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RESEARCH ARTICLE

Effectiveness of aerobic pretreatment of municipal solid waste for accelerating biogas generation during simulated landfilling

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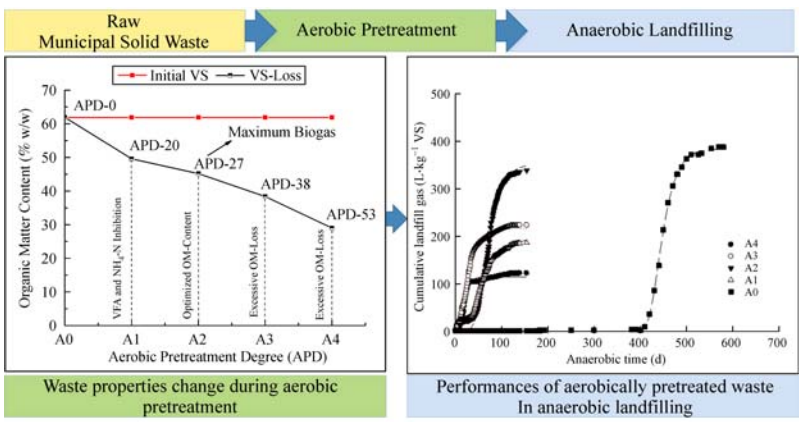
HIGHLIGHTS

- Effect of aerobic pretreatment of MSW on landfill gas generation was investigated.
- Volatile solid (VS) loss of MSW is an effective and comparable indicator.
- Chinese MSW requires at least a reduction of VS about 27% (w/w) prior to disposal.
- Aerobic pretreatment of MSW reduced lag phase more than 90% before methanogenesis.
- Aerobic pretreatment degree influences quantity of gas generation.

GRAPHIC ABSTRACT



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ABSTRACT

This study evaluates the effectiveness of aerobic pretreatment of municipal solid waste (MSW) on reducing lag phase and accelerating biogas generation. Aerobic pretreatment degree (APD) was determined on the basis of reduction in volatile solids (VS) on a wet weight basis. In this study, intermittent aeration (IA) was applied to three reactors as a main aeration mode; since a single reactor was operated under continuous aeration mode. However, the purpose of the experiment was to reduce VS content of waste, irrespective of the comparison between aeration modes. Fresh MSW was first pretreated aerobically with different aeration rates (10, 40, 60 and 85 L/min/m^3) for the period of 30–50 days, resulting in VS-loss equivalent to 20%, 27%, 38% and 53% on w/w basis for the wastes A1, A2, A3 and A4, respectively. The cumulative biogas production, calculated based on the modified Gompertz model were 384, 195, 353, 215, and 114 L/kg VS for the wastes A0, A1, A2, A3 and A4, respectively. Untreated waste (A0) showed a long lag phase; whereas the lag phases of pretreated MSW were reduced by more than 90%. Aerobically pretreated wastes reached stable methanogenic phase within 41 days compared to 418 days for untreated waste. The waste mass decreased by about 8% to 27% compared to untreated MSW, indicative that even more MSW could be placed in the same landfill. The study confirmed the effectiveness of aerobic pretreatment of MSW prior to landfilling on reducing lag phase and accelerating biogas generation.

1 Introduction

The control of biodegradable fractions of municipal solid

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waste (MSW) is one of the key parameters considered for the assessment of short or long-term environmental impacts of landfilling. The control of organic waste is often achieved by the source-segregation system and/or aerobic biological pretreatment prior to landfilling [1]. The segregation process of various MSW components at a source point (door-to-door collection) is more expensive in terms of transport facilities, fuel consumption, and other supplies, contributing up to 70% of the entire cost of MSW management [2]. Hence, aerobic pretreatment of MSW is preferred prior to landfilling, contributing to minimize the environmental impacts of MSW landfilling [3]. This is due to the fact that the stabilization of MSW directly in landfill even with appropriate technology (e.g. bioreactor landfill) can not be achieved due to the presence of fresh organic waste [3,4].

