Environ. Eng. Res. 2014; 19(3): 261-268
http://dx.doi.org/10.4491/eer.2014.S1.003

pISSN 1226-1025
eISSN 2005-968X

# Comparison of Solid Waste Stabilization and Methane Emission from Anaerobic and Semi-Aerobic Landfills Operated in Tropical Condition

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**ABSTRACT**

Leachate quality and methane emission from pilot-scale lysimeters operated under semi-aerobic and anaerobic conditions were monitored for 650 days. Two semi-aerobic lysimeters were filled with un-compacted and compacted municipal solid wastes whereas two anaerobic lysimeters containing compacted wastes were operated with leachate storage at 50% and 100% of waste height, respectively. Despite having high moisture in wastes and operating under tropical rainfall events, leachate stabilization in semi-aerobic lysimeters took place much faster resulting in BOD reduction by 90% within 60 days, significantly shorter than 180–210 days observed in anaerobic lysimeters. Nitrogen concentration in leachate from semi-aerobic lysimeter could be reduced by 90%. In term of gas emission, semi-aerobic lysimeter with un-compacted wastes had much lower methane emission rate of 2.8 $g/m^2/day$ compare to anaerobic lysimeters (62.6 $g/m^2/day$) through seasonal fluctuation was observed. Nevertheless, semi-aerobic lysimeter with waste compaction has similar performance to anaerobic lysimeter.

**Keywords:** Biodegradation, Landfill gas, Leachate, Semi-aerobic lysimeter, Tropical climate

## 1. Introduction

Direct landfill of untreated solid wastes is being used as the only disposal method for management of municipal solid wastes (MSW) in many countries. However, current landfill disposal techniques consider landfill site as a passive waste storage system, and disposed waste in the landfill is isolated from outside environment. The biodegradation of organic wastes in this type of 'dry tomb' disposal is restricted due to low moisture available in the landfills as it does not provide microorganisms with optimum environmental conditions [1]. The disposed wastes will therefore undergo through microbial biodegradation very slowly, and thus lengthening the process of landfill stabilization. As a consequence of this slow biodegradation process, landfill gas and leachate which are the by-product are hardly stabilized and its production can last for decades and therefore result in a significant long-term negative impact on human health and natural environment. In order to overcome this problem, several researches were carried out in attempt to seek new landfill techniques which can accelerate landfill stabilization process and reduce pollutant emission [2].

Semi-aerobic landfill concept has been initiated for improvement of disposal of MSW in Japan by the Fukuoka City and Fukuoka University [3]. In semi-aerobic landfill, air entered the leachate collecting pipe, which was partially filled with leachate and air flow was driven by the temperature difference between inside of the waste cell and ambient air. This air intrusion into the waste body leads to subsequent improvement of waste stabilization and leachate qualities due to the enhancement of the aerobic microbial activities within the waste cell [4]. Moreover, the provision of passive gas vent also helped to aerate the landfilled waste [5]. Under aerobic condition, organic matter present in wastes is subjected to biodegradation by aerobic microorganisms to carbon dioxide and water. Aeration of landfills results in rapid reduction of organic pollutants and in the reduction of odor emission [6, 7]. Twenty parameters of landfill leachate were investigated to compare the quality between semi-aerobic and anaerobic conditions



**Received** May 25, 2014 **Accepted** August 26, 2014

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and their results have shown that the concentrations of contaminants were reduced under semi-aerobic condition much greater than those in conventional landfill [8]. Therefore, it revealed that semi-aerobic landfill system is a viable method for reducing pollution from landfills and its application is also highly feasible based on the cost-benefit evaluation of the entire implementation process from the development stage to final closure [9]. In addition, semi-aerobic landfill can greatly shorten the time for stabilization of organic wastes in the landfill site, subsequently lead for faster reclamation of the landfill area [10].

Despite of its obvious benefit, the applicability of semi-aerobic landfill technology is tropical developing countries in still doubtful due to the fact that heavy rainfall during monsoon season may reduce air penetration into the landfill cell and turn the microbial activities into anaerobic condition. The limited aeration thus can result in relatively much slower waste stabilization process comparing to actively aerated landfills [11]. Therefore, landfill design and operation has to be adjusted for specific local settings of tropical landfills [12]. Very limited information regarding the influence of tropical rainfall on waste stabilization, leachate qualities and gas emission from landfills, specifically under semi-aerobic conditions are available. The possible influencing factors governing air supply for biodegradation of organic wastes in semi-aerobic landfills can be, for instance, waste composition, compaction density, precipitation intensities and efficiencies of leachate collection system. The primary objectives this research were to investigate long-term performance of semi-aerobic landfill lysimeters operated under simulated tropical conditions in terms of organic waste biodegradation as well as leachate qualities and methane emission and compared with those of conventional anaerobic landfill. Fate of carbon and nitrogen during semi-aerobic decomposition of wastes was studied in order to verify organic transformation and potential emission reduction which could be achieved in this specific landfill.

