ORIGINAL ARTICLE

The effect of precipitation on municipal solid waste decomposition and methane production in simulated landfill bioreactor with leachate recirculation

Penporn Petchsri[1], Sirintornthep Towprayoon[2], Pawinee Chaiprasert[3] and Annop Nopharatana[4]

Abstract

Petchsri, P., Towprayoon S., Chaiprasert, P. and Nopharatana, A.

The effect of precipitation on municipal solid waste decomposition and methane production in simulated landfill bioreactor with leachate recirculation

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The objective of this study is to investigate MSW degradation and methane production in a simulated landfill bioreactor with leachate recirculation under conditions with and without water addition at the representative level of annual precipitation. Experiments were carried out in four simulated reactors using 0.3 m diameter PVC pipe of 1.25 m height. Two leachate recirculation reactors were operated with water addition and the other two were operated without water addition. The results showed that leachate recirculation with precipitation led to greater performance in terms of accelerated biological stabilization and the onset of methanogenesis. In the reactors operated with precipitation, the reduction of COD was 24-54 times higher than that in reactors without precipitation. The percentage of waste decomposition was 59.0-61.4% and the methane production rate was 0.479-0.638 l/kg dry waste/day at the stabilization phase in the reactors operated with precipitation. Conversely, 19.6-22.4% of waste decomposition and 0.01 l/kg dry waste of methane production were found in reactors operated without precipitation. In this experiment, the feasibility

[1]M.Phil. Student in Environmetal Technology, [2]Ph.D.(Agriculture), Assoc. Prof., The Joint Graduate School of Energy and Environment, [3]Ph.D.(Chemical Engineering), Assoc. Prof., School of Bioresources and Technology, [4]Ph.D.(Environmental Science), Pilot Plant Development and Training Institute, King Mongkut's University of Technology Thonburi, Bangmod, Thungkru 10140 Thailand.
Corresponding e-mail: sirin@jgsee.kmutt.ac.th
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of introducing moisture only by leachate recirculation, with no precipitation, seemed to be unsuitable for recirculation due to the high concentration of leachate pollutant. A large quantity of buffering chemical was used. Therefore, during the hydrolysis and acidogenesis phases, precipitation or water added was important for the waste decomposition as to dilute and flush out high TVA concentration and create a favorable environment for methanogenesis.

Key words : landfill, leachate recirculation, bioreactor, precipitation

บทคัดย่อ

เพ็ญพร เพชรศรี [1] สิรินทรเทพ เต้าประยูร [1] ภาวิณี ชัยประเสริฐ [2] และ อรรณพ นพรัตน์ [3]

ผลของน้ำฝนต่อการย่อยสลายมูลฝอยชุมชนและการผลิตก๊าซมีเทนในถังจำลองการฝังกลบมูลฝอยที่มีการหมุนเวียนน้ำชะมูลฝอย

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การวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาการย่อยสลายมูลฝอยชุมชนและการผลิตก๊าซมีเทนในถังจำลองการฝังกลบมูลฝอยที่มีการหมุนเวียนน้ำชะมูลฝอยในสภาวะที่มีน้ำฝนและไม่มีน้ำฝน โดยใช้ถังจำลองการฝังกลบมูลฝอยขนาดเส้นผ่านศูนย์กลาง 0.3 เมตร ความสูง 1.25 เมตร จำนวน 4 ถัง โดยแบ่งเป็น ถังจำลองที่มีการหมุนเวียนน้ำชะมูลฝอยและอยู่ภายใต้สภาวะที่มีน้ำฝนเข้าสู่ระบบ จำนวน 2 ถัง และถังจำลองที่มีการหมุนเวียนน้ำชะมูลฝอยแต่ไม่มีน้ำฝนเข้าสู่ระบบ จำนวน 2 ถัง ผลการศึกษาพบว่า ถังจำลองมูลฝอยที่มีการหมุนเวียนน้ำชะมูลฝอยและอยู่ภายใต้สภาวะที่มีน้ำฝนเข้าสู่ระบบ จะมีการย่อยสลายของมูลฝอยและมีการผลิตก๊าซมีเทนในอัตราที่สูงกว่า รวมทั้งระบบมีการเข้าสู่กระบวนการเกิดมีเทน (Methanogenesis) ได้เร็วกว่าถังจำลองที่มีแต่เพียงการหมุนเวียนน้ำชะมูลฝอยแต่เพียงอย่างเดียว โดยสามารถลดค่าความเข้มข้นความสกปรกซึ่งวัดในรูปของซีโอดีได้มากกว่า 24-54 เท่า มีอัตราการย่อยสลายของมูลฝอย 59-61.4% และอัตราการผลิตก๊าซมีเทน 0.479-0.638 ลิตร/กก.น้ำหนักแห้งมูลฝอย/วัน ในขณะที่ถังจำลองการฝังกลบมูลฝอยที่มีการหมุนเวียนน้ำชะมูลฝอยแต่เพียงอย่างเดียว มีการย่อยสลายและการผลิตก๊าซมีเทนน้อยมาก คือ มีอัตราการย่อยสลายมูลฝอย 19.6-22.4% และการผลิตก๊าซมีเทนน้อยกว่า 0.01 ลิตร/กก.น้ำหนักแห้งมูลฝอย/วัน การศึกษาในครั้งนี้แสดงให้เห็นว่า ความเป็นไปได้ที่จะนำความชื้นเข้าสู่ระบบโดยการหมุนเวียนน้ำชะหมุนฝอยแต่เพียงอย่างเดียวนั้นไม่เหมาะสมโดยเฉพาะในช่วงระยะการแยกสลายด้วยน้ำ (Hydrolysis) และระยะของการเกิดกรด (Acidogenesis) ซึ่งมีค่าความเป็นกรดสูง ดังนั้น การนำน้ำฝนเข้าสู่ระบบหรือการเติมน้ำในช่วงนี้จึงมีความจำเป็นที่จะช่วยเจือจางและลดการสะสมค่าความเป็นกรดที่สูงและความเข้มข้นของมลสารในน้ำชะมูลฝอยและช่วยสร้างสภาวะแวดล้อมที่ดีให้กับ Methanogens ซึ่งช่วยเร่งระยะการเกิดมีเทนให้เร็วยิ่งขึ้น

[1]บัณฑิตวิทยาลัยร่วมด้านพลังงานและสิ่งแวดล้อม มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี ทุ่งครุ กรุงเทพฯ 10140 [2]คณะทรัพยากรชีวภาพและเทคโนโลยี [3]สถาบันพัฒนาและฝึกอบรมโรงงานต้นแบบ มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี บางขุนเทียน กรุงเทพฯ 10150