The disposal of fresh MSW in a sanitary landfill does not promote the sustainable disposal practice due to acid accumulation within landfill layers, ultimately waste stabilization becomes slower under anaerobic environment. To attain the concept of environmentally sustainable landfilling, the mechanical biological treatment (MBT) has gained more attention as a cost-effective and viable alternative to expensive incineration method [2,5]. The mechanical process aims at removing non-biodegradable fractions, thus creating optimal conditions for aerobic biological phase [5]. Aerobic biological pretreatment leads to faster degradation of organic matter compared to anaerobic treatment, owing to relatively high growth rate of involved microbes under aerated conditions [6,7]. Therefore, aerobic pretreatment of MSW prior to landfilling has emerged as an effective strategy worldwide which ensures the fast stabilization of residual waste in the subsequent anaerobic phase of landfilling [4,8,9].

A short-term aerobic biological pretreatment (2–4 weeks) to remove easily degradable organic matter and a long-term aerobic pretreatment (2–6 months) to achieve a higher degree of stabilization before landfilling, both approaches are common in the EU countries [4]. Generally, aerobic stabilization of waste significantly reduces the volume, mass and biogas generation potential depending on the process length [10].

In recent years, there has been a continuous impetus to increase the share of renewable energy resources due to limited petroleum resources and the environmental impacts of coal [11,12]. In 2014, there were 636 landfill gas (LFG) to energy projects in the US, generated about 16.5 billion kWh electricity with an additional supply of about 9 million cubic meter per day of LFG for direct-use application [13]. Meanwhile, Fazeli et al. [14] suggested to promote LFG recovery from sanitary landfills in Malaysia, indicating the significance of methane gas recovery.

Based on the above scenario, there are mainly two approaches in an efficient landfill management that ensure the long-term environmental sustainability (i.e., the EU scenario) and environmental and energy benefits (i.e., the US scenario) of landfilling [15]. To achieve environmental and energy benefits of MSW landfilling, both approaches are available for economically developing countries (e.g. China).

In China, landfilling is a predominant method of MSW treatment [16–21]. In 2015, approximately 191 million metric tons annually were collected and mainly treated by landfilling, incineration and composting. Landfilling contributed about 64% of the total treated MSW followed by incineration (34%) and others (2%) [22]. Fresh MSW contains a relatively high moisture content (40%–60%) and volatile solids (50%–70%) on a wet weight basis which are the unique characteristics compared to MSW generated in developed countries [23]. These characteristics are attributed to the mixed collection of food waste from households and restaurants [24]. The characteristics of MSW reported in various research studies are summarized in Table 1. The Chinese government is keen to establish an effective MSW source separation program. The source separation system of MSW is generally one of the most expensive services; since an effective source separation system has not yet been established in China [25]. Hence, there has been increased emphasis on the aerobic pretreatment of MSW prior to landfilling.

The critical problem of the sanitary landfill is directly linked with the disposal of fresh MSW, which creates a significant lag in the early phase of landfilling. This is because of the accumulation of volatile fatty acids (VFAs) and prolonged pH drop within landfill layers [8,16,18,27,28,33,35]. The high concentration of VFAs is responsible for creating an acidic environment within the waste mass; thus impeding the methanogenic activity in an anaerobic landfill [31]. To control acidification in the early phases of anaerobic landfilling, various research studies have suggested that the aerobic pretreatment (compost-like process) of MSW prior to landfilling is necessary [9,18,36,37]. Despite the fact that the aerobic stabilization of the waste is an effective step to reduce emission potential of the waste; since it is not always possible for developing countries to thoroughly stabilize MSW before landfilling. Therefore, the critical point in the practical application is to eradicate some easily degradable organics with the aim of avoiding acid inhibition and conserving refractory organic matter for the enhancement of landfill gas.

In literature, a short-term aerobic pretreatment of MSW was recommended for 6–10 days of active composting in developing countries [18,37]. However, a time-based indicator can vary for the active and passive methods of aerobic pretreatment [38]. The characteristics and behavior of MSW differ from each other and the extent of aerobic pretreatment in literature varied widely from one week to 20 weeks according to aerobic operation modes [9,18,37,39,40]. Hence, a reduction in volatile solids (VS) during aerobic pretreatment could be an effective and

