Anaerobic digestion of municipal solid waste in thermophilic sequential batch process

R. ADHIKARI, J.P. JUANGA, C. VISVANATHAN*

Environmental Engineering and Management Program, Asian Institute of Technology, P.O. Box 4, Klong Luang, Pathumthani, 12120, Thailand

**Corresponding author: visu@ait.ac.th*

SUMMARY: Anaerobic digestion of organic fraction of municipal solid waste is an attractive technology for waste stabilization with generation of valuable byproducts, biogas and stabilized waste. Shortening the digestion time along with enhanced process efficiency is one of the important aspects of this study. This paper presents the results from pilot scale experimental investigation on sequential batch anaerobic digestion under thermophilic condition. The process involves coupling of stabilized and freshly loaded reactor for leachate cross- recirculation until the fresh reactor shifted to active methane phase ($CH_4 \geq 50\%$; pH ≥ 7). Three cycles of sequencing operation were conducted with different leachate recirculation rates. The reactor used for start-up is operated using an optimized combined process (pre-stage: microaeration and flushing; methane phase: pH adjustment and inoculum addition) for a period of 76 days with methane yield of 143 L CH_4/kg VS. The results show that start-up period decreased with subsequent cycles; consequently digestion period has been reduced from 26 days to 23 days and 21 days for Cycle I, Cycle II, and Cycle III, respectively. It was observed that increased recirculation rate from 0.34 to 0.58 m^3/m^3 waste.day results into higher methane yield and shorter digestion time. Cycle III exhibits an optimum process efficiency of 81.7% (240 L CH_4/kg VS) as compared with the methane yield from lab-scale biochemical methane potential (BMP) test (294 L CH_4/kg VS). Thus, anaerobic digestion in subsequent sequencing operation under thermophilic condition is a viable option of organic solid waste treatment.

Keyword: Anaerobic digestion, biogas, municipal solid waste, leachate cross-recirculation

1 Introduction

Rapid waste generation along with urbanization and population growth creates critical concerns on municipal solid waste (MSW) management strategies. Generally, improper waste management generates numerous problems including environmental pollution, degradation of sanitation, unhygienic living conditions, etc. Proper MSW management such as source reduction, recycling, and composting are presently practiced in most developing countries in Asia. However, the existing management was not able to tackle huge amount of waste which has been resorted only to dispose in open dumps or unsanitary landfills. Importantly, MSW characteristics in most Asian countries is known for its high organic and moisture content, and low calorific value which makes it unsuitable for direct landfill disposal and incineration because of potential emissions (Visvanathan et al. 2004). Recently, increased environmental awareness and concern over direct landfilling issues have stimulated new approaches for organic fraction of MSW treatment prior disposal. In this regard, aerobic and anaerobic biological processes are considered as useful pre-treatment technologies for volume reduction and waste stabilization prior to landfilling.

The importance of anaerobic digestion for organic waste treatment is a growing interest towards sustainable MSW management and able to support for alternative renewable energy resources. The process involves the conversion of waste biodegradable fraction into biogas and stable residue that can be used as fertilizer or compost. Anaerobic biodegradation proceeds in the absence of oxygen and produce byproducts after a series of metabolic interactions among various groups of microorganisms. Anaerobic system generates energy in the form of methane as a source of electricity that can be used to operate the process with energy surplus. From the life cycle assessment (LCA) perspective, anaerobic digestion is considered as the best LCA of all renewable energies like wind, water, etc. In life cycle assessment using eco-indicator method, it also showed an excellent LCA

performance as compared to other treatment technology like composting and incineration (Edelmann et al., 2004).

Anaerobic digestion is classified into two processes based on the stages of operation, namely batch and continuous process. The sequential batch anaerobic composting (SEBAC) process uses a combination of high solid fermentation and leachate recycling between new and stabilized reactor to provide moisture, nutrients and inocula for rapid start-up (Chynoweth et al., 1992; Chynoweth et al., 2003). Researches have proved that biogas production is relatively low under mesophilic (37°C) than thermophilic (55°C) condition. Besides, digestion period can be considerably shortened under higher operating temperature (Juanga, 2005; Cecchi et al., 2003). State-of-the-art research on sequential batch anaerobic digestion needs further investigation especially by employing several cycles of sequencing operation with increased leachate cross-recirculation rate for an attempt to further optimize the process performance.