Moisture content is a major factor affecting the rate and extent of waste decomposition (Reinhart and Al-Yousfi, 1996; Timmothy *et al.*, 1998). The recommended moisture content as reported in the literature ranges from a minimum of 25% to optimum levels of 40-70% (Reinhart and Townsend, 1998). The principle source of moisture in a conventional landfill is precipitation over the landfill site, although other contributors are ground water, initial moisture from waste and biological decomposition. When the accumulation of moisture within the waste bed reaches its field capacity, leachate is produced. Leachate quantity is site specific and ranges from 0 in arid states to nearly 100 percent of precipitation in wet climates during active landfill operation (Reinhart and

Townsend, 1998). After landfill closure, the leachate quantity depends on the permeable capacity of the final cover material and precipitation management. In some countries, leachate is recirculated back to the landfill in order to increase the moisture content and accelerate waste decomposition. This technique is known as "*landfill bioreactor or leachate recirculation*". Most investigations have identified the advantages of leachate recirculation, such as accelerated waste stabilization, improved leachate quality, enhanced methane gas production rate and waste volume reduction (Pohland, 1975; 1980; Leckie *et al*., 1979; Titlebaum, 1982; Kinman *et al*., 1987; Reinhart and Al-Yousfi, 1996). However, questions remain regarding the necessity of adding moisture in terms of rainfall or precipitation in leachate recirculated landfills. The feasibility of landfill bioreactors in arid countries needs to be studied, as well as the feasibility of reducing the leachate quantity by limiting the precipitation entering the landfill area and introducing moisture content only by leachate recirculation. This investigation was conducted on leachate recirculation reactors operated with and without water addition at the representative level of annual precipitation with the initial densities at 600 and 700 kg/m^3.

Materials and Methods

1. MSW preparation

Municipal solid waste (MSW) from On-nuch Transfer Station, Thailand, was collected, and certain items removed including the bulked wastes, big pieces of plastic and recyclables (such as cans and bottles). Plastic bags containing solid waste were torn manually and then mixed by backhoe using the quartering method to maximize the homogeneity of the wastes. The mixed wastes were used for reactor loading, determining the waste composition and analyzing moisture content. The physical composition of the MSW could be separated into 12 categories as shown in Table 1. Food waste was the major component (49.86% by wet weight) of the MSW. To analyze moisture content, 1 kg of solid waste was dried in an oven at 100ºC for 4 days. Weights of sample before and after drying were used to calculate moisture content of waste. Analyzing result indicated that MSW had approximately 60.67% moisture content. It had high moisture content because of the high organic composition of waste as shown in Table 1 (Typically, the overall bulk moisture content of solid waste in Bangkok is in the range 44.16-

Table 1. The physical composition of MSW

Constituents	Weight (kg)	% by wet weight
Organic wastes		
1. Food waste	12.18	49.86
2. Paper	5.06	20.71
3. Plastic & Foam	1.16	4.75
4. Leather & Rubber	0.06	0.25
5. Textiles	0.48	1.96
6. Wood	0.21	0.86
7. Stone & Ceramics	0.24	0.98
8. Trimmings from gardens	2.76	11.30
9. Bone & shell	1.08	4.42
10. Miscellaneous organics	0.35	1.43
Inorganic wastes		
11. Glass	0.56	2.29
12. Metal	0.29	1.19
Total	24.43	100.00

60.46%; Public Cleansing Department, 2005). The chemical composition on a dry basis consisted of 47.32 % C, 5.67 % H, 1.59 % N, 85.17 % VS and 14.83 % ash.

2. Experimental Design

2.1 Simulated landfill reactors

To accomplish the objective, the experiments were carried out in four simulated landfill reactors using 0.3 m diameter PVC pipe of 1.25 m height equipped with a tap water addition port, gas sampling port, gas collection and leachate collection, as shown in Figure 1. Two reactors, compacted with initial waste densities of 600 and 700 kg/m^3, were operated as leachate recirculation reactors without precipitation (group A). The other 2 reactors, packed with the same waste densities, were operated as leachate recirculation reactors with precipitation (group B). The quantity and initial-density in each reactor is shown in Table 2. The moisture content of solid waste packed in each reactor was 60.67%.

2.2 Simulated precipitation

Typically, the final cover material of landfill sites in Thailand is of compacted soil with a surface slope of 3%, runoff coefficient of 0.18-0.22 (Surface type: lawns type heavy soil) and evapotranspiration of 28% so that the quantity of rainfall percolating through a landfill is approximately 50% of the total precipitation (CMU and JICA, 1992). Tap water, used as simulated rainfall in the landfill, was added directly to the top of the reactor every other day. The quantity of water to be introduced was 50% of the mean of the monthly rainfall calculated from 30 years (1966-1995) of climatological data at Don Muang Airport Station.

2.3 Leachate Recirculation

Leachate recirculation started when the leachate characteristics within the reactor became stable and the ratio of the total volatile acid (TVA) and total alkalinity (TAK) was lower than 0.8 thus preventing the failure of the system. The accumulative leachate from the closed container was re-circulated back to the top of the reactor every day.