Table 1 Composition of MSW in various cities of China

Area	Year	Moisture content	Food waste	Paper waste	Plastic and rubber	Others	References
Beijing	2016	57.5	63.0	13.0	5.0	19.0	[18]
Beijing	2014	62.6	64.0	12.0	13.9	10.1	[26]
Beijing	2012	64.5	62.7	12.9	5.8	18.6	[27,28]
Beijing	2011	61.0	63.4	11.1	12.7	12.8	[29]
Beijing	1996	58.81	56.01	11.76	12.6	19.63	[30]
Shanghai	2015	–	69.0	7.0	7.0	17.0	[17]
Shanghai	2005	–	56.0	19.0	14.0	11.0	[31]
Shanghai	1996	58.85	58.55	6.68	11.84	22.93	[30]
Shenzhen	2014	49.7	55.0	10.0	10.0	25.0	[32]
Shenzhen	1996	55.0	57.0	4.65	14.05	24.3	[30]
Panjin	2013	–	59.8	13.5	10.7	16.0	[33]
Chongqing	2009	–	59.2	10.1	15.7	15	[34]
Guangzhou	1996	50.12	56.63	3.65	13.05	26.67	[30]
Hangzhou	1996	57.28	55.28	1.8	5.02	37.9	[30]

Notes: Composition of MSW is given as percentage (%) of wet weight

comparable indicator for different types of MSW. The determination of VS represents an approximation of the organic matter present in MSW [41]. In a particular Chinese context, a VS-loss based indicator is an effective measure to investigate the removal efficiency of VS during aerobic pretreatment. The depletion of VS over time has already been taken in to account during modeling and simulation of LFG production [42]. Moreover, the organic matter decomposes under anaerobic conditions [7] and the amount of LFG produced per kg of VS, validates the effectiveness of a VS-loss based indicator when aerobic pretreatment degree (APD) is correlated with biogas generation [36,43].

The key objective of the study is to evaluate the effectiveness of aerobic pretreatment of MSW for accelerating biogas generation in the subsequent anaerobic phase of the landfill. Therefore, APD was determined on the basis of VS-loss as a percentage during aerobic pretreatment stage. Thereafter, various levels of APD were also correlated with the biogas generation rates using modified Gompertz model.

2 Materials and methods

2.1 Fresh MSW sample

The fresh MSW about 500 kg was collected from the transfer station before disposal into Beishenshu landfill located in Beijing. The fresh MSW was manually sorted to classify the components. The composition of waste sample is summarized in Table 2. The fresh waste was characterized by the high proportion of biodegradable waste and moisture content on a wet weight basis. To ensure the homogeneity of the sample, the coning and quartering method was applied to the waste before filling up into the bioreactors. The initial moisture content, VS (w/w), and total carbon of the sample were 64.5%, 61.9%, and 34.9%, respectively.

Table 2 Composition of untreated MSW sample[a)]

Components	Values
Food waste	62.7
Paper	12.9
Textile	3.7
Wood	1.0
Plastic and Rubber	5.8
Metal	0.3
Glass	1.7
Stone	3.8
Others	8.1

Notes: a) Percentage of wet weight

2.2 Experimental set up

Five simulated reactors made of high-density polyethylene (HDPE) material with the dimensions of 0.5 m diameter and 0.75 m height, were used in these experiments at landfill site, each providing a total volume of 137 L. All reactors were labeled as R0, R1, R2, R3 and R4, and filled with 77.5 kg (on a wet weight basis) of untreated waste at a packed height of 60 cm, reaching a density of 657 kg/m^3 after a slight compaction. The waste samples filled in all reactors were labeled as A0, A1, A2, A3 and A4. All bioreactors were equipped with an aeration pump, leachate and biogas collection system, temperature probes, and solid waste sampling ports, as shown in Fig. 1.