## 2. Materials and Methods

Pilot-scale solid waste lysimeters were made of steel with 0.9 m diameter and 2.7 m height. They were filled with MSW obtained from a local authority in Thailand to an initial height of 1.8 m. The waste composition was 19.1% food wastes, 19.1% paper, 16.4% plastic, 17.7% textile, 5.7% wood, 19.4% glass, and 2.7% foam, representing typical MSW composition received at a solid waste disposal site in Thailand. The composition (wet and dry weight basis) and chemical characteristics of solid wastes used in this study are shown in Table 1. Solid waste sampling and characterization were performed according to the standard methodology [13]. Two lysimeters were operated under semi-aerobic condition by providing air ventilation pipe above leachate drainage pipe, one of them was prepared without waste compaction (semi-aerobic lysimeter Sm I containing 730 kg wastes with compaction density of 640 $kg/m^3$) and the other with compaction (semi-aerobic lysimeter Sm II, 880 kg wastes, 770 $kg/m^3$). Two well compacted anaerobic solid waste lysimeters were operated with leachate level at 50% (anaerobic lysimeter An I, 830 kg wastes, 730 $kg/m^3$) and 100% (anaerobic lysimeter An II, 730 kg wastes, 720 $kg/m^3$) of initial height of waste layer, respectively. The mail purpose for having different level of leachate storage in the anaerobic lysimeters was to simulate anaerobic landfill operation with different leachate drainage efficiencies. Based on our previous study, internal storage of leachate can affect degree of waste stabilization as well as leachate qualities and gas production [14]. In all lysimeters, the waste layer is covered with 0.3 m sand layer. The schematic of lysimeters is shown in Fig. 1.

The lysimeters were operated and monitored over 650 days. For determining solid waste physical characteristic changes during the lysimeter operation, moisture content and temperature inside the lysimeters were continuously monitored at five different levels along the waste height (i.e. 0.55 m, 1.05 m, 1.55 m, 2.05 m, and cover material) using moisture (SM200 model; Delta-T Device, Cambridge, UK) and temperature (thermocouple type K; Sankei-Rika, Tokyo, Japan) probes connected to a data logger (GL200A; Graphtec, Yokohama, Japan). To simulate tropical rainfall condition, actual rainwater was discharged into the lysimeters from rainfall collection pans having 70% of lysimeter footprint area as the runoff coefficient was assumed to be 0.3. During the experimental period, waste settlement rate, leachate quantity, and characteristics were monitored once a week. The determining parameters included pH, biochemical oxygen demand (BOD), total organic carbon (TOC), suspended solids (SS), total dissolved solids (TDS), ammonium nitrogen ($NH_4^+$), total kjeldahl nitrogen (TKN), phosphate ($PO_4^{3-}$), and electrical conductivity (EC). All water quality analyses were performed according to Standard Methods for

**Table 1.** Physical Composition and Chemical Characteristics of Solid Wastes

| | % wet wt. | % dry wt. |
|---|---|---|
| **Waste component** | | |
| Food wastes | 19.07 | 13.67 |
| Paper | 19.07 | 16.02 |
| Plastic | 16.36 | 17.98 |
| Textile | 17.71 | 15.23 |
| Woods | 5.72 | 7.03 |
| Glass | 19.35 | 27.34 |
| Foam | 2.72 | 2.73 |
| Total | 100 | 100 |
| **Chemical characteristic** | | |
| Moisture | 30.24* | 79.19 |
| Volatile solids | - | 20.81 |
| Ash | - | 49.49 |
| Carbon (C) | - | 4.94 |
| Hydrogen (H) | - | 21.97 |
| Oxygen (O) | - | 2.24 |
| Nitrogen (N) | - | 0.16 |
| Phosphorus (P) | - | 0.39 |
| Sulfur (S) | - | - |

*The moisture content of wastes have reached their field capacities of 530 mm/m for un-compacted wastes and 600 mm/m for compacted waste at the beginning of lysimeter operation.