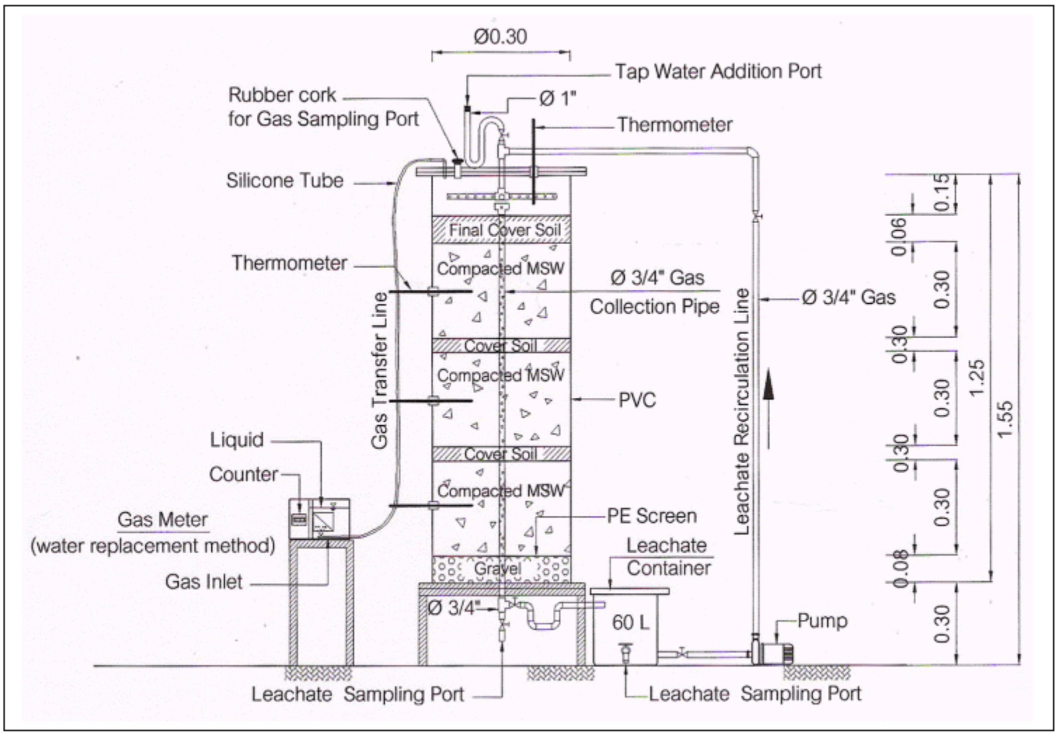


Figure 1. Cross section of simulated landfill reactor

Table 2. The quantity and initial-density in each reactor.

Reactors		Volume/lift (liters)	Density (kg/m^3)	Total waste weight/ reactor (kg wet weight)
Without precipitation	With precipitation			
A2	B2	21.2	600	38.16
A3	B3	21.2	700	44.52

The recirculation rate was started at the same rate as the daily leachate production. The difference in initial waste density affected the daily leachate production and waste decomposition. It is important to control the LR rate with the same quantity. Therefore, LR rate was adjusted to 150 ml/day, which was the average volume of leachate produced at a certain period. The increasing rate was set by a rate of 100 ml/week (LR rate = 150, 200, 300..., 800 ml/day) for increasing the organic loading rate. OLR of reactors B2 and B3 were in the range of 32-209 $g/m^3/day$ and 195-858 $g/m^3/day$, respectively. Leachate was recirculated every day until the increasing was 900-1,000 ml (OLR of reactor B2 = 766 $g/m^3/day$ and OLR of reactor B3 = 1,252 $g/m^3/day$). The recirculation frequency was adjusted every 3 days because of the reduction in methane percentage being observed.

3. Analytical Methods

Leachate produced from each simulated landfill reactor was quantitatively determined every day and collected every week for analysis of the characteristics i.e. pH, chemical oxygen demand (COD), total volatile acid (TVA) and alkalinity. The characteristics were determined according to the Standard Methods for the Examination of Water and Wastewater (APHA, 1995). Gas production was measured by using the water replacement method every day during the first 120 days and every week after that. The biogas composition was analyzed by using a gas chromatograph model GC-9A of Shimadza Co., LTD, Thermal Conductivity Detector and 80/100 mesh Porapak N. Columumn. This sampling was done every 3 days during the first month of operation and after that once per week.

4. Governing Calculations

4.1 Water Balance Calculation

The water balance diagram is shown in Figure 2. The equations are as follows;

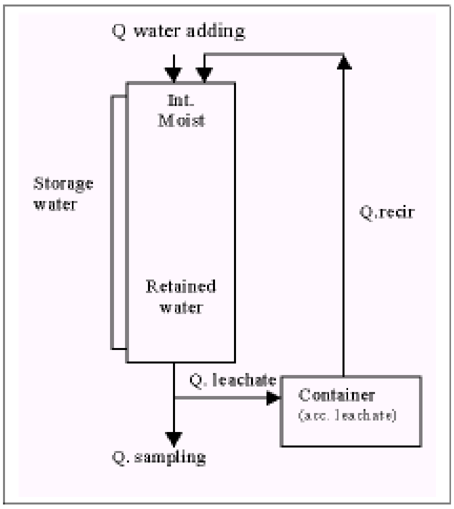


Figure 2. Diagram of Water Balance

Water input = Water output + Storage water (1)

Therefore,

Q water adding + Q initial moisture + Q recir = Q leachate + Storage water (2)

$\therefore$ Storage water = (Q water adding + Q initial moisture + Q recir) day_{n-1} - Q leachate day_n (3)

$\therefore$ Field Capacity; FC (%) = (Storage water/kg wet weight of waste) x 100 (4)

$\therefore$ Retained water = Mean Storage water - Q initial moisture content of waste (5)

When:

Q water adding	=	quantity of precipitation water (l)
Q recir.	=	quantity of recirculated leachate (l)
Q leachate	=	quantity of leachate generation (l)
Q initial moisture	=	quantity of initial moisture of refuse (l)
day_n	=	day n of experiment (n = 1,2,3.....578)
day_{n-1}	=	day n -1 of experiment (n = 1,2,3.....578)

4.2 Waste Decomposition Calculation

Solid waste was degraded from solid state into soluble organics in leachate and then converted to biogas. This can be calculated in terms of total g COD leached out, compared with g COD of initial refuse to find the percentage waste decomposition as follows (Figure 3).

1) g. COD of the initial refuse

1 g.VS refuse = 1 g. COD (adapted from McCarty, 1964; Tchobanoglous, 1993)

2) Total g. COD leach out

$$\text{g.COD leach out} = \sum_{i=1}^{n}(\underbrace{\text{g.COD in}_{\text{leachate}}}_{[1]} + \underbrace{\text{g COD}_{\text{converted to CH4 gas}}}_{[2]})$$

$$[1]\ \text{g.COD in}_{\text{leachate}} = \underbrace{(Q_{out} \times COD_{out})}_{[1.1]} - \underbrace{(Q_{recir} \times COD_{recir})}_{[1.2]} - \underbrace{(Q_{S+E\ adding} \times COD_{S+E\ adding})}_{[1.3]}$$

$$[2]\ \text{g.COD}_{\text{converted to CH4 gas}} = \sum_{i=1}^{n}(\text{g COD}_{\text{converted to CH4 gas}})$$

where, 1 ml CH_4 = 1/350 g. COD (Tchobanoglous, 1993)

finding,

$$\%\ \text{waste decomposition (\% VS)} = \frac{\text{Total g.COD leach out}}{\text{g.COD of initial refuse}} \times 100$$