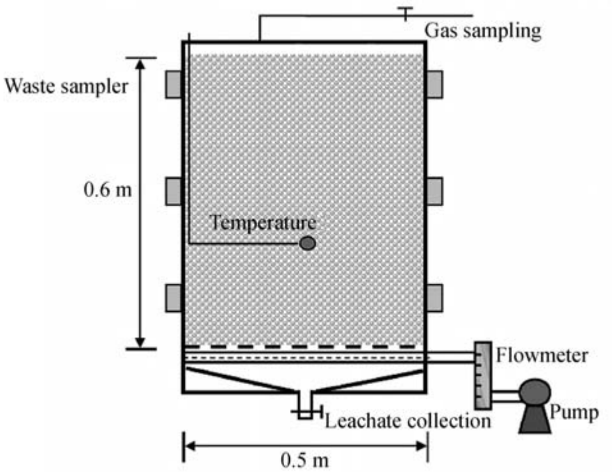

Fig. 1 Schematic of the reactor with changeable aerobic and anaerobic operations

2.3 Experimental procedure

Reactors were placed on the weighing machine to record the weight of reactor before and after filling up the waste sample. The density was calculated by dividing the mass of waste sample to the volume of reactor it occupied. The settlement and weight of the waste were recorded at the end of aerobic and anaerobic pretreatment stages to determine the change of material density. Similarly, the solid waste samples about 10–20 g were collected from six sampling ports. All the reactors were operated in a temperature controlled room maintained at 25°C±5°C.

The intermittent aeration (IA) was applied as a main aeration mode suggested by Xu et al. [17], aiming at accelerating biogas generation. Cossu et al. [44] demonstrated the efficiency of IA for promoting faster reaction kinetics in subsequent anaerobic phase; thus, highest methane yield (102 L/kg VS) was reported. Meanwhile, Nikolaou et al. [45] confirmed that IA proved to be a favorable mode for nitrification process, consequently a significant reduction of ammonia toxicity in leachate was observed. In this study, the intermittent aeration (IA) mode was applied to three reactors (R2, R3 and R4); since a single reactor was operated in continuous aeration mode (R1). Aerobic pretreatment was not applied to the reactor R0 (control reactor), which represents the current situation of a sanitary landfill. Reactor R1 was remained under observation for 30 days of aerobic pretreatment. While, reactors R2, R3 and R4 were remained under observation for 50 days with different aeration rates as shown in Table 3.

There was no leachate recirculation during the experiments including aerobic pretreatment and anaerobic treatment stages. This is due to the fact that fresh MSW already contains a lot of moisture content. However, tap water was added to the reactors during anaerobic treatment phase to provide a conductive environment to anaerobic microbes, responsible for converting VS into biogas. As a rainfall simulation, tap water (600 mL per week) was added at the precipitation rate of 12 mm per month. Leachate samples about 10–20 mL were collected on weekly basis and were analyzed for pH and ammonium nitrogen (NH_4^+-N) during anaerobic phase of simulated landfilling.

2.4 Analytical methods

The moisture content was determined by heating the samples at 105°C±5°C for 24 h. The VS content was determined using mass loss of TS by ignition at 550°C for 3 h in a muffled furnace. The total carbon and nitrogen were measured using Elemental Analyzer (Equipment CE 440, Exeter Analytical Inc., USA). The fractions of CO_2 and CH_4 in biogas, on a volumetric basis, were measured using a specific landfill gas analyzer (GA2000 +, ONWEE, China). The pH was measured with a calibrated pH meter (PHS-25, INESA, China). NH_4^+-N was determined by UV-Vis spectrophotometer (UV752, YOUKE, China) using the Nessler method.

APD indicates the difference between VS content (% w/w) of aerobically pretreated and untreated waste samples, which was calculated using Eq. (1).

$$\mathrm{APD} = 100\left(1 - \frac{VS_{\mathrm{AP}}}{VS_0}\right), \tag{1}$$

where VS_{AP} and VS_0 are the VS contents of the aerobically pretreated and untreated waste samples, respectively.

The modified Gompertz model [18] was used to predict

Table 3 Pretreatment operational modes of the reactors

Reactor number	Waste number	Rate a) (L/min/m^3)	Frequency	Time (d)
R0	A0	–	–	–
R1	A1	10	b)	30
R2	A2	40	c)	50
R3	A3	60	c)	50
R4	A4	85	c)	50

Notes: a) Air volume flow per cubic meter of waste volume per minute; b) Continuously; c) Intermittent 30 min run and 15 min break the cumulative biogas generation as given in Eq. (2).

$$y = A\exp\left(-\exp\left(\frac{\mu \mathrm{m}^{\mathrm{e}}}{A}(\lambda - t) + 1\right)\right), \tag{2}$$

where y is the cumulative biogas generation (L/kg VS) at time t (d), A is the maximum biogas generation potential (L/kg VS), μ_{m} is the maximum daily biogas generation rate (L/kg VS/d), λ is the lag time taken to produce biogas (d), and e is the mathematical constant (2.718). The regression model was completed using the 2001 version of Sigma-Plot.

