the organics losses were mainly contributed by amylums (> 60%), followed by lipids (about 19%) and proteins (about 14%), whereas lignocelluloses, mostly consumed in the aerobic stage, contributed only a little to the organics losses (about 7%) (Fig.5).

After 16 d of operation, 64.0% (*W/W*, in wet basis) of the initial wastes for 2 times/d × 4 d scenario were reduced. The values for 6 times/d × 4 d, 10 times/d × 4 d, 6 times/d × 6 d, and 10 times/d × 6 d scenarios were 70.0%, 68.8%, 66.9%, and 69.2%, respectively.

2.3 Extracellular enzyme activities

Figure 6 indicates the temporal evolution of amylase, lipase, protease, FPase, and CMCase activities during biodrying. Both amylase and protease activities had a

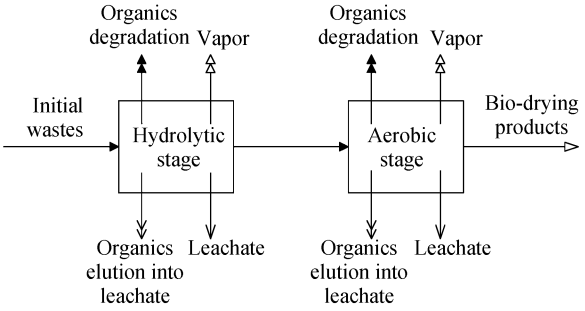

Fig. 4 Material balance for the combined hydrolytic-aerobic biodrying processes.

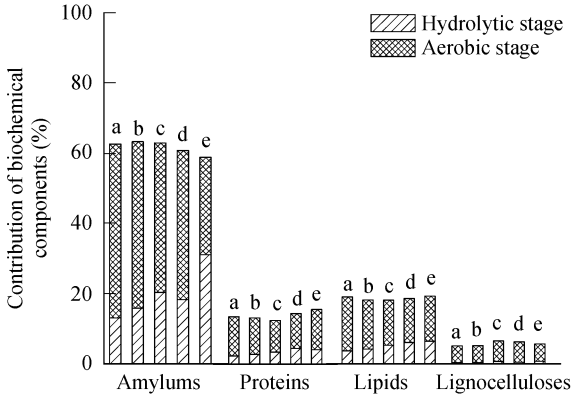

Fig. 5 Contribution of biochemical components degradation to total organics losses during biodrying.

Table 2 Material balance for the combined hydrolytic-aerobic biodrying processes

Scenario	Initial wastes (kg)	Hydrolytic stage				Aerobic stage				Products (kg)
		Organics degradation (kg)	Organics elution into leachate (kg)	Vapor (kg)	Leachate (kg)	Organics degradation (kg)	Organics elution into leachate (kg)	Vapor (kg)	Leachate (kg)	
2 times/d × 4 d	32.00	0.66	0.15	0.32	3.33	3.38	0.02	12.20	0.43	11.51
6 times/d × 4 d	32.00	0.80	0.20	0.67	5.33	3.30	0.02	11.84	0.25	9.59
10 times/d × 4 d	32.00	1.09	0.27	1.51	5.72	3.09	0.02	10.03	0.33	10.00
6 times/d × 6 d	32.00	1.06	0.23	0.84	5.81	3.11	0.02	9.79	0.48	10.66
10 times/d × 6 d	32.00	1.91	0.24	2.20	5.98	2.93	0.01	8.79	0.08	9.86