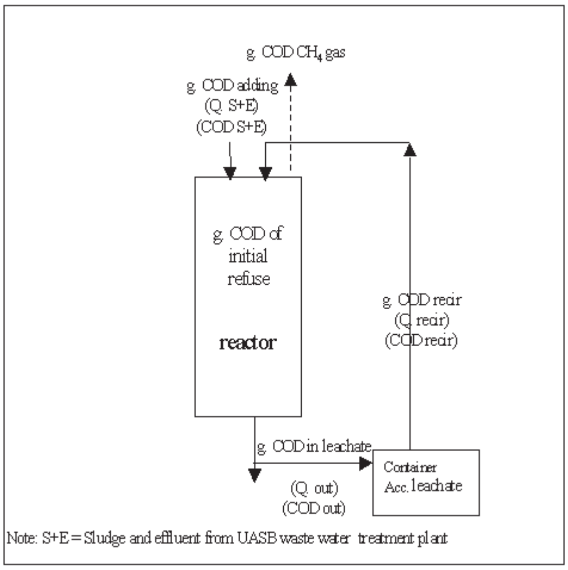


Figure 3. Diagram of COD Balance.

Results and Discussion

The experiment was conducted over 578 days. The results of each experiment can be summarized into 4 phases according to the operating duration of the reactor group B as shown in Table 3. The results of experiment can be concluded as follows;

1. Leachate Quantity

1.1 Water Balance

Preliminary analyses indicated that the solid waste had approximately a 60.67% moisture content as the field capacity of the waste calculated from the water balance equation in topic 4.1 (the maximum amount of moisture that can be held in waste sample) was equal to 61%. This indicated that MSW had high moisture content and was close to its field capacity so that the little water added made the waste reach FC and leachate was produced quickly. The conclusive data from the calculation is shown in Table 4. The values of FC obtained in this experiment were not different, as the retained water within the reactors with and without precipitation were high at higher density (B3 > B2 and A3 > A2). This was due to the initial moisture content of waste being very close to its FC. Therefore, the reduction of waste pore space at high density was not of much influence on the FC. However, it impaired the ability of leachate movement through waste bed as well as caused uneven distribution and meandering of leachate migration, leading to slower movement of leachate through waste bed and higher retained water at high density. Therefore, the leachate generation was lower. In addition, at the same density, the retained water within the reactor with precipitation was higher than in the reactor without precipitation. This illustrated that solid waste within the reactor operated with precipitation was in the saturated condition with water from precipitation and leachate recirculation. Solid waste within the reactor operated without precipitation was relatively dry due to lack of water adding and could not be recirculated in phase 2 of the experiment. Therefore, moisture within the reactor only comes from the initial moisture content of waste and waste decomposition. Water produced from waste decomposition was absorbed to maintain moisture content within the waste. Therefore lower retained water occurred in the condition without precipitation.

1.2 Leachate Volume

The cumulative leachate of reactors

Table 3. The operation phases of experiment.

Phases	Time Period	Operations	Remarks
1. Before leachate recirculation	Days 0-115	- Only tap water was added into the reactors operated with precipitation (group B).	- Free flow of leachate to close container.
2. Leachate recirculation (without buffer adding)	Days 116-261	- LR was set to start when : leachate characteristics within the reactor became stable (The variations of pH, COD and TVA concentration were not fluctuate especially COD was rather consistent which reflected that the decomposition of readily organic fraction of waste was really finished). : TVA/alkalinity ratio < 0.8	- Daily drainage - Reactor group A could not be started LR due to TVA/alkalinity ratio > 0.8
3. System improvement	Days 262-402	- Flushing out high TVA concentration and adding seed with a high content of methanogenic bacteria. - Using effluent and sludge from a UASB wastewater treatment plant treating piggery waste at Rachaburi Province.	- The faster decrease in methane percentage - low waste decomposition in reactor group A
4. Leachate recirculation with $NaHCO_3$ buffering	Days 403-578	- LR coupled with buffer adding was restarted in both groups	- Weekly drainage

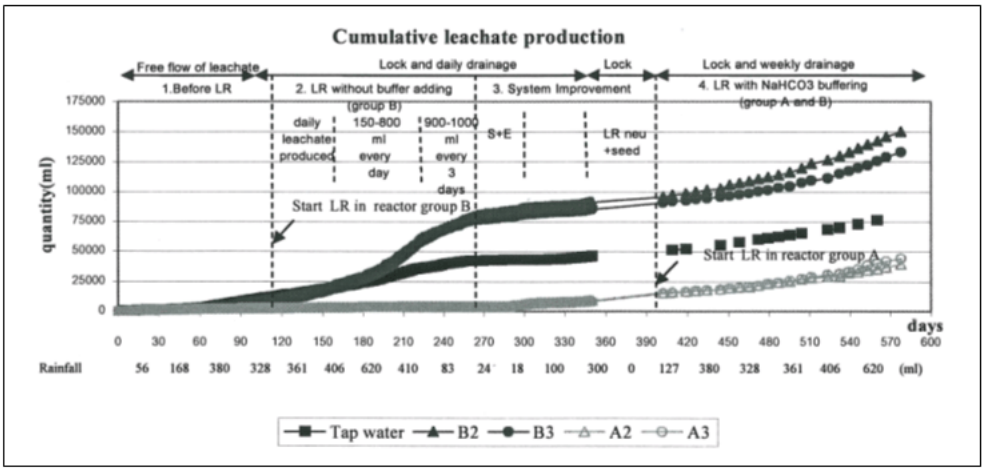
Note: LR = Leachate recirculation

Table 4. Conclusive data from the calculation of field capacity and retained water within reactors

Reactors	Mean storage water (l/d)	Initial moisture content (l)	Retained water (ml)	Field capacity (l/kg wet weight)	Field capacity (% wet weight)
With precipitation					
B2 (600 kg/m^3)	23.26	23.15	110	0.609	61.0%
B3 (700 kg/m^3)	27.17	27.01	160	0.610	61.0%
Without precipitation					
A2 (600 kg/m^3)	23.22*	23.15	70*	0.610	61.0%
A3 (700 kg/m^3)	27.10*	27.01	90*	0.608	61.0%

Note: *Retained and mean storage water in reactor A2 and A3 were calculated during day 0-261 (Before water adding to improve the system)

operated with and without precipitation as well as the quantity of leachate generation are shown in Figure 4 and Table 5, respectively. In the reactors operated with precipitation, leachate was produced from added water used as precipitation and leachate recirculation. During the period without leachate recirculation (phase 1), the quantity of leachate generation was 69.88-85.3% of precipitation. Precipitation plus LR in phase 2 occurred leachate quantity 89.26-89.66% of water input.



