

Enhancing Landfill Gas Production by Methanogenic Sand Layer

N. Sapari, S. Mustapha and H. Jusoh

Abstract—Landfill gas, particularly methane is one of the greenhouse gases which contributes to global warming. This paper presents the findings of a study on methane gas production from simulated landfill reactor under saturated conditions. A reactor was constructed to represent a landfill cell of 2.5 m thickness on sandy soil. The reactor was 0.2 m in diameter and 4 m in height. One meter of sand and pebble layer was packed at the bottom of the reactor followed by 2.5 m of solid waste layer and 0.4 m of sand layer as the cover soil. Degradation of waste in the solid waste layer was at acidification stage as indicated by the leachate quality with COD as high as 55,511 mg/L and pH as low as 5.1. However, methanogenic environment was established at the bottom sand layer after one year of operation indicated by pH of 7.2 and methane gas generation. Leachate degradation took place as the leachate moved through the sand layer at an infiltration of rate 0.7 cm/day. This resulted in landfill gas production of 77 mL/day/kg containing 55 to 65% methane. The application of sand layer contributed to the gas production from landfill by an in-situ degradation of leachate in the sand at the bottom of the landfill.

Keywords—Gas production, methane, methanogenic sand layer, municipal solid waste, saturated landfill

I. INTRODUCTION

LANDFILLING of solid waste is a common practise in many cities. The problem with landfills is that they generate gases that contribute to global warming. Initial gas production from the landfill, during acinogenic phase, is mainly carbon dioxide with some 5% other gases consisting of nitrogen and hydrogen [1]. In the later phase, during methanogenic stage, nitrogen and hydrogen diminish and the landfill gas contains mainly methane (55%) and carbon dioxide (45%) [2]. These gases may be emitted to the atmosphere through gas vents or the surface of the landfill. Methane is a potent green house gas 21 times higher than carbon dioxide in terms of its potential to cause global warming [3].

Current practice of landfill gas extraction is to collect the gas from the waste layer [4]. However, the recovery rate of the gas is generally low at around 50% from of the theoretical volume [5]. This is probably due to some of the gases escaping through

the surface of the landfill or leachate collection pipes. Studies have shown that methane production decreases at pH value less than 6.0 [6]-[7]. While young landfills produce leachate with pH around 5, mature landfills generate leachate with pH above 7 [8]. The pH of the leachate will depend not only on the concentration of the acids that are present but also on the partial pressure of the carbon dioxide in the landfill gas that is in contact with the leachate [9]. When the process of anaerobic degradation of municipal solid waste in a landfill reaches the methanogenic, more organic material is transferred into the gaseous phase and less into the liquid phase. As a result, biogas production increases, more profitable energy is available and less energy and cost are required for treatment of the leachate [10]. Experiences in many countries of the world show that landfill gas can be successfully used as an alternative energy source [11]. Countries like United States, West Germany, United Kingdom, Sweden, Denmark, Canada and Australia have managed to exploit landfill gas as a fuel for electricity generation [12]. In addition, collecting and generating energy from landfill gas provide economic benefits to landfill owners [13]. Therefore, it is necessary to improve the gas extraction system in order to maximize the gas collection for recovery purposes and environmental protection.

The purpose of this paper is to presents the findings of a laboratory study on leachate degradation and gas production from a simulated landfill under saturated condition. The objective of the study was to examine the use of sand layer placed below the landfill as anaerobic filter for the enhancement of the methanogenic process.

II. MATERIALS AND METHODS

A laboratory landfill reactor was constructed from a PVC pipe column with dimensions of 4 m height and 0.2 m in internal diameter (Fig. 1). The column was divided into four sections of 1 m each and were stacked after packing them one by one from the bottom upwards by using flanges. Rubber gaskets were used to seal the gaps between the flanges.

The reactor was equipped with probes and leachate sampling taps to facilitate the monitoring of temperature, leachate quality, pH, Eh and gas production. One opening was also made at the bottom of the reactor for drainage and sampling of the leachate. Two openings were made at the top cover; one with a slightly lower projection tube for the input water and the other was for the gas outlet. Two 31 L water tanks; one at a level higher than the top of the reactor and the other at the lower level, were used to feed the water into the reactor. Both tanks were connected to a pump; the lower tank was used to feed the higher tank and the higher tank was used to feed the reactor. The reactor was fed with rainwater without recirculating the leachate.