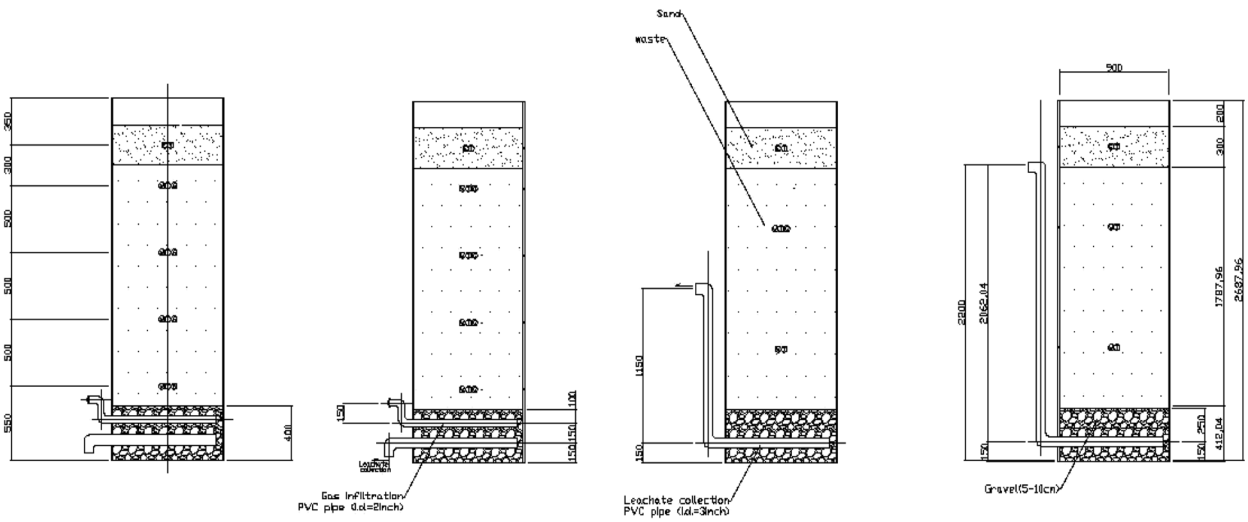


**Fig. 1.** Schematic of lysimeters.

the examination of water and wastewater 20th edition [15]. TOC was analyzed by a TOC analyzer (Shimadzu 5000A).

Landfill gas composition ($CH_4$, $CO_2$, $O_2$) and surface methane and carbon dioxide emission rates were also regularly measured at once a month interval. In order to evaluate the degree of anaerobic condition in the lysimeters, methane ratio at mid-height of the waste layer is used as an indicator and it was determined from $CH_4$ and $CO_2$ concentrations in the sampled gas as follows.

$$\text{Methane ratio} = 1 \text{ when } [CH_4]/([CH_4]+[CO_2]) \geq 0.6$$
$$= [CH_4]/([CH_4]+[CO_2]) / 0.6 \text{ when } [CH_4]/([CH_4]+[CO_2]) < 0.6 \quad (1)$$

Where $[CH_4]$, $[CO_2]$ are methane and carbon dioxide concentrations in landfill gas, respectively. This determination of methane ratio is derived from the fact that under complete anaerobic condition in the lysimeter, methane content in produced gas which composed mainly of methane and carbon dioxide would be at 60%. With the presence of oxygen, methane would be produced at a lesser amount while carbon dioxide would be produced more from aerobic decomposition. This will result in having lower methane ratio in the produced gas.

For determining surface methane and carbon dioxide emissions, a close flux chamber with the same footprint area as the lysimeters was placed at the top of lysimeter and incremental rate of methane concentration in the chamber was determined by periodical sampling the gas from the chamber and analyzing their composition by a gas chromatography (Shimadzu GC-14B, FID detector). $CH_4$ and $CO_2$ fluxes were then determined by the following equation:

$$F = V/A \ (dC/dt) \quad (2)$$

where F is gas flux (g/m$^2$/day), V is volume of close flux chamber (m$^3$), A is footprint area of close flux chamber (m$^2$), and dC/dt is incremental rate of gas concentration in the chamber (g/m$^3$/day). The close flux chambers used in this study were made of acrylic with a diameter of 0.94 m and 0.30 m height equipped with an acrylic cap at the top of the chamber. To protect against air intrusion, the chambers were sealed to the bottom of chamber by placing under water in the ring channel at the top of the lysimeters.

## 3. Results and Discussion

### 3.1. Waste Characteristics

During 650 days operating period, daily rainfall volume discharged into the lysimeters were recorded and their variations are shown in Fig. 2. The volume of discharged rainwater ranged from 0 to 151 L/day, exhibiting clearly different pattern between rainfall and dry period. As a results of rainfall input, the produced leachate from semi-aerobic lysimeters (Sm I, Sm II) and anaerobic lysimeters (An I, An II) over the entire operating period were determined as 15.30%, 15.11%, 12.54%, and 11.62% of rainfall volume, respectively. The productions of leachate in both semi-aerobic lysimeters were found to be statistically different from anaerobic lysimeters. Higher quantity of leachate found in semi-aerobic lysimeters could be explained by higher decomposition of organic wastes and complete drainage of leachate from the lysimeters. On the other hand, anaerobic lysimeters had internal leachate storage at 50% and 100% of waste height in An I and An II lysimeters, respectively. The evidence of higher degree of organic waste biodegradation in semi-aerobic lysimeters was also shown in term of solid waste settlement. Observed settlement over the entire operating period in semi-aerobic lysimeters (Sm I, Sm II) was between 0.3 to 0.4 m or 12%–16% of initial height, higher than 0.15 m (6%) observed in the anaerobic lysimeters.

Previous research has suggested that highest temperature in a semi-aerobic landfill could elevate up to 50°C–76°C [2]. Nevertheless, average temperature in the lysimeters observed in this study was