Daily leachate production rate

- reactor with precipitation

Tap water; y = 144.99X - 1380.5, R^2 = 0.9679

B2; y = 298.64X - 13699, R^2 = 0.9377

B3; y = 277.22X - 12729, R^2 = 0.9196

- reactor without precipitation

A2; y = 14.334X+943.66, R^2 = 0.9475

A3; y = 12.506X+933.96, R^2 = 0.9548

Figure 4. Cumulative leachate production

The leachate generation increased after leachate recirculation and was much higher than the volume of added tap water. During phase 3 that was the winter and summer, the leachate generation decrease due to low quantity of precipitation. However, it increased again after LR was restarted in phase 4. leachate generation was 73.66-94.12%. The daily leachate mean rates of reactors B2 and B3 obtained by fitting a curve with linear equation were equal to 298 and 277 ml/day or 19.93 and 15.88 ml/kg dry waste/day, respectively. As for the reactors operated without precipitation, leachate was only produced from waste decomposition during phase 1 and 2 (LR could not be started in phase 2). Produced leachate of reactors A2 and A3 were very little with the rates of 14.3 and 12.5 ml/day, respectively. But, after water adding for improving the system in phase 3 and restarting LR in phase 4, leachate generation increased in the range 67.6-99.6% of water input. The results showed an obvious difference in leachate quantity. The leachate quantity of reactors operated with precipitation was much higher than that of reactors operated without precipitation, throughout the experiments. These confirmed that the amount of leachate produced from waste decomposition was very small. Therefore, when the added water brings the moisture content in the waste up to its field capacity, the quantity of leachate produced depends on the quantity of water added (or rainfall) and the recirculated leachate. In addition, the results showed that the higher density resulted in the lower leachate generation (leachate generation of reactors B2 and B3 = 90.32% and 80.54% of water input, respectively). This was due to the slowdown in the ability of leachate to move through the waste bed, which resulted from the collapsed pore space available for leachate migration. Therefore, the retained water was high at higher density. However, the reactors operated without precipitation, which was in the dry condition during phase 1 and 2. The waste decomposition was very low. Although the retained water of reactor A3 was higher than that of reactor A2, it had less affect on leachate generation because the produced leachate was absorbed to maintain moisture within the waste bed. Considering the leachate generation after the system improvement in phases 3 and LR

Table 5. Quantity of water adding and leachate production according to the experimental phases

Phases (Time period; month)	Details	Reactors: With precipitation B2	Reactors: With precipitation B3	Reactors: Without precipitation A2	Reactors: Without precipitation A3	Remarks
1. Before LR (Feb.-Jul.)	water input (l) (precipitation)	12.15	12.15	0	0	
	leachate production (l)	10.37	8.49	2.71	2.49	
	leachate production (% of water input)	85.3%	69.88%	-	-	
2. LR without buffer adding (Jul.- Nov.)	water input (l) (precipitation + LR)	77.06	76.25	0.10	0.10	- Cannot further LR in reactor group A due to TVA/alkalinity > 0.8
	leachate production (l)	69.09	68.06	1.55	1.36	
	leachate production (% of water input)	89.66%	89.26%	-	-	
3. System improvement (Nov.-Apr.)	water input (l) (water adding + effluent & Sludge adding)	19.33	19.33	18.20	18.20	- All reactors were improved
	leachate production (l)	16.38	14.71	12.35	12.31	
	leachate production (% of water input)	84.74%	73.30%	67.90%	67.6%	
4. LR with buffer adding (Apr.-Sep.)	water input (l) (precipitation+ LR)	57.65	57.65	28.14	28.14	- Stopped LR in reactor group A on day 474 and added tap water for improving the system
	leachate production (l)	54.26	42.47	22.46	28.04	
	leachate production (% of water input)	94.12%	73.66%	85.15%	99.6%	
Total	water input (l)	166.19	165.38	46.34	46.34	
	leachate production (l)	150.10	133.19	39.07	44.20	
	leachate production (% of water input)	90.32%	80.54%	84.31%	95.38%	

Note: Water input (not include initial moisture content of waste)

with buffering in phase 4, the quantity of cumulative leachate generation of reactors A2 and A3 were 84.31 and 95.38% of water input, respectively. To obtain clear results, it was compared in term of quantity per a unit of kg dry waste. The leachate production of reactors A2 and A3 throughout the experiment were 4.36 and 4.5 ml/kg dry waste/day. This confirmed that leachate generation was lower at higher density.

2. Leachate and gas characteristic

The variations of leachate composition in terms of concentration and mass leach-out per unit of kg dry waste along with gas characteristics were used to reflect the waste stabilization taking place in the simulated landfill reactors. The results of the experiments are shown in Figures 5-7. Phases 1 and 2 of the experiment are the hydrolysis and acidogenesis stages as evidenced by the rapid