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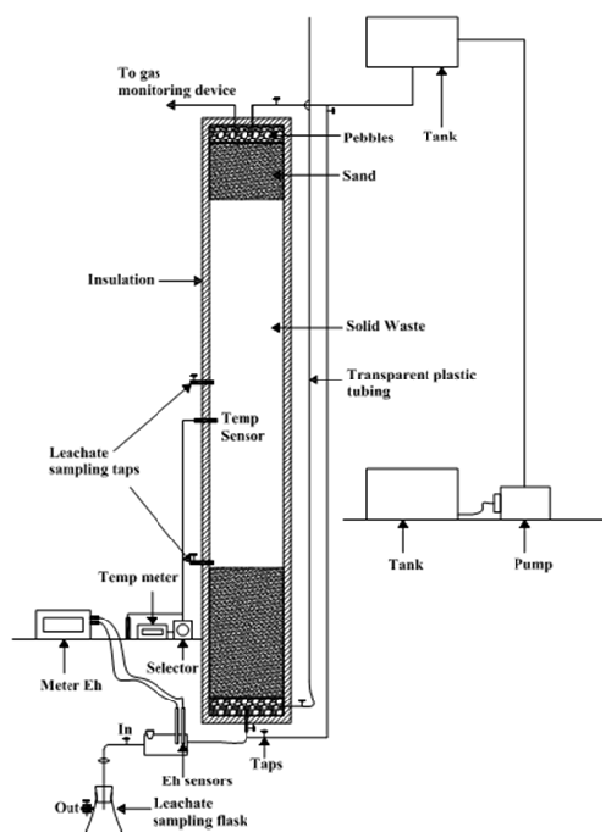


Fig. 1 Reactor assembly

A. Packing of Reactor

The packing of the reactor was carried out from the bottom upwards in the following order:

i. Bottom Pebble And Coarse Sand Layer

The bottom part of the reactor was packed with quartz pebble of 1 cm average diameter, to a depth of approximately

10 cm. Above this, coarse sand (retained by sieves of 1.7 mm, 1.4 mm, 500 μ m and 350 μ m) was packed to another 10 cm depth with the finest grain layer at the top. The function of this pebble layer was to support the material above so that it would

Top	0.05	top pebble layer
	0.45	covering sand
	2.50	solid waste layer
	0.80	underlying sand layer
Bottom	0.20	supporting pebble layer

elutriate through the bottom opening during the sampling of the leachate. Pebble was chosen as it is inert in nature and chemical reactions between this material and leachate could be avoided.

ii. Underlying Sand Layer

A sand layer was packed on top of the pebble layer. The packing was carried out at an increment of 3.8 cm thickness with an average packing density of 1.58 g/cm³. This value was based on the bulk density of the sandy soil in the field. The sand was packed to a depth of 80 cm at the bottom 1 m section of the reactor. This sand layer was designed to allow leachate and gas movement below the reactor under controlled condition.

iii. Solid Waste Layer

Solid waste with a composition similar to the average composition of municipal waste in Malaysia was packed inside the reactor to a thickness of 2.5 m. The composition of the solid waste is shown in Table I. A total of 43.775 kg solid waste was needed to fill up the reactor with a packing density of 0.52 g/cm³.

The solid waste was cut into small pieces (average size between 1 and 2 cm) and was mixed thoroughly before packing. The size reduction was done to facilitate the packing process. The size reduction also could speed up the degradation process [14]. Thus, it allows faster stabilization of the waste.

TABLE I
SOLID WASTE COMPOSITION WET WEIGHT AND MOISTURE
CONTENT PERCENTAGE

Composition	Wet weight (%)	Moisture content of the total waste (%)
Paper products:		
Corrugated card	12.6	0.63
Newspaper	11.4	0.68
Food waste:		
Meat scraps and fats	11.4	0.50
Seafood scraps	22.9	3.41
Vegetable waste	13.4	1.62
Fruit waste	0.9	0.01
Garden waste:		
Lawn clippings	8.0	0.38
Plant clippings	5.6	0.25
Metal:		
Steel cans	4.1	0.12
Aluminum	0.3	0.01
Ferrous and other metals	1.7	0.05
Wood	0.3	0.06
Rag	0.5	0.14
Others (glass, plastic and inert waste)	6.9	0.14
Total	100	8.00

iv. Soil Cover

A layer of sand was placed on top of the solid waste to a thickness of 40 cm as a cover material. Above the sand, a layer of 5 cm quartz pebble was placed as a final cover. This pebble layer was used to reduce the scouring effects of water as it was introduced from the top of the reactor.