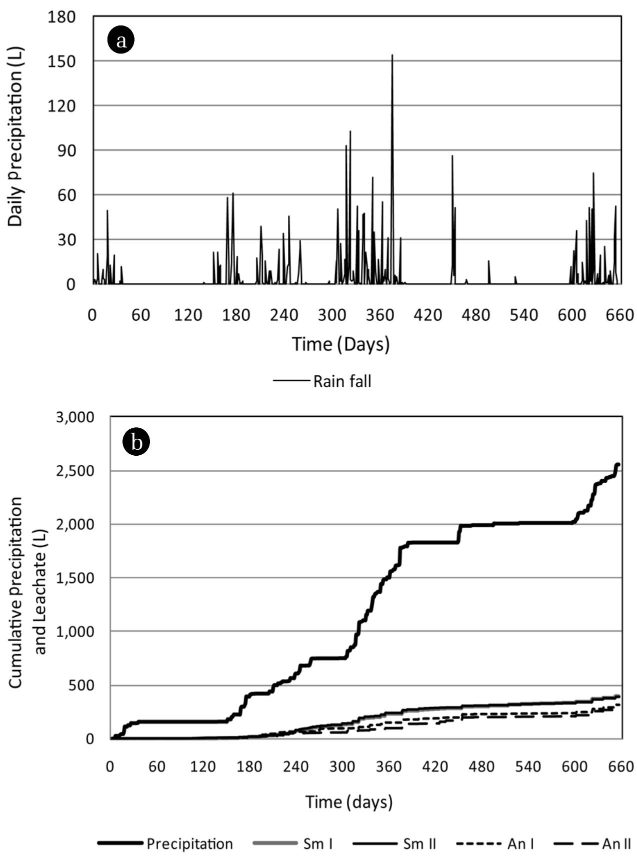


**Fig. 2.** Rainwater input and leachate production in the lysimeters: (a) variation of rainfall volume (b) cumulative volume of rainfall and produced leachate.

found to be only 31.9°C±1.7°C in semi-aerobic lysimeter containing lower waste density (Sm I) and 30.8°C±1.9°C in semi-aerobic lysimeter containing higher waste density (Sm II). For anaerobic lysimeters (An I and An II), the temperature was slightly lower (29.3°C±1.8°C). One of the possible explanations for lower temperature observed of this study was due to heat lost through dissipation from the lysimeter wall which prevented the elevation of temperature inside the lysimeters. During the operation, average moisture content of solid wastes in the lysimeters were found to vary between 48.2%–67.46% except those solid wastes which was submerged under water in the anaerobic lysimeters. It was found that lowest moisture content was observed in Sm I whereas the highest was found in anaerobic lysimeters. This observation could be explained by the loss of moisture with naturally ventilated air in the semi-aerobic lysimeters.

## 3.2. Leachate Characteristics

Fig. 3 show the variation of leachate characteristics during the lysimeter operation. It was found that leachate from semi-aerobic and anaerobic lysimeters with higher waste density (Sm II, An I, and An II) was initially acidic and became neutral afterwards. Nevertheless, neutral condition was always maintained in semi-aerobic lysimeter with lower waste density. BOD in leachate

**Table 2.** Leachate Characteristics and Methane Emission from the Lysimeters

| Lysimeter | pH (–) | BOD (mg/L) | TKN (mg/L) | $NO_3$ (mg/L) | $CH_4$ ratio (–) |
|---|---|---|---|---|---|
| Sm I | | | | | |
| Avg. | 7.89 | 2,591 | 615 | 121 | 0.43 |
| Min. | 7.06 | 10 | 90 | 90 | 0.01 |
| Max. | 8.50 | 44,000 | 1,999 | 139 | 1.00 |
| SD | 0.28 | 6,435 | 639.16 | 17.18 | 0.34 |
| Sm II | | | | | |
| Avg. | 7.36 | 21,239 | 910 | 382 | 0.52 |
| Min. | 6.03 | 250 | 56 | 118 | 0.63 |
| Max. | 8.44 | 70,000 | 3,315 | 984 | 1.00 |
| SD | 0.78 | 28,063 | 884.63 | 260.25 | 0.39 |
| An I | | | | | |
| Avg. | 6.69 | 17,217 | 975 | 256 | 0.74 |
| Min. | 5.55 | 217 | 151 | 9 | 0.13 |
| Max. | 7.62 | 5,400 | 1,715 | 632 | 1.00 |
| SD | 0.82 | 19,486 | 435.02 | 246.25 | 0.31 |
| An II | | | | | |
| Avg. | 6.76 | 20,437 | 1,219 | 118 | - |
| Min | 5.61 | 200 | 73 | 11 | - |
| Max | 7.65 | 70,000 | 1,714 | 439 | - |
| SD | 0.82 | 22,334 | 435.02 | 152.56 | - |

Sm I: semi-aerobic lysimeter containing 730 kg wastes with compaction density of 640 kg/m$^3$, Sm II: semi-aerobic lysimeter containing 880 kg wastes, 770 kg/m$^3$, An I: anaerobic lysimeter, 830 kg wastes, 730 kg/m$^3$, An II: anaerobic lysimeter, 730 kg wastes, 720 kg/m$^3$.

were correspondingly of organic condition and significantly reduced afterwards. While BOD and TOC were decreasing, pH remained around neutral range and nitrogen as TKN remained elevated [16]. Both COD and $NH_3$-N can be used as stabilization criteria in semi-aerobic landfill [17]. In this study, time required for 90% reduction of BOD concentration in leachate from 44,000 to 5,000 mg/L was only 60 days in the semi-aerobic lysimeter with un-compacted wastes (Sm I), much shorter than 180–210 days for the others. The trend of TOC reduction was similarly to that of BOD. Meanwhile, TKN were sharply increased after a lag period of about 60 days. Afterwards, they were maintained relatively constant in anaerobic lysimeters but gradually reduced under semi-aerobic condition. Nitrite and nitrate detected in leachate from the semi-aerobic lysimeters could be transformed during nitrification reaction under the presence of oxygen in the lysimeters as it was simultaneously observed together with TKN reduction. The destabilization time of semi-aerobic lysimeter in this study was found at the same range as that of aerobic lysimeter operated over 70 days [18] and it required much shorter time than that of anaerobic conditions [18, 19]. Table 2 shows average values and variations of leachate characteristics in terms of pH, BOD, TKN, and $NO_3^-$ in the lysimeters.