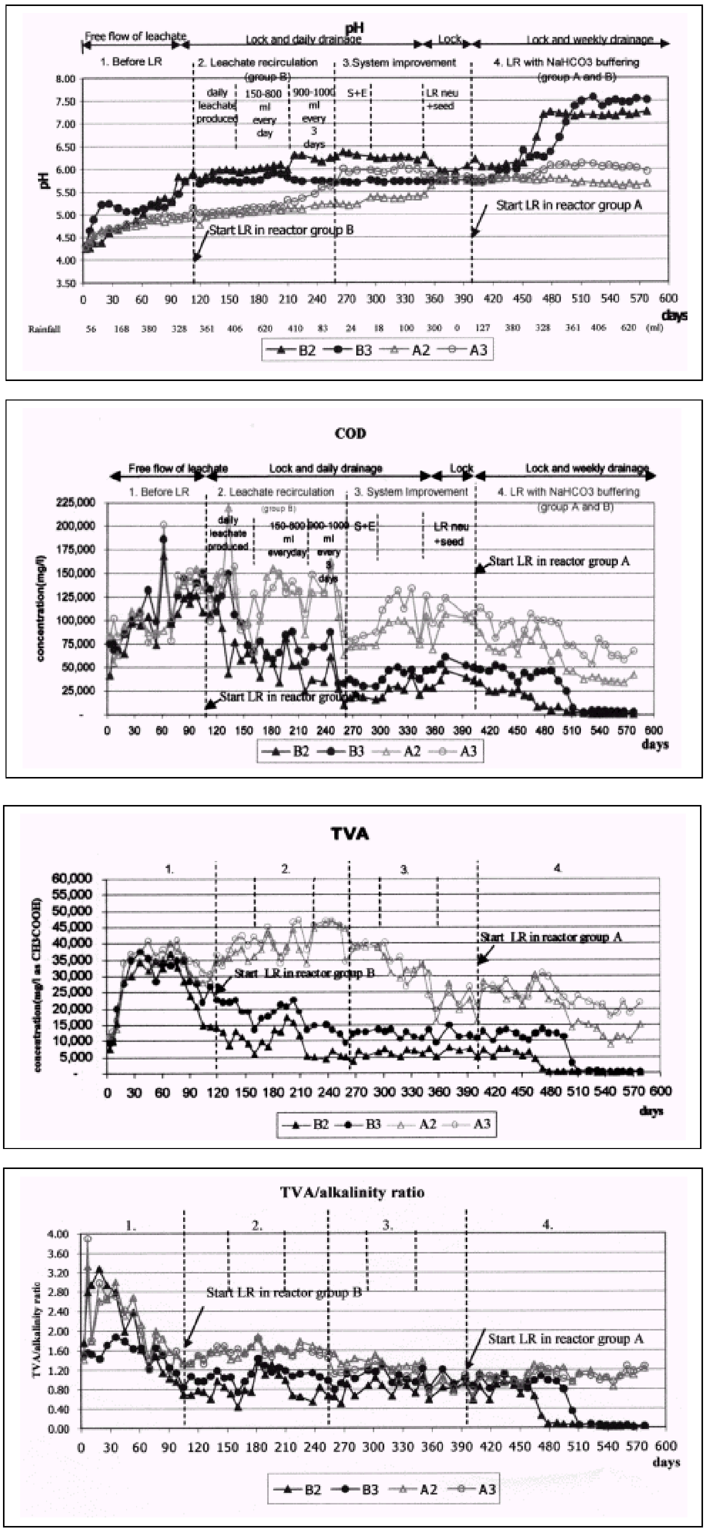


Figure 5. Leachate characteristic in terms of concentration from reactors operated with and without precipitation.

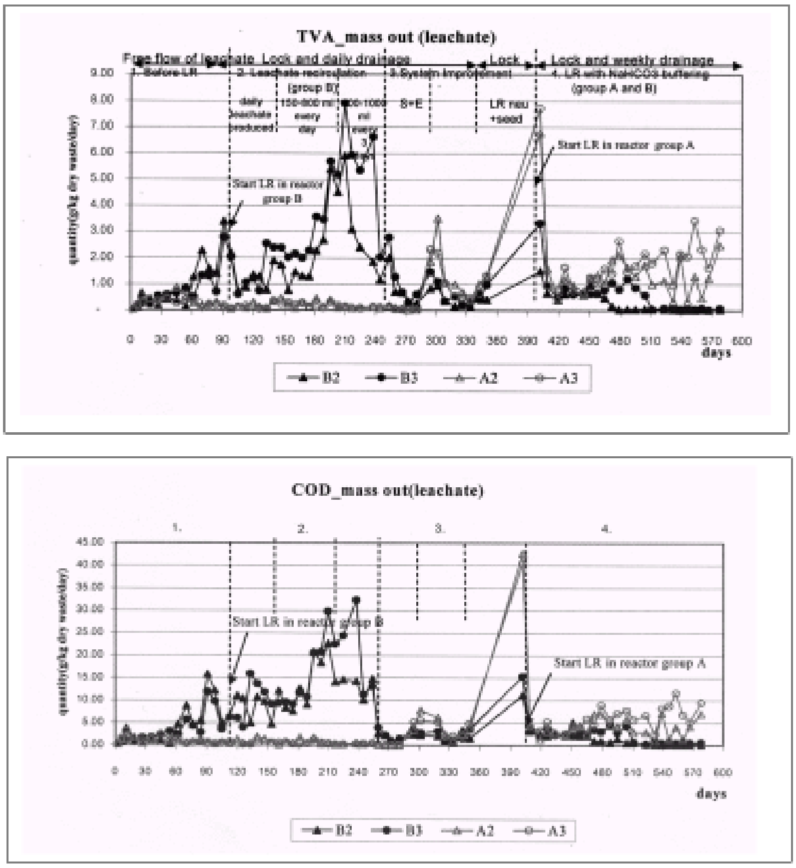


Figure 6. Mass of TVA and COD produced in the leachate from reactors operated with and without precipitation.

production of soluble COD and TVA. During phase 1 (before LR), only the reactors operated with precipitation were added with water while in the other group, no tap water was added. Leachate was in free flow to the closed container during the first 105 days. During the first 70 days, the leachate characteristics, both in terms of concentration and mass leach-out, are not different due to the low amount of water added. But, after a higher amount of water was added, the difference in leachate characteristics can be markedly observed. The leachate pH in the reactors with precipitation (group B) was brought up into 6 and was higher than that from the reactors operated without precipitation (group A) which remained stable at pH 5. The TVA concentration decreased with time and was lower than in the reactors without precipitation as the methane gas amount was lower than 1%. However, the TVA and COD mass-leachouts of the reactors with precipitation were much higher. This resulted from the effect of the added water diluting and flushing the high concentration of TVA and accelerating the hydrolysis of waste as evidenced by the higher mass-leachout, which coincided with the percentages of waste decomposition of the reactors in group B with the rate of 6.8-8.5% as compared to 1.7-1.9% as found in the reactors in group A (see Table 6). The higher in COD and TVA concentration in the reactors without precipitation, due to the absence of water for dilution and flushing of the hydrolytic and acidogenic products led to the accumulation of high organic strength and a limiting of the waste decomposition. Although the solid waste