B. Reactor Initiation and Monitoring

Moisture was introduced gradually from the bottom part of the reactor by connecting the bottom drainage with the higher tank using a plastic tubing and a control tap as shown in Figure 1. A total of 49.9 L rain water was introduced into the reactor at the beginning of the experiment. The level of the water and the pressure inside the reactor were monitored by an open-ended plastic tube, connected to the lower part of the reactor, placed vertically at the side of the reactor to a level as high as the feed tank. The reactor was operated at a saturated condition and the level of water inside the reactor was always kept above the top of the solid waste layer. Leachate and gas quality generated by the reactor were monitored over a total period of 24 months. The leachate samples were collected from the middle of the reactor, from the base of solid waste layer and the bottom drainage to analyze the COD and the pH. Performance of the methanogenic process in the bottom sand layer as an anaerobic filter to enhance landfill gas production was examined by test loading and continuous loading of the sand layer with COD through leachate mobilization.

i. Gas Monitoring

The arrangement of the gas monitoring apparatus is shown in Fig. 2. The flow of gas through the system was controlled by 3 valves.

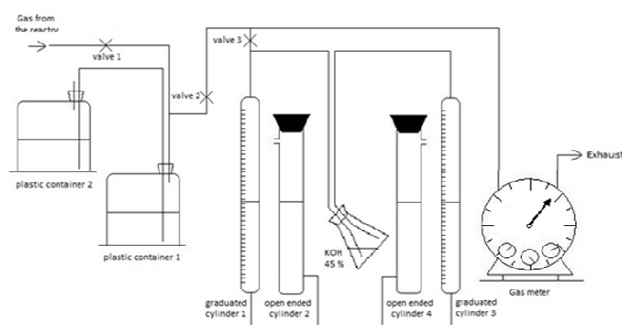


Fig. 2 Gas monitoring apparatus

The gas emitted from the reactor was collected in a 4 L plastic container 1 above acidified water by closing valve 2. Gas from the reactor developed a pressure that pushed the acidified water into another 4 L plastic container 2. The plastic container 1 was air tight, while the plastic container 2 had an opening at the top of the container, for pressure equalization to the surrounding environment. The height of the plastic container 2 was adjustable so that the acidified water could flow from container 2 to container 1, or vice versa, through siphoning effect. Container 1 was also used as a gas reservoir for gas sampling to determine the methane content, by bubbling the gas through 45% KOH solution. The procedure involved sampling of 500 mL of gas into a specially designed graduated cylinder which had opening at the top and at the bottom of the cylinder, above acidified water. The cylinder was connected to another open ended cylinder which is connected through a plastic tubing. The level of water inside

the cylinder was adjustable by controlling the height of the open ended cylinder, based on siphoning effect.

The determination of methane content was done by closing valve 1, 2 and 3, to allow the sampled gas in the graduated cylinder 1 to be bubbled through KOH solution. The gas in the graduated cylinder 1 was flushed out by increasing the height of the open ended cylinder 2. After the gas was bubbled through KOH solution, the gas would fill up the graduated cylinder 3. Similar arrangement was made for graduated cylinder 3 and open ended cylinder 4. Repeated bubbling procedure was made by tilting the conical flask that contained KOH from one side to another. The bubbling process was considered complete when the volume of gas remaining in the graduated cylinder remained constant. This determination of methane percentage in the gas was conducted weekly.

After the determination process, valve 1 and 2 were opened and valve 3 was closed so that the gas from the reactor would flow directly to the gas meter for gas volume determination on weekly basis. A wet gas meter (V1-2L by MaxiFlo) was connected to the gas outlet tubing for the measurement of total gas production.

ii. Test Loading

The test loading was introduced into the sand layer by draining 3.5 L of leachate from the bottom opening. Through this, similar amount of leachate would flow from the solid waste layer into the underlying sand layer.

Leachate movement into the sand layer was calculated based on the pore volume of the sand layer. From the calculations it was found that the total pore volume of the sand layer and the supporting pebble layer was 13.5 L. It means that the 3.5 L of leachate from the solid waste layer was equivalent to about 26% of the total liquid inside the bottom sand and pebble layers.

A similar volume of rain water was introduced into the landfill reactor through the top opening. By this procedure, the amount of moisture inside the reactor was considered to be approximately constant.