## 3.3. Gas Composition and Methane Emission

The variations of $CH_4$, $CO_2$, and $O_2$ concentrations in waste layer

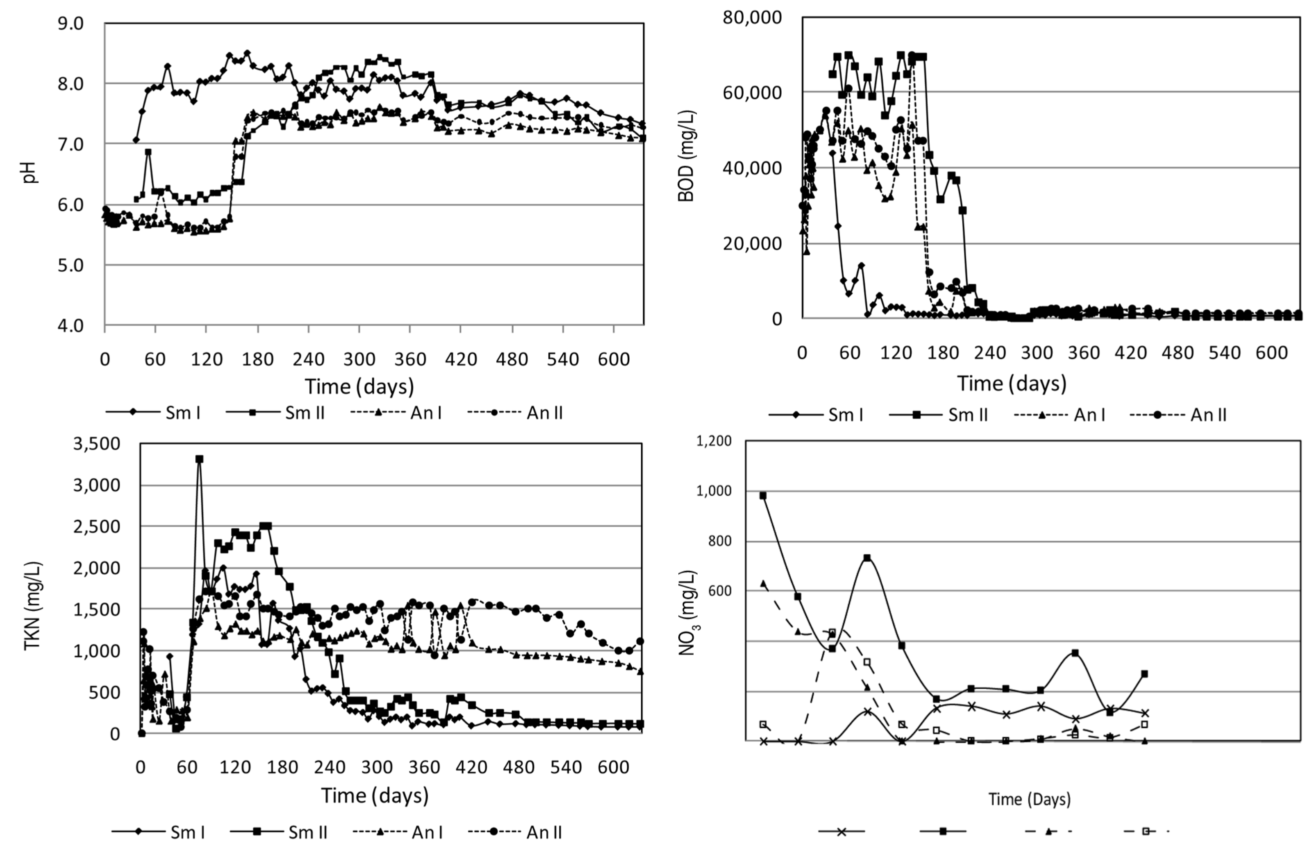


**Fig. 3.** Variation of leachate characteristics during lysimeter operation.

of different lysimeters are monitored. $CH_4$ content in gas from anaerobic lysimeter with 50% leachate storage (An I) was found increased to 60% (v/v) after 120 days and maintained until 480 days of operation. Subsequently, $CH_4$ concentration decreased to about 20%–30% (v/v) afterwards. The changes in $CH_4$ concentrations in An I lysimeter was related to precipitation, being high during day 120–400 and low during day 420–540. In the semi-aerobic lysimeters, $CH_4$ increased to 30% (v/v) and 50% (v/v) in Sm I and Sm II. An increasing in $CH_4$ concentrations in semi-aerobic lysimeter without waste compaction (Sm I) corresponded with rainfall. $CO_2$ in semi-aerobic lysimeters (Sm I, Sm II) were found in range 10%–35% (v/v) along operation period and tended to decrease. On the other hand, anaerobic lysimeter (An I) had $CO_2$ concentration in range between 25%–50% along the operation period. These phenomena indicate the presence of aerobic condition in semi-aerobic landfills (Sm I and Sm II) and it could reduce $CH_4$ and $CO_2$ concentrations from those of anaerobic condition in long-term operation.