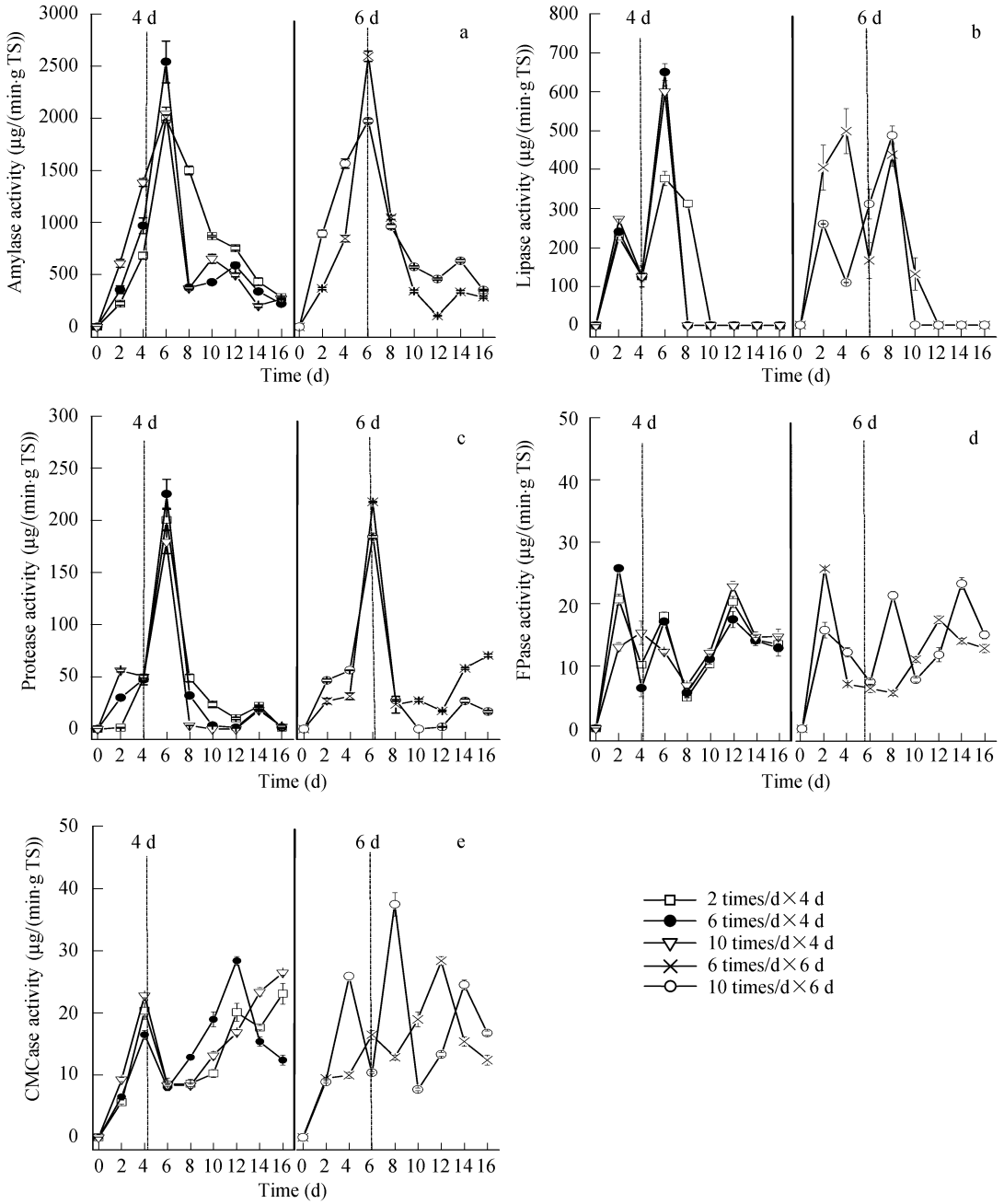

Fig. 6 Temporal evolution of amylase (a), lipase (b), protease (c), FPase (d), and CMCase (e) activities during biodrying.

positive correlation with the ventilation frequencies during the hydrolytic stage (Figs.6a and 6c). However, their activities in the aerobic stage were lower for the scenarios with higher ventilation frequencies during the hydrolytic stage due to the higher hydrolytic rate of amylums and proteins. The lipase activities showed two peak values on day 2 and from day 6 to 8 (Fig.6b) due to the shift of microorganism population caused by temperature transformation between hydrolytic and aerobic stages. And in the last 4 d, no lipase activities could be detected, which might be attributed to the complete degradation of lipids. The activities of both FPase and CMCase increased and then remained stable in the first 2 d (Figs.6d and 6e). However, their activities showed an obvious fluctuation during the shift from hydrolysis to aerobic degradation. It could be explained that the rapid increase of temperatures during the stage shift led to the replacement of dominant microorganisms and the resultant fluctuation of extracellular enzyme activities. Nevertheless, the lignocelluloses maintained active during the whole biodrying.