3 Results and discussion

3.1 Change of MSW characteristics

A significant loss of VS was observed within the waste mass of A1, A2, A3, and A4 during aerobic pretreatment compared to untreated waste A0. APDs during aerobic pretreatment for waste samples A1 to A4 were 20%, 27%, 38%, and 53%, respectively as shown in Table 4. The similar observations related to the VS-loss have been reported by various authors [5,9,46]. Meanwhile, the changes in a VS content has been considered as one of the key parameters during aerobic pretreatment. In this study, a significant change in VS content was observed due to the removal of the easily degradable organic matter of MSW. Thereafter, the biodegradability of the pretreated waste was relatively faster during the subsequent anaerobic stage, which resulted in the maximum degradation within a short period of time relative to untreated waste. The situation confirmed that the aerobic pretreatment of MSW is an effective step that ensures the faster stabilization of residual waste in the sanitary landfill.

The effect of aerobic pretreatment on the mass and volume of MSW is shown in Fig. 2. The total mass of the pretreated waste (w/w) decreased by 8%–27%. The water evaporation contributed to about 20%, 45%, 46% and 49% decrease of the waste mass for A1, A2, A3, and A4, respectively, while the degradation of the VS contributed to the rest. As the extent of aerobic pretreatment was increased, there was a significant increase in the density from 657 to 845 kg/m^3 at the end of the aerobic pretreatment. It should be noted that wastes with similar extent of aerobic pretreatment via different aeration rates could behave differently during the anaerobic stage. Additionally, the space demand of aerobically pretreated wastes (A1–A4) decreased by 32%, 37%, 39%, and 43%, respectively, compared to the original waste (A0). In China, there has been a strong push to reduce the demand for landfill space because there is an acute scarcity of land to establish new landfill facilities, especially in megacities. Along with many environmental benefits of aerobic pretreatment, decrease in waste mass indicated that even more MSW could be placed in the same landfill.

3.2 Effect of aerobic pretreatment degree on landfill gas generation

Landfill gas collection started shortly after the reactor environment switched to anaerobic conditions. The cumulative volumes of landfill gas from the five wastes (A0 to A4) are illustrated in Fig. 3. The parameters obtained from the regression of experimental data using the modified Gompertz model are shown in Table 5.

The lag phase significantly decreased as APD increased. The lag phases of aerobically pretreated MSW were reduced by more than 90%, whereas untreated waste showed long lag phase before methanogenesis. Aerobically pretreated wastes reached stable methanogenic phase within 41 days, faster than untreated waste in 418 days. The results suggest that the aerobic pretreatment of MSW can lead to an earlier onset of methanogenesis during the anaerobic phase of landfilling. Different biogas yield trends were observed in all bioreactors. The biogas generation potential of A0, A1, A2, A3, and A4 were 384, 195, 353, 215, and 114 L/kg VS, respectively. Aerobic pretreatment significantly reduced the VS and the potential of landfill gas production depending on the length of the aerobic process. However, a good agreement between the removal of some easily degradable organic matter and preservation of slowly biodegradable organic matter, can be an effective solution to enhance biogas generation. The main objective of this study was to enhance biogas generation rather than to achieve a stabilized waste with zero landfill emission potential. The waste A2 with an APD of 27% showed a better performance in terms of the early onset of methanogenesis

Table 4 Characteristics of waste before and after anaerobic treatment

Waste number	Aerobic pretreatement degree (APD) (%)	Aerobically pretreated waste		Anaerobically treated waste	
		Moisture (%)	VS (%)	Moisture (%)	VS (%)
A0	0	64.5	61.9	72.0	32.8
A1	20	70.2	49.6	70.0	36.9
A2	27	68.4	45.2	70.2	24.3
A3	38	71.0	38.4	69.8	26.4
A4	53	70.0	29.0	70.4	16.1