The measurement of $O_2$ concentration was also used to confirm the presence of semi-aerobic condition in the lysimeters Sm I and Sm II. The $O_2$ concentration at 0.55 m from the bottom of the lysimeters decreased during initial 120 days of operation. Subsequently their concentrations in Sm I increased to about 20% during day 200–520. In Sm II, the concentration increased gradually after 360 days and finally reached about 15% at the end of experiment. Meanwhile, those in An I maintained lower than 5% throughout the experimental period. Higher concentrations detected at the bottom of the semi-aerobic lysimeters indicated the effectiveness of air intrusion into the waste layer despite having high moisture content at field capacities in those lysimeters (530 mm/m in Sm I and 600 mm/m in Sm II and An I) operated through tropical rainfall event period.

Based on measured $CH_4$ and $CO_2$ concentrations, methane ratio in landfill gas were calculated and their variations are shown in Fig. 4. Their average values and variations are also presented in Table 2. The anaerobic lysimeter (An I) had their methane ratio increased and research completed anaerobic condition (methane ratio=1) after about 100 days of operation whereas those in semi-aerobic lysimeters gradually increased and reached higher degree of anaerobic condition (with methane ratio of 0.6–1.0) after day 200. During the rainfall period (day 160–400), methane ratio in the two semi-aerobic lysimeters were found to be statistically different (0.43 for Sm I and 0.52 for Sm II). Sm II with compacted wastes had higher methane ratio similar to An I lysimeter but methane ratio in Sm I without waste compaction had its methane ratio decreased after 330 days back to original low value at day 420. Reduction of methane ratio in Sm I was well responding to the end of heavy rainfall period after day 270. It was maintained at about 0.3–0.4 during subsequent lower rainfall period during day 320–400 and further reduced to 0 afterwards when the rainfall

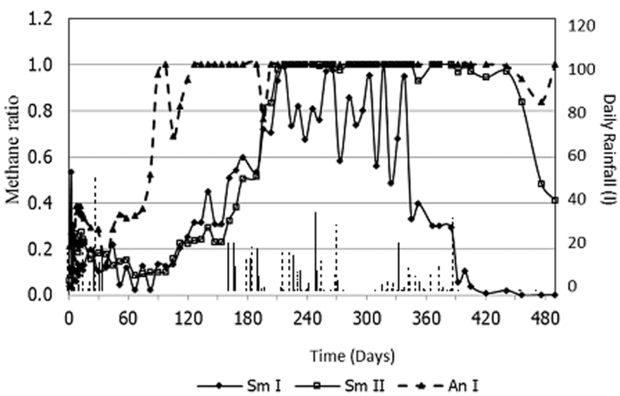


**Fig. 4.** Variation of methane ratio in gas and rainfall events in the lysimeters.

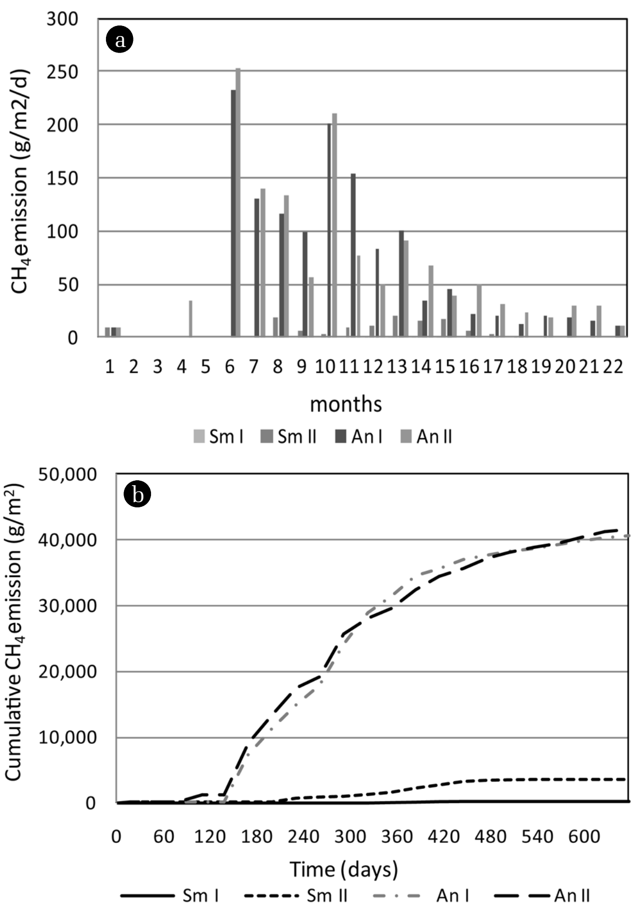


**Fig. 5.** Surface methane emission from the lysimeters: (a) monthly variation and (b) cumulative methane emission.

period was completely terminated. At the end of rainfall period, the moisture content of the waste at the bottom of lysimeter where air was introduced into the lysimeter was found to be about 28%–30%.