2 Materials and Methods

Experiments were conducted in pilot scale reactors made of stainless steel. The total volume of reactor is approximately 375 L while the designated volume available for waste compaction is 260 L. The digesters were equipped with top removable cover for waste loading and unloading. Optimum thermophilic condition of 55°C was maintained by a digital temperature controller wherein hot water from water bath was pumped within the water jacket. The leachate recirculation system consists of the reactor's bottom outlet connected to leachate storage tank. The tank is equipped with pump, flow meter, and liquid distribution line up to the top inlet of the reactor. The sprinkler placed at 3 cm below the top cover, distributes water throughout the waste surface. The reactor is equipped with biogas sampling port and biogas production measurement by using drum-type gas meter (Ritter TG05/2).

2.1 Feedstock Characteristics

The substrate used collected from Tahklong municipality dumpsite (Pathumthani, Thailand) was manually segregated to remove bulky and inorganic materials. After segregation, sorted waste was shredded to a particle size of approximately 30 mm. The physical characteristics of waste showed high moisture content of 80-85% with total solid (TS) ranging from 15-20% and volatile solid (VS) content of 72-81%.

2.2 Experimental Set-up

Shredded organic waste was loaded into the reactor with compaction density of 600 kg/m^3 together with bulking agent (bamboo cutlets). Figure 1 shows the operation conditions involved in this study. In order to start Cycle I, stabilized reactor should be generated. In this case, Reactor 1 (R1) is loaded with fresh waste and undergone bio-methanization process under combined anaerobic digestion process. This process consist of pre-stage and methane phase under mesophilic condition. Pre-stage strategy involves microaeration (0.15 L/kg.hr) and flushing as 0.75 L/kg.hr for 3 days as recommended by (Juanga and Visvanathan, 2006). Pre-stage operation enhances oxidation of organics, partially remove dissolved organic compound to reduce organic load and to avoid inhibition due to VFA and low pH condition (Nguyen et al., 2005). A detailed operation involves for R1 start-up is illustrated in Figure 2. After 3 days of pre-stage operation, the pH of the system was adjusted from 5.6 to 7.0 by using NaOH solution to help enhance for the onset of methane phase as the pH range for methanogenesis is 6.5-7.3 (Gerardi, 2003).

Moreover, inoculum was added at the top of the feedstock after pH adjustment in day 5. The seeding material (10% of substrate) consists of a mixture of cow dung, digested waste, and anaerobic sludge. In order to ensure the distribution of inoculum throughout the waste bed, leachate was percolated for 2 days. The system was left undisturbed while biogas production and composition was monitored daily. Methane composition of ≥ 50% in biogas and pH value of ≥ 7 were used as an indicator of an active methane phase. The reaction temperature for R1 has been increased gradually by 2°C/day until it reached thermophilic condition (55°C). The process was deemed necessary to avoid unbalanced situation resulting from sudden temperature change as reported by Cecchi

et al. (2003). The gradual increase in temperature reduces stress situation without affecting biogas production. The process behaviour in transient condition was investigated and subsequent experiments were carried out in thermophilic condition.

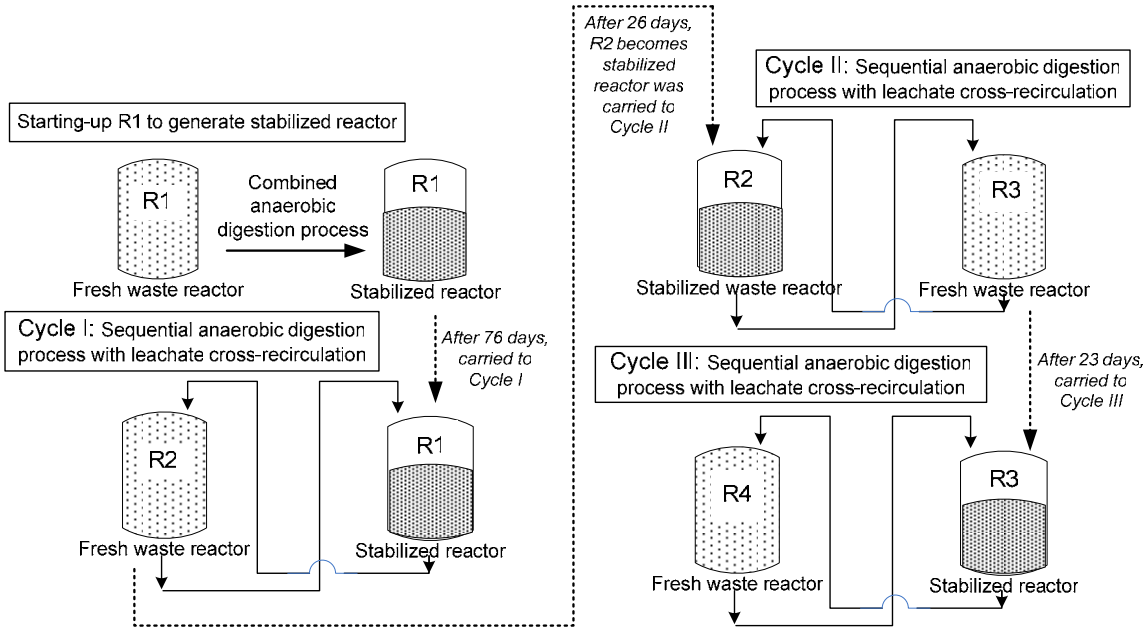


Figure 1 Preparation of stabilized reactor and the sequencing staging operation at three cycles