After draining the leachate the reactor was monitored for another 2 months. The daily rate of gas production was monitored by using a gas meter. Weekly samples of the gas were collected for analyzing the methane content according to the procedure in Section 2.2.1

iii. Continuous Loading

After the test loading and a rest period of about 8 weeks, a continuous loading experiment was carried out. Leachate generated by the solid waste layer was introduced into the underlying layer weekly by draining 1.5 L of leachate from the bottom drainage. At this draining rate it was calculated that the leachate would have an average detention time of 9 weeks with leachate flow in the sand layer at the rate of 0.7 cm/day. This calculation was based on the total pore volume of the sand and the supporting pebble layers divided by the volume of the leachate collected weekly. Obviously, gas developed inside the sand layer and the effective pore volume had become smaller; therefore the actual detention time could be shorter than the

calculated value. Based on the internal diameter of the reactor of 20 cm, the internal surface area of the reactor was 314 cm². Thus, the infiltration rate was calculated to be 0.7 cm/day.

The continuous loading experiment lasted for about 3 months. During the period, samples of leachate from the bottom drainage, the base of the solid waste layer and the middle of the solid waste layer were collected every week. The samples were analysed for pH, COD and BOD. Nutrient levels, namely ortho-P and ammonia-N, were also determined. Redox conditions (Eh) were also determined during the collection of samples.

Before collection of the leachate, approximately 3 L of gas was collected from the reactor in 4 L plastic containers. This was done by closing the outlet taps. This method was done to maintain the pressure inside the landfill model even during sampling of leachate through the bottom drainage. The temporary gas storage chamber also provided gas samples for the determination of the methane and carbon dioxide ratio (percentage of other gases was considered small). A sample of 0.5 L gas was used for each determination by bubbling through 45% KOH solution to a constant volume. Two samples of gas were determined every week. The volume of the leachate samples collected every week were measured and recorded. Replacement rain water of similar volume was then introduced into the reactor through the top water inlet.

A total of 18.7 L of leachate was collected from the bottom drainage over the period of the continuous loading experiment. The total amount of leachate collected was equivalent to about 1.4 times the pore volumes of the underlying sand and pebble layers.

Monitoring of the reactor were conducted until the end of the 24 months research period. The monitoring were done based on gas production and leachate quality from the middle solid waste layer, the base solid waste layer and the bottom sand layer.

III. RESULTS AND DISCUSSION

A. Reactor Monitoring

Results of the reactor monitoring is presented in forms of leachate quality and rate of the gas production. The average leachate quality in every six-month period is shown in Table II.

Leachate quality from the middle section of the reactor in the first six months, shows gradual increase in COD to almost 5000 mg/L. This can be seen from the high standard deviation of 3410 mg/L with the mean of 4560 mg/L. Further increase of COD was found in the following six and twelve months. After 18 months, the COD levels from the middle section stabilized at around 36000 mg/L. Leachate quality from the base of the solid waste layer indicated that the COD increased from 1340 mg/L to maximum of 4590 mg/L after 18 months of operation. The level decreased to around 4000 mg/L in subsequent months.

Leachate from the bottom sand layer, shows that COD levels increased from around 900 mg/L to maximum of 2600 mg/L over a period of 18 months. In the subsequent months, the COD reduced to 2280 mg/L.

The pH condition in the middle of the solid waste layer was found to be consistent at around 5.1. However, pH of the leachate from the base of the solid waste layer and the bottom of the sand layer were always higher than 7.1. The pH levels in both base and bottom indicated favourable condition for methanogenic process to take place. This process can be examined from the quality of gas generated by reactor.

The laboratory temperature, reactor temperature and total gas production for a period of two years is depicted in Fig. 3a and 3b. The gas production indicates slight variation in the rate which most probably was influenced by the temperature variation during the experiment. During the 10th and 12th months when the temperature was lower, the production of gas was also low. A steady rate of gas production was achieved approximately 4 months after complete saturation. At this stage, a maximum gas production of 3.65 L/kg solid waste per week was generated.