The variation in methane emission rates during lysimeter operation is shown in Fig. 5. In the anaerobic lysimeters, methane emission rates were found varied between 9.7–261.4 $mg/m^2/day$ with an average value of 62.6 $mg/m^2/day$. In semi-aerobic lysimeter, the emission rates were mostly lower than 20 $g/m^2/day$ except few events after heavy rainfall. Average emission rate in Sm I was 2.8 $mg/m^2/day$, more than 95% reduction from those under anaerobic condition. The emission rates in Sm II with waste compaction was about 2 times higher than Sm I. Significant reduction in methane emission could be achieved in semi-aerobic condition operated under tropical rainfall events. Interestingly, methane concentrations in waste layer at mid-depth of waste layer in semi-aerobic lysimeter with compaction (Sm II) were found nearly at the same level as anaerobic lysimeter with 50% leachate storage but its methane emission rate was lower by about 90%. The measurements of $CH_4$ concentrations along the depth of waste layer in Sm II revealed that their concentrations at the lower part of waste layer (i.e., 0.55 m) was kept lower than 10% most of the time except during day 240–330. Effective introduction of air at the bottom of lysimeter Sm II during majority of the operation period helped reducing methane concentrations at the upper part of the lysimeters through dilution and oxidation mechanisms thus decreasing their emission by surface diffusion.

### 3.4. Carbon and Nitrogen Balance

Table 3 shows the determination of inflow and outflow of carbon and nitrogen in the lysimeters. During the operation, it was found that carbon was leaching out with leachate from semi-aerobic lysimeter with un-compacted wastes by about 1.8% of original wastes, significantly lower than 3% found in other lysimeters. Other pathway for carbon outflow was via gas emission in the forms of $CH_4$ and $CO_2$. The operation of lysimeter under semi-aerobic condition helped reducing carbon outflow of methane from 16.6%–17.3% in anaerobic lysimeters to only 0.5%–1.4%. Simultaneously, $CO_2$ outflow in gas was also reduced from 13.1%–15.0% to 5.8%–6.4%. Especially in semi-aerobic with un-compacted wastes, $CH_4$ emission could be reduced by more than 99% from that in anaerobic landfill. Previous research has demonstrated that aerobic pre-treatment of wastes facilitated the transfer of organic carbon from uncontrolled biogas and highly polluted leachate to aerobically generated $CO_2$ [20]. In term of nitrogen, nitrogen outflow from the lysimeters as $NH_3$ and organic nitrogen was consid-

**Table 3.** Fate of Carbon and Nitrogen in the Lysimeters

| Element | % of initial waste wt. | Sm I | Sm II | An I | An II |
|---|---|---|---|---|---|
| Carbon | Residual | 41.70 | 46.47 | 56.40 | 36.61 |
| | Leachate | 1.83 | 3.03 | 3.27 | 3.04 |
| | Gas as $CH_4$ | 0.52 | 1.39 | 16.60 | 17.27 |
| | Gas as $CO_2$ | 6.39 | 5.76 | 15.02 | 13.09 |
| | Unaccounted | 49.55 | 43.35 | 8.72 | 29.98 |
| Nitrogen | Residual | 8.30 | 10.22 | 14.41 | 8.90 |
| | Leachate as organic nitrogen | 9.41 | 11.04 | 25.43 | 35.07 |
| | Leachate as $NH_3$ | 7.68 | 9.21 | 27.60 | 42.47 |
| | Unaccounted | 74.61 | 69.53 | 32.57 | 13.57 |

ered as the $N_2$ emission in gaseous form could not be accounted. Similar to the carbon trend, nitrogen outflow from semi-aerobic lysimeters could be reduced from 28%–42% and 25%–53% in $NH_3$ and organic nitrogen forms to 7.7%–9.2% and 9.4%–11.0%, respectively. Majority of unaccounted nitrogen in semi-aerobic lysimeters was possibly contributed from nitrogen transformed through nitrification and denitrification reactions under semi-aerobic condition in the lysimeters. During their transformation, the oxidized nitrogen forms ($NO_2^-$, $NO_3^-$) could be produced by the introduction of oxygen during semi-aerobic condition and subsequently reduced back mainly to $N_2$ gas. In real operating landfills, nitrogen can also be found in the drainage layer, or could be lose as $NO_x$ or $N_2O$ gas [21]. $N_2O$ could also be generated from the aerated landfills where nitrification and denitrification existed simultaneously [22, 23]. Other possible mechanism could be the transformation of nitrogen by anammox bacteria in the system [24].

## 4. Conclusions

Semi-aerobic landfill operated under natural ventilation helped improving leachate quality and reducing methane emission in comparison to anaerobic condition. Despite of having high moisture wastes operated under tropical rainfall period, more than 90% of organic reduction in leachate could be achieved within 60 days. Ammonia nitrogen in leachate also reduced up to 90% through nitrification reaction. Nevertheless, waste compaction should be properly controlled to facilitate air flow into the waste body. Methane emission rate from semi-aerobic lysimeter was fluctuated seasonally but maintained at 2.8 $g/m^2/day$ on average, much lower than 62.6 $g/m^2/day$ observed under anaerobic condition.