3 Discussion

3.1 Association between water and organics losses and extracellular enzyme activities

Two stages (the hydrolytic and the aerobic stages) were involved in the combined biodrying process. During

the hydrolytic stage, inadequate air was ventilated into the column to maintain the facultative conditions. The metabolism of facultative microbes produced extracellular enzymes to hydrolyze macromolecular compounds and destructed the cell walls or membranes of putrescible organics, so as to release lots of cell-contained water mainly as leachate. During the aerobic stage, adequate ventilation could promote the rapid proliferation of aerobic microorganisms. They were active not only in secreting enzymes to hydrolyze macromolecular substrates but also in degrading monomer hydrolytes, generating more heat and resulting in high temperatures. High temperatures were preferable for enhancing the driving forces for vapor transportation and then increasing water removals with aerated air. In these ways, the water contents of MSW could be reduced effectively.

There was a positive correlation between the water and the organics losses in both stages (R = 0.944, $p < 0.01$) (Fig.7), i.e., during the hydrolytic stage, more organics losses resulted in destruction of more cell walls or cell membranes and generation of more leachates; during the aerobic stage, more vapor removals also needed more heat created by more aerobic biodegradation. In this study, during the hydrolytic stage, the organics losses increased with the enhanced ventilation frequencies, resulting in the increment of water removals. It was possibly attributed to the increasing microbial activities promoted by more O_2 with the rise of ventilation frequencies. However, the organics degradation during the subsequent aerobic stage might be reduced for the scenarios with the higher ventilation frequencies during the hydrolytic stage due to substrate limitation, causing less water evaporation. Additionally, the longer spans also led to more organics losses and water removals in the hydrolytic stage. Correspondingly, less organic matters might be degraded in the subsequent aerobic stage, resulting in fewer water removals. Therefore, the total water losses of biodrying process with combined hydrolytic-aerobic stages were the result of organics consumption and its allotment between the two stages.

Extracellular enzymes played essential roles in the hydrolysis of organic compounds (Goel *et al*., 1998). The evolution of extracellular enzyme activities was consistent with organics losses, i.e., if the enzyme activities were higher, there were more organics losses during biodrying and vice versa. Therefore, appropriate ventilation frequencies and temporal spans during the hydrolytic stage might regulate the enzyme activities to enhance biodrying performance for the combined process. Low activities of the FPase and CMCase suggested that the enzymes related to the hydrolysis of lignocelluloses played minor roles in organics consumption during biodrying.

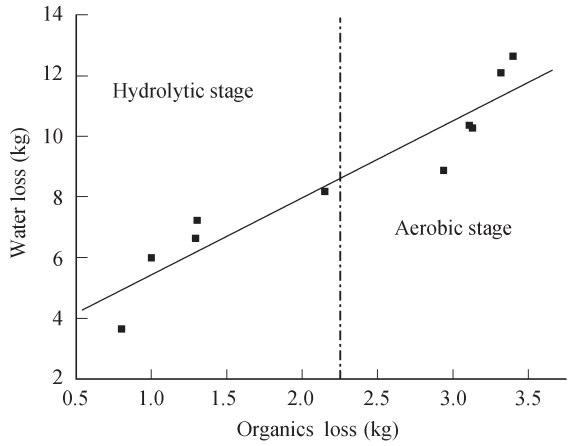

Fig. 7 Linear correlation between water and organics losses for the combined hydrolytic-aerobic biodrying processes.