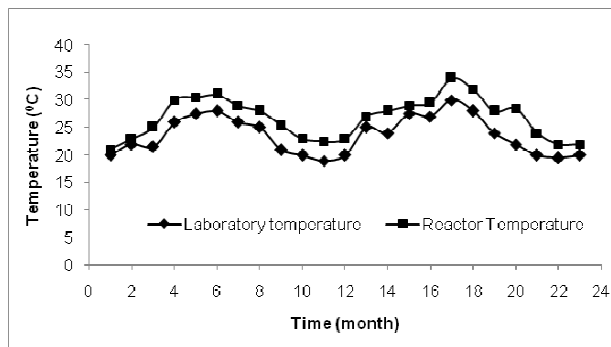


Fig. 3a Laboratory and reactor temperature

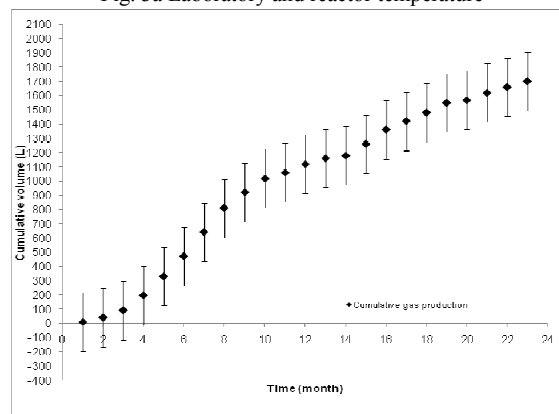
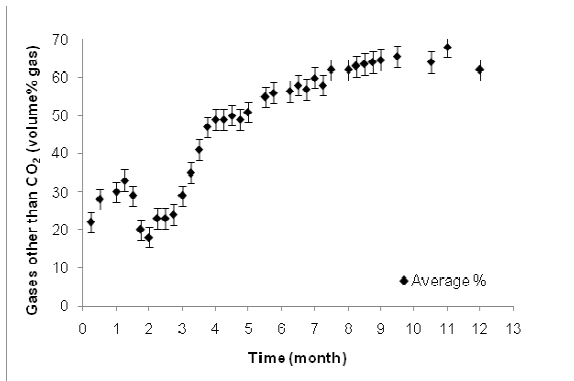


Fig. 3b Cumulative gas production from the reactor

TABLE II
AVERAGE OF LEACHATE QUALITY FROM REACTOR IN EVERY SIX MONTHS

Section of reactor	Parameter	Mean and Standard deviation	Period (month)			
			6	12	18	24
Middle solid waste layer	COD x 10 ³ mg/L	\bar{X}	4.56	37.83	36.17	35.65
		SD	0.34	1.32	2.04	1.08
	pH	\bar{X}	5.22	5.22	5.18	5.12
		SD	0.12	0.08	0.06	0.07
	COD x 10 ³ mg/L	\bar{X}	1.34	3.15	4.59	3.93
		SD	0.38	0.28	0.22	0.23
Base solid waste layer	pH	\bar{X}	7.17	7.11	7.09	7.15
		SD	0.06	0.09	0.08	0.09
	COD x 10 ³ mg/L	\bar{X}	0.91	2.17	2.58	2.28
		SD	0.03	0.24	0.9	0.2
	pH	\bar{X}	7.24	7.35	7.33	7.20
		SD	0.13	0.12	0.11	0.08

Results from the volume determination of the gas after CO₂ removal by KOH is presented in Fig. 4. The first two months represent the early phase of gas production where the peak may indicate the presence of other gases that did not react with KOH, such as nitrogen and hydrogen as mentioned by Farquhar and Rovers [2]. This period is interpreted as the acid-producing stage. The two-month period after this represents the beginning of the methanogenic stage.

Fig. 4 Volume percentage of gases other than CO₂

After six months, a steady methane content of approximately 55% (with variation around 3%) was achieved. Further determinations of the methane content indicated a gradual increase from 55% to about 65% after one year (Fig. 4). The result is comparable to the findings of researchers that the methane content increases to around 55% during the methanogenic stage [1],[2],[15]. After one year, the percentage of methane remained at around 65% till the end of the experiment.

B. Results of Leachate Mobilization

i. Leachate Characteristic

The pH of the leachate sample from the middle of the reactor was always low with an average of 5.1. However, the leachate sample from the bottom tap was found to have pH level consistently above 7 as shown in Fig. 5a. The increase in pH was obviously due to an increase in methanogenic activity within the underlying sand layer that resulted in an increase of alkalinity from carbon dioxide contact with the leachate. The Eh level of the leachate dropped very rapidly to below 250 mV as shown in Fig. 5b. This Eh level was found to be consistently low through out the study period.