## Acknowledgments

This research was carried out under Center of Advanced Studies in Industrial Technology, Faculty of Engineering, Kasetsart University as a collaborating project between Kasetsart University, King Mongkut's University of Technology Thonburi, and National Institute for Environmental Studies, Japan. The authors would like to thank Kasetsart University Research and Development Institute for providing partial funding for this research work.

## References

1. Booker T, Ham R. Stabilization of solid waste in landfills. *J. Environ. Eng.* 1982:26:1089-1100.
2. Huang Q, Yang Y, Pang X, Wang Q. Evolution on qualities of leachate and landfill gas in the semi-aerobic landfill. *J. Environ. Sci.* 2008:20:499-504.
3. Hanashima M. Pollution control and stabilization process by semi-aerobic landfill type: the Fukuoka method. In: SARDINIA 99: Proceedings of the Seventh International Waste Management and Landfill Symposium; 1999 Oct 4-8; Cagliari, Italy. p. 313-326.
4. Intergovernmental Panel on Climate Change. 2006 IPCC Guidelines for national greenhouse gas inventories. Hamaya: Institute for Global Environmental Strategies; 2006.
5. Kim HJ, Yoshida H, Matsuto T, Tojo Y, Matsuo T. Air and landfill gas movement through passive gas vents installed in closed landfills. *Waste Manag.* 2010;30:465-472.
6. Read AD, Hudgins M, Phillips P. Aerobic landfill test cells and their implications for sustainable waste disposal. *Geogr. J.* 2001;167:235-247.
7. Huo SL, Xi BD, Yu HC, Fan SL, Jing S, Liu HL. In situ simultaneous organics and nitrogen removal from recycled landfill leachate using an anaerobic-aerobic process. *Bioresour. Technol*. 2008:99:6456-6463.
8. Aziz SQ, Aziz HA, Yusoff MS, Bashir MJ, Umar M. Leachate characterization in semi-aerobic and anaerobic sanitary landfills: a comparative study. *J. Environ. Manag.* 2010;91:2608-2614.
9. Chong TL, Matsufuji Y, Hassan MN. Implementation of the semi-aerobic landfill system (Fukuoka method) in developing countries: a Malaysia cost analysis. *Waste Manag.* 2005;25:702-711.
10. Dong L, Wang Q, Li H, Huang SH. The research of acceleration for stabilization in the landfill site. *China Environ. Sci.* 2000; 20:461-464.
11. Ritzkowski M, Stegmann R. Landfill aeration worldwide: concepts, indications and findings. *Waste Manag*. 2012;32:1411-1419.
12. Tränkler J, Visvanathan C, Kuruparan P, Tubtimthai O. Influence of tropical seasonal variations on landfill leachate characteristics--results from lysimeter studies. *Waste Manag.* 2005;25:1013-1020.
13. ASTM International. Standard test method for determination of the composition of unprocessed municipal solid waste. West Conshohocken: ASTM International; 2003. ASTM D5231-92: 2003.
14. Chiemchaisri C, Chiemchaisri W, Sittichoktam S, Tantichantakarun T. Application of partially submerged bioreactor landfill for leachate management in the tropics. *Int. J. Environ. Waste Manag*. 2009:3:78-90.
15. Clesceri LS, Greenberg AE, Eaton AD. Standard methods for the examination of water and wastewater. 20th ed. Washington: American Public Health Association; 1999.
16. Benson CH, Barlaz MA, Lane DT, Rawe JM. Practice review of five bioreactor/recirculation landfills. *Waste Manag.* 2007; 27:13-29.
17. Tang P, Zhao Y, Liu D. A laboratory study on stabilization criteria of semi-aerobic landfill. *Waste Manag. Res.* 2008;26: 566-572.
18. Sun Y, Sun X, Zhao Y. Comparison of semi-aerobic and anaerobic degradation of refuse with recirculation after leachate treatment by aged refuse bioreactor. *Waste Manag.* 2011;31:1202-1209.
19. Erses AS, Onay TT, Yenigun O. Comparison of aerobic and anaerobic degradation of municipal solid waste in bioreactor landfills. *Bioresour. Technol.* 2008;99:5418-54 26.
20. Zhang Y, Yue D, Nie Y. Greenhouse gas emissions from two-stage landfilling of municipal solid waste. *Atmos. Environ.*

2012:55:139-143.

21. Valencia R, van der Zon W, Woelders H, Lubberding HJ, Gijzen HJ. Achieving "Final Storage Quality" of municipal solid waste in pilot scale bioreactor landfills. *Waste Manag.* 2009;29:78-85.
22. Carter MS. Contribution of nitrification and denitrification to $N_2O$ emissions from urine patches. *Soil Biol. Biochem.* 2007:39:2091-2102.
23. He P, Yang N, Gu H, Zhang H, Shao L. $N_2O$ and $NH_3$ emissions from a bioreactor landfill operated under limited aerobic degradation conditions. *J. Environ. Sci. (China)* 2011;23:1011-1019.
24. van Niftrik LA, Fuerst JA, Sinninghe Damsté JS, Kuenen JG, Jetten MS, Strous M. The anammoxosome: an intracytoplasmic compartment in anammox bacteria. *FEMS Microbiol. Lett.* 2004;233:7-13.