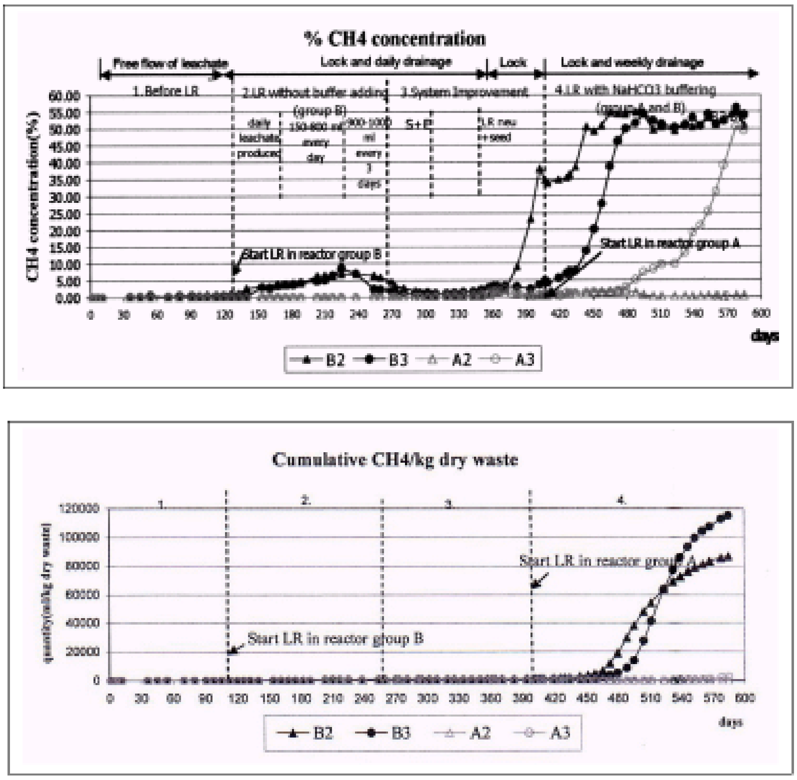


Figure 7. Gas characteristic from reactors operated with and without precipitation

Table 6. Percentage of waste decomposition according to the experimental phases

Phases	Percentage of waste decomposition (% VS of initial refuse)			
	With precipitation (group B)		Without precipitation (group A)	
	B2 (600 kg/m³)	B3 (700 kg/m³)	A2 (600 kg/m³)	A3 (700 kg/m³)
1 (Before LR)	8.50	6.80	1.90	1.70
2 (LR without buffer adding)	18.25	10.24	1.58	1.16
3 (System improvement)	3.18	3.38	7.34	7.04
4 (LR with buffer adding)	31.44	38.52	8.78	12.50
Total	61.40	59.0	19.60	22.40

had a high moisture content and reached its field capacity, moisture addition was still necessary for waste decomposition and to provide a favorable environment for microorganisms.

During phase 2, leachate recirculation (LR) was set to start when the TVA/alkalinity was lower than 0.8 and the leachate characteristics within the reactor were stable. The results show that, LR can be previous started in the reactor operated with precipitation on day 116. At this time, concentration of leachate compositions did not fluctuate. Leachate COD was rather consistent which reflects that the readily available organic fraction of waste was final decomposed. The TVA/alkalinity ratio of leachate from the reactor was in the range of 0.7-1.1 and that from the container used for recirculation was in the range 0.3-0.7. The pH of recirculated leachate was in the range 6.3-7.6. Conversely, reactors operated without precipitation could not be recirculated due to the TVA/alkalinity ratio both from the reactor and the container, being higher than 0.8 and the TVA concentration being around 32,000 mg/l, which is toxic to methanogenesis. In reactor operated with precipitation, during the days 116-160, the accumulative leachate from the closed container was recirculated back to the reactor at the same rate as the daily leachate production (150-673 ml/day). After that, the rate was adjusted to 150 ml/day for about one week. It was then increased to 200 ml/day and then gradually increased by a rate of 100 ml/week (150, 200, 300, 400,....800 ml/day) for increasing the organic loading rate. OLR of reactor B2 and B3 were in the range 32-209 g/m^3/day and 195-858 g/m^3/day, respectively. After leachate recirculation, the onset of methanogenesis was observed as evidenced by the increasing methane percentage to around 6.5-8% (Figure 7). The quantities of TVA and COD mass leach-out, as well as the percentage of waste decomposition, were much higher than these of phase 1 (Figure 6). However, the accumulation of TVA and COD was observed when the increasing LR rate was at 800 ml/day. A change in the frequency of recirculation from every day to every 3 days, at a LR rate of 900-1,000 ml, can reduce the accumulation of high TVA but a decreasing methane percentage occurred. This indicated that, although the addition of water and leachate recirculation diluted and flushed out the high concentration of TVA and accelerated the onset of methanogenesis. The high level of organic loading and leachate recirculation rate were not good for the onset of methanogenesis due to the methanogens being flushed out and not having sufficient time to grow and multiply. This led to an imbalance of organic influents and the number of methanogens, which converts TVA to CH_4.

During phase 3, the system was improved by using the effluent and sludge seeding for flushing out of the high TVA concentration and adding an amount of methanogenic bacteria during days 278-299. After that, on days 350-402, the leachate was neutralized with effluent from the UASB wastewater treatment plant coupled with sludge addition and then circulated back to the reactor. The drainage pipe was locked to allow the microorganisms to acclimatize to the environment. After the improvement, the results show that gas production and CH_4 percentage restarted in both groups. Although a small CH_4 percentage was detected, there were good signs for the improvement of the system by increasing the buffer capacity of the system. This was confirmed in that the CH_4 percentage was high only in reactor B2 where optimization of pH and buffer capacity were appropriate for methanogenesis as low pH values occurred in the other reactors.

During phase 4, LR was restarted in both groups, the recirculated leachate was adjusted to a TVA/HCO_3^- ratio of 0.4 and the pH to neutral by adding $NaHCO_3$. Except in reactor B2, in which the TVA/HCO_3^- ratio of the recirculated leachate was lower than 0.4 and the pH higher than 7. The recirculation rate was restarted at the same quantity as in phase 2 but the frequency rate was gradually increased. The recirculation rate was restarted at 150 ml/2 days and drained out every week for one month. It was then increased to 200 ml/2 days and then gradually increased by a rate of 100 ml/month (150, 200, 300, 400 ml/2 days) until the increasing rate was 500 ml/2 days. The rate was increased by 100 ml every 2 weeks. The results show that the leachate pH of the reactor operated with precipitation reached neutrality faster than the reactors operated without precipitation. When the pH reached neutral, the reduction of the TVA and COD concentration decreased sharply until it reached a minimum level and stabilized. At the end of the experiment, the COD concentration of the reactor operated without precipitation was about 24-54 times higher than with precipitation (A2 = 42,320 mg/l, B2 = 782 mg/l, A3 = 68,080 mg/l, B3 = 2,760 mg/l). Methane production was obtained at the rates of 0.479 and 0.638 l/kg dry waste/day for the reactors B2 and B3, respectively. The lower methane production was 0.01 l/kg dry waste/day obtained from the reactor operated without precipitation indicating that the rate of waste stabilization of the reactor operated with precipitation was higher than that of the reactor without precipitation. Although in the reactor operated without precipitation, LR could be started, it had to be stopped after 2 months of LR. The concentration of TVA increased and reached a peak at about 30,000 mg/l and 105,000 mg/l for reactors A2 and A3. TVA/alkalinity increased from 0.9 to 1.3. HCO_3^- decreased sharply to lower than 3,000 mg/l and a large volume of buffer chemicals was used. Therefore, on day 466 the reactors operated without precipitation were supplied with water, at the same rate as the reactors with precipitation, to dilute these concentrations. After this operation, the concentration of TVA and COD decreased with time. The CH_4 concentration from reactor A3 increased rapidly with time and peaked at 50%. The CH_4 concentration of reactor A2 was lower than 2% with a smaller amount of gas production. This resulted from the pH value not being favorable for methanogenesis and a high TVA toxic to methanogens (pH should be in the range of 6-8 and TVA concentration should be lower than 10,000 mg/l). This confirmed that water added for flushing and diluting of organic strength particularly TVA concentration more quickly provided a favorable environment for microorganisms during hydrolysis and the acidogenesis stage. However, the enhancement of methane production was also dependent on providing favorable environmental conditions for methanogen (pH should be maintained at neutral and VA/T-alkalinity in the range of 0.3 to 0.4).