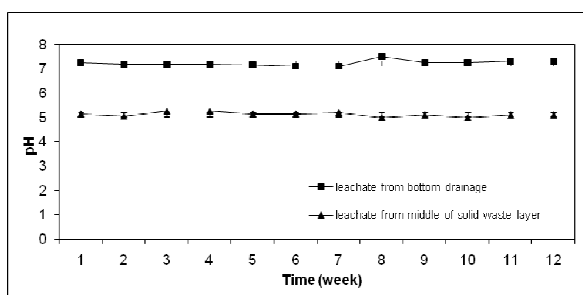


Fig. 5a pH levels of the leachate collected during continuous loading

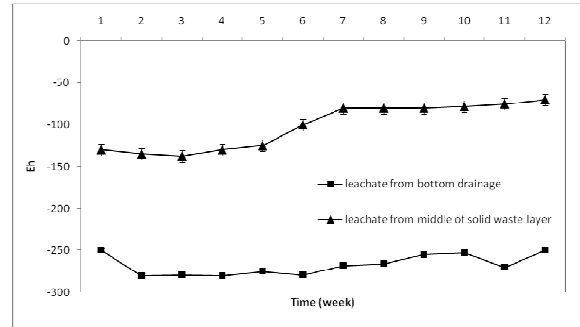


Fig. 5b Eh levels of the leachate collected during continuous loading

The results of the leachate analysis from the middle of solid waste layer and the bottom of sand layer at the beginning of the test loading are presented in Table III. The leachate from the middle of solid waste layer contained high COD and ammonia levels at 55,511 and 1,480 mg/L, respectively. The pH of the leachate was 5.1

TABLE III
LEACHATE QUALITY FROM MIDDLE OF SOLID WASTE LAYER
AND BOTTOM OF SAND LAYER AT THE BEGINNING OF TEST
LOADING

Parameter	Leachate quality	
	Leachate from middle of solid waste layer	Leachate from bottom of sand layer
COD	55,511 mg/L	2,736 mg/L
BOD	39,042 mg/L	635 mg/L
Ammonia-N	1,480 mg/L	738 mg/L
Ortho-P	14.5 mg/L	5.6 mg/L
pH	5.1	7.4

Twelve months before the test load, the reactor was kept in a very minimal leachate mobilization. During the period, the movement of leachate into the saturated bottom sand layer was through diffusion process and limited flow due to leachate sampling from the bottom tap at the rate of 300 mL/week. With this minimal leachate movement the levels of COD in the reactor remained high at around 55,511 mg/L as shown in Table III.

Under complete saturation conditions and slow mobilization of leachate, as in this study, the methane fermentation process in the middle of the reactor was inhibited by the low pH. The high level of COD in the leachate is the evidence of this phenomenon (Fig. 6). Ammonia level in the leachate was as high as 1,480 mg/L but this level is below the limit that can cause toxicity to anaerobic process [16]. Nevertheless, the level of ammonia in the leachate from the bottom of the sand layer was found to be lower than leachate from the middle of solid waste layer, probably due to the dilution effect and assimilation into the biomass in the sand layer.

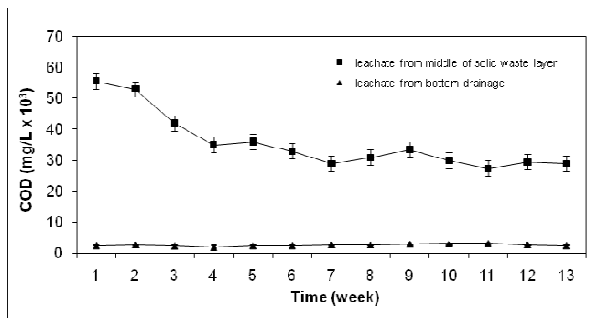


Fig. 6 COD levels in the leachate collected during continuous loading

ii. Temperature Condition During Test And Continuous Loading

Average weekly laboratory and reactor temperature, and average total gas production are presented in Fig. 7a and 7b. The average temperature was measured weekly and found to be fluctuating between 21 and 34°C. Results of the temperature monitoring inside the reactor indicated that, in general, the average reactor temperature was slightly higher by 3 to 4°C than the average laboratory temperature.