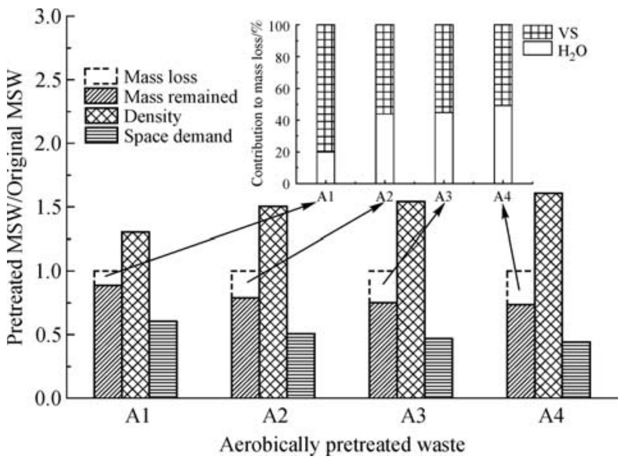

Fig. 2 Comparison of mass, density, and volume between aerobically pretreated and original MSW. The *Y*-axis indicates the normalized mass, density, and landfilling space demand of the aerobically pretreated waste compared with that of the untreated waste

Table 5 Parameters of modified Gompertz model

Waste number	Experimental biogas generation A (L/kg VS)	Predicted biogas generation A (L/kg VS)	Maximal daily biogas generation μ_m (L/kg VS/d)	Lag time λ (d)	Correlation coefficient R^2
A0	387	384	6.6	418	1.00
A1	186	195	2.6	18	0.98
A2	338	353	6.2	41	0.99
A3	223	215	5.3	6	0.99
A4	121	114	5.2	8	0.98

in 41 days with the highest recovery of biogas 353 L/kg VS. Whereas, higher VS losses of 38% and 53% for waste A3 and A4, respectively, led to a decrease of biogas yields in the anaerobic phase; the similar trend demonstrated by Gerassimidou et al. [9]. In general, the higher degree of aerobic pretreatment results in a smaller amount of VS that is left for anaerobic degradation. The generated biogas yields from the aerobically pretreated wastes A1, A2, A3, and A4 accounted for 44%, 71%, 38%, and 15%, respectively, compared to the untreated waste A0.

The aerobic pretreatment was observed to be more effective at promoting the quicker onset of methanogenesis in subsequent anaerobic phase. The biogas completely ceased from the aerobically pretreated waste reactors in just 154 days of anaerobic treatment, while the biogas from the untreated waste lasted up to 580 days. The biogas generation potentials of wastes A0 and A1 were observed to be lower than waste A2. In contrast, the organic content of wastes A0 and A1 were relatively more than waste A2. The low biogas generation of waste A0 could be attributed to the leachate pH, which was between 5 and 6 for the first 200 days; while the pH for wastes A1 to A4 was reached the level between 7 and 8 quite earlier, and methanogenesis was established within 41 days. The performance of waste A1 was found to be influenced by the release of ammonium nitrogen.

3.3 Release of ammonium nitrogen and its effect on gas generation

During the anaerobic phase, the microbial degradation of proteins and amino acids results in the accumulation of ammonium nitrogen (NH_4^+-N) in the leachate. It is important to note that the high concentration of ammonium nitrogen above 3000 mg/L is one of the inhibitors to methanogenesis irrespective of pH [47]. The results of the NH_4^+-N concentrations measured in leachate samples during an anaerobic phase are shown in Fig. 4.

Unexpectedly, the highest NH_4^+-N concentration more than 6000 mg/L was detected in leachate generated from the reactor R1 that was operated under continuous aeration (CA) mode. The initial sharp increase can be explained by the direct leaching of ammonia from waste A1, which impeded the biogas generation. It has been observed that, 30 days of aerobic pretreatment with CA mode and lowest aeration rate (10 L/min/m^3) could not remove sufficient protein content, thus ammonium nitrogen was released very fast during anaerobic phase of landfilling. The described condition of faster release of ammonium nitrogen can be one of the reasons that the anaerobic degradation of waste A1 behaved differently. On the other hand, the concentrations of NH_4^+-N detected in other reactors were between 1000 and 3000 mg/L during the