3. Waste decomposition

The percentage calculations of waste decomposition are shown in Table 7. The percentage of waste decomposition of reactors B2, B3, A2 and A3 were equal to 61.4, 59.0, 19.6 and 22.4%, respectively. The result show that the waste decomposition of the reactors operated with precipitation was much higher than that of the reactors without precipitation. This resulted from the limited moisture addition, which is essential in the hydrolysis stage, as the solid organic waste must be solubilised before the microorganisms can utilize it. In addition, the absence of flushing and diluting of high concentrations of TVA created an unsuitable environment for methanogenesis. Direct LR with high TVA concentrations would have accumulated to toxic concentrations causing unsuccessful methanogenesis. A slow rate of waste decomposition was obtained.

In addition, the results indicated that waste

Table 7. The calculated results of percentage of waste decomposition

Reactors	g. COD of initial refuse	Acc. g. COD in leachate (1)			Acc. g. COD convert to CH_4 gas [2]	Total g. COD leach-out ([1.1]-[1.2]] - [1.3] + [2])	waste decomposition (% VS of initial refuse)
		g. COD out [1.1]	g. COD recir [1.2]	g. COD S+E* [1.3]			
With precipitation							
B2 (600 kg/m^3)	12,783	5,451	1,244	31.28	3,668	7,843	61.4
B3 (700 kg/m^3)	14,913	7,493	4,287	32.75	5,618	8,791	59.0
Without precipitation							
A2 (600 kg/m^3)	12,783	2,787	253	32.42	0.32	2,502	19.6
A3 (700 kg/m^3)	14,913	3,905	612	32.53	89.33	3,350	22.4

Note : * Sludge and Effluent from a UASB waste water treatment plant

densities in both groups can have different effects on waste decomposition. In reactors operated with precipitation, the higher compaction had lower waste decomposition (B3 < B2). Conversely, in the reactors operated without precipitation, the lower waste decomposition was obtained at lower compaction (A3 > A2). The initial waste density affected the retention time and moisture movement. Therefore, the more waste decomposition depends on which condition creates the better favorable environments for microorganism at the certain time. In the reactor operated with precipitation during phase 1 and 2, which are the hydrolysis and acidogenesis stages, the fast hydrolysis of the easily degraded organic fraction results in a high concentration of TVA so that the flushing out and dilution of high TVA is essential for providing a favorable environment for microorganisms. The lower compaction (B2) can more quickly provide a good environment with low TVA and COD concentration and higher pH, as well as a better distribution of moisture content through the waste bed and enough retention time for methanogen to grow and multiply at the onset of methanogenesis (lower compaction than at a waste density of 600 kg/m^3 is not suitable for microorganism growth and multiplication, especially at the onset of methanogenesis, with methanogen being flush out of the system, Petchsri *et al.*, 2004). With higher compaction (B3) the retention time in reactor B3 was higher but high concentrations of TVA and low pH creating the toxic environment for methanogen. However, after LR coupled with buffer adding in reactor B3, methanogenesis was successful.

In the reactors operated without precipitation, during phases 1 and 2, the waste decomposition of reactors A2 and A3 are not much different because of the lack of moisture content. During phase 4, LR with buffering for about 2 months and water adding after that, waste decomposition of A3 was higher than reactor A2. This illustrates that, at higher density, moisture can be held in the waste bed better than that in the lower density. However, due to buffer chemical being added in this phase, the higher amount retained water was good in this case. Unlike the case of reactor B3 during phase 2 with LR without buffering, the higher in retained water was not good due to the accumulation of TVA concentration. However, a large volume of buffer chemical was added in reactors without precipitation which is unsuitable in real landfill. Therefore, during the hydrolysis and acidogenesis stages, flushing and diluting by precipitation or water adding is better for providing a favorable environment for microorganisms.

Conclusions

Based on all the experimental results, the effects of precipitation on waste decomposition and methane production are as follows:

1. Leachate recirculation operated with precipitation led to greater performance in terms of accelerated biological stabilization and the onset of methanogenesis, as evidenced by the significant reduction in leachate composition, time required for waste stabilization and the higher percentage of waste decomposition compared with leachate recirculation operated without precipitation, with a high concentration of leachate pollutant throughout the experiment.

2. In this experiment, the feasibility of introducing moisture only by leachate recirculation, without precipitation, seemed to be unsuitable for recirculation due to the high concentration of leachate pollutant. A large quantity of buffering chemicals must be added. Therefore, during the hydrolysis and acidogenesis stages, flushing and diluting of high TVA concentration is essential for providing a favorable environment for organisms. Adding water can more quickly provide a suitable environment with lower TVA, VA/T-alkalinity and a higher pH for methanogenesis.

3. At the onset of methanogenesis, the leachate recirculation should be carefully conducted with a small quantity of leachate recirculation and organic loading rate, especially in the case of LR without buffering. The frequency rate of LR should be gradually increased due to the methanogen being flushed out and not having sufficient time to grow. In addition, the long period of time from the first

detection of CH_4 until the CH_4 percentage reaches 50-60% of 2-3 months, indicated the slow growth of methanogens and risked failure from a high organic loading.

4. Leachate recirculation coupled with precipitation accelerated waste decomposition and the onset of methanogenesis. However, the success of methanogenesis is also dependent on favorable environmental conditions for methanogens. The pH should be maintained at neutral and VA/T-alkalinity in the range of 0.3 to 0.4.

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