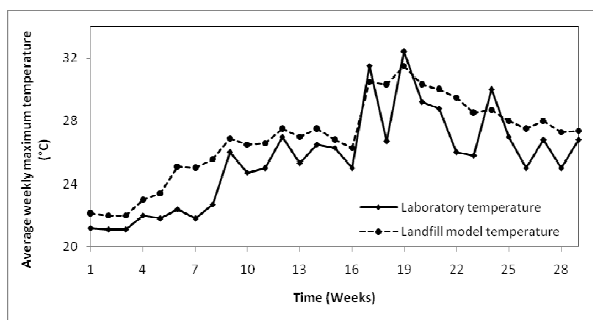


Fig. 7a Average weekly laboratory temperature and reactor temperature

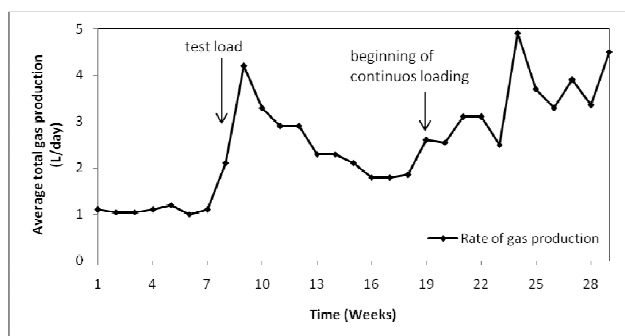


Fig. 7b Rate of gas production

The temperatures were found to have influence on the rate of gas production. The average weekly gas production rates during the hotter weeks were higher than the rates in the cooler weeks.

iii. Gas Production And Leachate Quality During Test

Loading

The general pattern of gas production indicates a strong correlation with the movement of leachate from the solid waste layer into the underlying sand layer. Before the leachate was mobilized, gas production ranged between 0.85 and 1.1 L/day. Based on the total weight of the solid waste inside the reactor (43.8 kg), it was calculated that the total gas production was equivalent to 19.4 mL/day/kg to 25 mL/day/kg of solid waste with an average rate of around 22 mL/day/kg.

Results from the test load were associated with a marked increase in gas production (Fig. 7b). The daily gas production increased from about 22 mL/day/kg to about 47.9 mL/day/kg. In the following week, the production increased again to around 94 mL/kg/day. This indicates that the introduction of leachate during the test load resulted in rapid methanogenic conversion of fatty acid in the sand layer.

The test load was followed by a resting period of about two months. During the resting period, the average weekly laboratory temperature fluctuated between 24 and 26°C. The daily rate of gas production during the resting period decreased gradually from 94 mL/day/kg to an average of 43.8 mL/day/kg.

Taking into consideration that 3.5 L of leachate with 635 mg/L BOD were withdrawn and consequently 1.5 L of leachate with 39042 mg BOD/L were introduced into the sand layer, it was calculated that 50 g of carbon was converted into gas. This calculation was based on 12 g carbon require 32 g O₂ to be oxidised. However, based on the total gas production from the reactor it was found that a total of 90 g carbon had been removed in the form of gas. This indicated that 50 g out of 90 g Carbon were converted into gas in the sand layer. Thus, the introduction of leachate into the sand layer had increased the production of gas from the reactor by more than 50%.

During the sampling of leachate at the bottom of solid waste layer, it was found that gas accumulated at the bottom of the solid waste layer as it was indicated by the hissing sound of gas escaping through the sampling port followed by gas bubble that came out together with leachate. This was not the case for the leachate sampling taps from the middle of solid waste layer and from the bottom of sand layer. This shows that gas movement through the sand layer is faster than the movement through the solid waste layer.

The increase in gas production to 4.2 L/day as shown in Fig. 7b indicates that methanogenic process became active as the result of the introduction of degradable organic materials in leachate into the sand layer. The gradual decrease in gas production during the rest period indicated that the amount of degradable organic material was decreased gradually with time as the process of fermentation continued. Nevertheless, the production rate was maintained at a certain minimal level of around 2 L/day. This minimal rate was probably due to the movement of organic materials through diffusion from high

COD concentration area particularly in the middle solid waste layer to areas of lower COD concentration at the base of solid waste layer and the sand layer. Methane gas may also be generated from certain part of solid waste layer where methanogenesis may occur.

Anaerobic fermentation of leachate inside the underlying sand and pebble layers during test loading resulted in an increased production of methane and carbon dioxide gases as shown in Fig. 6. In the process, COD was removed. The condition inside the sand layer was found to be favourable for the methanogenic process as indicated by favourable pH and Eh conditions (Fig. 5). The methanogenesis process inside the reactor converted the acid in leachate to methane and carbon dioxide and resulted in increase of pH to above 7. Similar observation of increase in pH during methanogenic phase was made by other researcher [9].

iv. Gas Production During Continuous Loading

Results of gas monitoring during the continuous loading experiment (Fig. 7b) indicated that the gas production rate increased to a maximum of 106 mL/day/kg with an average of 77 mL/day/kg. This suggested that the introduction of leachate into the sand layer increased the methanogenic activities in the bottom layer. These results are in agreement with the earlier observation that leachate mobilization into the sand layer resulted in higher gas production rate with an average of 77 mL/day/kg. This rate was achieved for the high strength leachate (COD above 30000 mg/L) under continuous movement of leachate at infiltration rate of 0.7 cm/day.