3.2 Optimal parameters for the combined hydrolytic-aerobic biodrying process

When water removal was the dominant target of the combined hydrolytic-aerobic process, there existed an optimal ventilation frequency during the hydrolytic stage, where 6 times/d (0.075 $m^3/(kg \cdot m^2)$ air inflow per time) were suggested. Taking into account both the hydrolytic and aerobic stages, the scenarios with the ventilation frequency of 6 times/d during the hydrolytic stage removed more water than the others. In contrast, the scenarios with higher ventilation frequencies (10 times/d) in the hydrolytic stage removed less water during the successive aerobic stage due to less organics degradation. Likewise, the scenarios with the lower ventilation frequencies (such as 2 times/d) generated fairly less leachate during the hydrolytic stage since fewer cell walls or membranes were destructed.

Similarly, the temporal span of the hydrolytic stage was suggested not to be prolonged. Although the longer hydrolytic spans ($\geqslant$ 6 d) might slightly cause more leachate released from MSW, much more organics were consumed during the stage. Influenced by the hydrolytic stage, fewer organics were degraded during the subsequent aerobic stage, resulting in fewer water removals in the form of vapor. As a whole, the scenarios with longer hydrolytic spans ($\geqslant$ 6 d) could remove less water.

Furthermore, the scenarios with a hydrolytic span of 6 d had higher final water contents than those of 4 d when ventilation frequencies in the hydrolytic stage were higher than 4 times/d, suggesting that the hydrolytic spans played a more important role in reducing MSW water content than the ventilation frequencies for the combined process.

4 Conclusions

(1) High water removal effectiveness could be obtained for biodrying of MSW with high water content through the combined hydrolytic-aerobic process. If the operation condition was controlled as the scenario with the ventilation frequency of 6 times/d and the hydrolytic span of 4 d, 78.5% of the initial water in MSW would be removed, of which 54.7% might be in the form of vapor, whereas the other 23.8% would be in the form of leachate. Its final water content was 50.5% decreased from the initial 72.0%.

(2) There existed an optimal ventilation frequency in the hydrolytic stage and 6 times/d is recommended. The

temporal span of hydrolytic stage should not be prolonged and 4 d were suggested as a suitable one.

(3) In general, there was a positive correlation between the water and organics the losses in both hydrolytic and aerobic stages of combined biodrying process. The performance of total water removal was influenced by allotment of organics losses between the two stages.

(4) The evolution of extracellular enzyme activities was consistent with organics losses; thus, appropriate conditions might be favorable for enzymes' action on organics losses.

Acknowledgments

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Appendix

The water losses at time t (W^t_{loss}, kg) are calculated by:

$$W^t_{\text{loss}} = (\text{WM}_0 \times w_0) - (\text{WM}_t \times w_t) \quad (1)$$

where, WM_0 (kg) and WM_t (kg) are the wet materials at the initial time and time t, respectively, w_0 (%) and w_t (%) are water contents at initial time and at time t, respectively.

The total organics losses at time t ($\text{TO}^t_{\text{loss}}$, kg) are given by:

$$\text{TO}^t_{\text{loss}} = \text{WM}_0 - \text{WM}_t - W^t_{\text{loss}} \quad (2)$$

The organics losses into leachate ($\text{LO}^t_{\text{loss}}$, kg) are calculated by:

$$\text{LO}^t_{\text{loss}} = \text{Accumulated TOC}_t / C_t \quad (3)$$

where, accumulated TOC_t (kg) is the accumulated total organic carbons in leachate at time t, C_t (%) is the carbon content of MSW at time t.

The organics degradation losses at time t ($\text{DO}^t_{\text{loss}}$, kg) are calculated by:

$$\text{DO}^t_{\text{loss}} = \text{TO}^t_{\text{loss}} - \text{LO}^t_{\text{loss}} \quad (4)$$

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