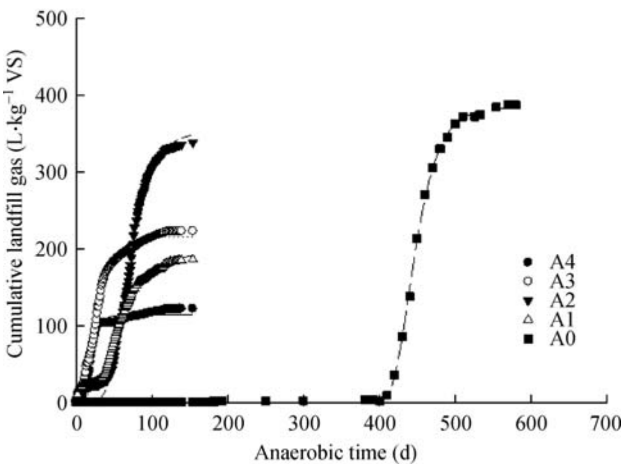

Fig. 3 Cumulative landfill gas generation during the anaerobic stage

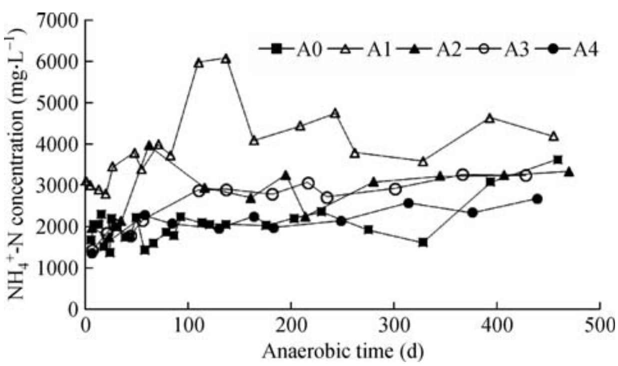

Fig. 4 NH_4^+-N concentration in leachate of pretreated wastes during the anaerobic stage

anaerobic phase. Figure 5 shows the maximum ammonium nitrogen release rates for the waste A0, A1, A2, A3, and A4 were 0.25, 0.90, 0.45, 0.54, and 0.22 g NH_4^+-N/kg total nitrogen/day, respectively.

This dissimilarity of NH_4^+-N concentration among the reactors with IA and CA can be explained by the rate of nitrification process. The possible explanation for the lower NH_4^+-N concertation in the leachate generated from reactors A2, A3 and A4 can be attributed to the nitrification process, described by Nikolaou et al. [45]; and microbial uptake for the growth of new cells [48]. During the experiments of this study, an intermittent aeration was observed to be a favorable mode for the development of nitrifying bacteria such as, Nitrobacter and Nitrosomonas [49]. Since, the effects of aeration mode on protein degradation and microbial diversity need to be investigated in future.

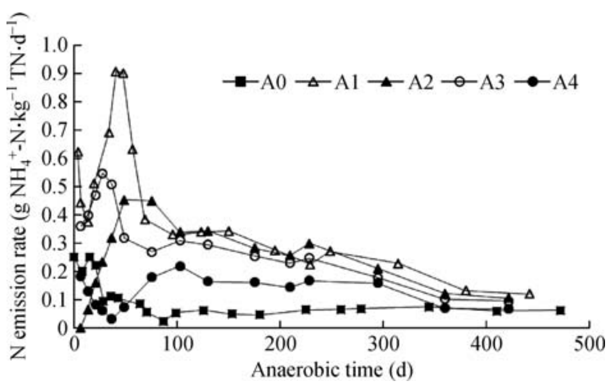

Fig. 5 NH_4^+-N emission rates of pretreated wastes during the anaerobic stage

4 Conclusions

On the basis of the results discussed above, the following conclusions are made.

1) The aerobic pretreatment prior to landfilling reduced lag phase before methanogenesis during anaerobic landfilling, and thus, the ability to control the behavior of MSW was observed.

2) MSW containing VS about 60% (w/w), requires at least a reduction of 27% during aerobic pretreatment in order to achieve early onset of methanogenesis and enhance biogas generation in anaerobic landfilling.

3) The highest biogas generation was achieved with more than 90% reduced lag time for the waste subjected to a decrease in 27% of the VS. However, an APD of 38% and 53% showed a significant reduction in biogas generation potential due to the excessive VS-loss during aerobic pretreatment.

4) An APD of 27% also proved to be a suitable degree of stabilization for decreasing the space demand by about 37% compared to that of untreated waste, indicating that even more waste could be accommodated within the same landfill cell.

5) The quicker accumulation of ammonium nitrogen caused an inhibition of biogas generation in a reactor that was operated under continuous aeration mode, short duration and lowest aeration rate. Hence, further investigation is required to evaluate the effectiveness of protein removal during aerobic pretreatment under intermittent and continuous aeration modes.

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