The ratio between nutrient elements and organic materials (N:P:BOD) was found to be 102:1:2700 in the leachate samples from the middle of the solid waste layer. This ratio was lower than the recommended optimum ratio of 5:1:100 for treatment of organic waste water by aerobic processes [17]. However, despite the low levels of soluble phosphate, the methane fermentation was took place normally inside the underlying sand layer. This situation was clearly indicated by the high rate of gas production associated with reduction of COD over 95%. The ratio in the leachate after flowing through the sand layer was about 110:130:1.

IV. CONCLUSION

Young landfills of less than two years old under a saturated condition produces leachate that contains high COD and BOD up to 55000 mg/L and 35000 mg/L respectively. The pH of the leachate is low at around 5.2. This high strength leachate can be treated to produce methane gas in a sand layer below the landfill. The sand layer with a thickness of 1 m can be acclimatized for methanogenesis by gradual introduction of the leachate into the sand over a 12-month period. Leachate mobilization through the sand layer at an infiltration rate of 0.7 cm/day increases the production of the gas by about 50 percent. Thus, the gas can be collected for energy recovery even from young landfills.

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REFERENCES

- [1] Pohland, F. G., 1991. Critical review and summary of leachate and gas production from landfills, EPA/600/S2-86/073, U.S. EPA Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, 1987.
- [2] Farquhar, G.J., and Rovers, F.A., 1973. Gas production during refuse decomposition. *Water, Air and Soil Pollution* 2, 403-495.
- [3] Ayalon, O., and Avnimelech, Y., 2009. Solid waste treatment as a high-priority and low-cost alternative for greenhouse gas mitigation. *Environmental Management*, Vol. 27, No. 5, 697-704.
- [4] Vesilind, P. A., Worrell, W. and Reinhart, D., 2002. *Solid Waste Engineering*, 133.
- [5] Augenstein, D., and Pacey, J., 1992. Landfill gas energy utilization: technology options and case studies. EPA-600-R-92-116, EPA, Research Triangle Park.
- [6] Brummeler, E., Hulshoff, P. L., Dolfing, J., Lettinga, G., and Zehnder, A., 1985. Methanogenesis in an upflow anaerobic sludge blanket reactor at pH 6 on an acetate-propionate mixture. *Applied and Environmental Microbiology*, Vol. 49, No. 6, 1472-1477.
- [7] Speece, R., 1996. *Anaerobic biotechnology for industrial wastewaters*.
- [8] Ehrig, H. J., 1983. Quality and quantity of sanitary landfill leachate. *Waste Management and Research* 1, 53-68.
- [9] Tchobanoglous, G., Theisen, H., and Vigil, S. A., 1993. Integrated solid waste management. *Engineering principles and management issues*, 387.
- [10] Iglesias, J.R., Pelaez, L.C., Maison, E.M., and Andres, H.S., 2000. Biomethanization of municipal solid waste in a pilot plant. *Wat. Res.*, Vol. 34, No. 2, 447-454.
- [11] Gendebian, A., Pauwels, M., Constant, M., 1992. Landfill gas, from environment to energy, commission of the European communities.
- [12] Richards, K.M., 1987. Landfill gas- a global review. *Biodegradation*, Vol. 7, 161-175.
- [13] Spokas, K., J. Bogner, J.P. Chanton, M. Morcet, C. Aran, C. Graffa, Y. Moreau-Le Golvan, I. Hebe, 2006. Methane mass balance at three landfill sites: what is the efficiency of capture by gas collection systems? *Waste Management*, Vol. 26, 516-525.
- [14] Hentrich, R. L., Swartzbough, J. T. And Thomas, J. A., 1979. Influence of municipal solid waste [rocessing on gas and leachate production. *Municipal Solid Waste*.
- [15] Parker, A., 1983. Chapter 7. Behaviour of wastes in landfill- Leachate. Chapter 8. Behaviour of wastes in landfill- Methane generation. In Holmes, J. R. (ed.) *Practical waste management*. John W. and Sons, Chicster, England.
- [16] Koster, I. W. and Lettinga, G., 1984. The influence of ammonia-nitrogen on the specific activity of pelletized methanogenic sludge. *Agris wastes*, 9, 205-216.
- [17] Boyle, W.C., and Ham, R.K., 1974. Treatability of leachate from sanitary landfill. *Journal Water Pollution Control Fed.* 46(5), 860-872.