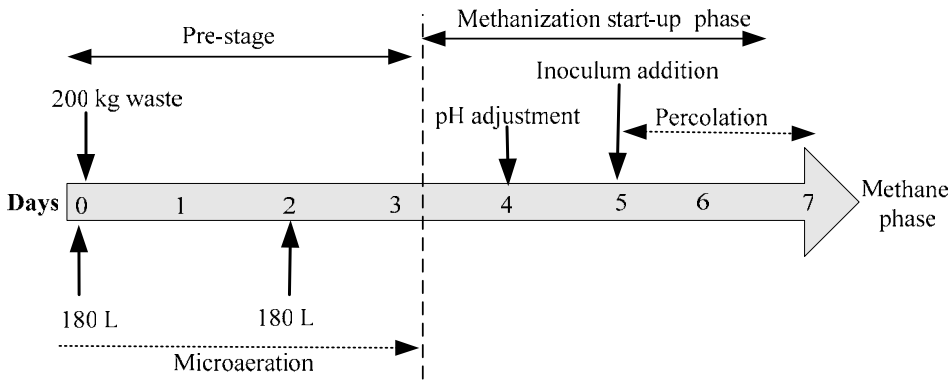


Figure 2 Start-up operation in R1

2.3 Concept of Sequential Staging

To start Cycle I of sequential staging operation, a new reactor (R2) was loaded with fresh waste after pre-treatment (segregation and size reduction to 30 mm). Mature leachate from stabilized reactor (R1) was recirculated to new reactor (R2). R2 was flushed with 90 L mature leachate from old reactor (R1). The cross-circulation rate in this cycle was 3 L/min for 30 min/day. The pH of leachate and biogas composition in R2 was monitored daily. Once the pH reached 7 and methane composition was 50%, the reactor was assumed to be in active methane phase. Thus, R2 becomes an active reactor and it was uncoupled with R1. This time, an active reactor (R2) operates independently by direct leachate recirculation. After R2 exhausted its methane potential (biogas produced is very low approximately 5 L/day) and became stabilized, R3 was loaded with fresh waste for Cycle II operation. Leachate cross-recirculation at a rate of 4 L/min is conducted by coupling these reactors until the new reactor (R3) shifted to active methane phase then uncoupling is done. Similar operation was followed

for Cycle III employing R3 (stabilized) and R4 (new) for leachate cross-recirculation at a rate of 5 L/min. The variable in three cycles is the cross circulation rate as shown in Table 1.

Table 1 Cross circulation rate in three cycles of sequential staging operation

Operation	Volume of leachate used for cross-circulation	Cross-circulation rate
Cycle I	90 L	3 L/min (0.34 m^3/m^3 waste.day)
Cycle II	120 L	4 L/min (0.46 m^3/m^3 waste.day)
Cycle III	150 L	5 L/min (0.58 m^3/m^3 waste.day)

2.4 Analytical Methods

Leachate samples were analyzed for pH, alkalinity, dissolved organic carbon (DOC), volatile fatty acids (VFA) and ammonium nitrogen (NH_4-N) using analytical procedures of standard methods in APHA et al. (1998). Biogas composition was analyzed by using gas chromatograph (GC-14A-SHIMADU) equipped with a thermal conductivity detector. Laboratory scale biochemical methane potential (BMP) assay based on the study of Hansen et al. (2004) was conducted to determine methane yield and performance of anaerobic digestion process. Methane yield obtained from lab-scale BMP and pilot-scale set-up are compared for determining process efficiency.

3 Results and discussions

3.1 Anaerobic Digestion Performance of R1

Cumulative pollutant load in flushed leachate after pre-stage operation generate as much as 234 g of TCOD, 196 g of SCOD, 161 g of TDS per kg of TS (Figure 3). Likewise, considerable amount of NH_4-N (18.8 g) and TKN (27.3 g) were removed per kg of TS load. Biogas production and composition was monitored daily. The volume of biogas produced is converted into standard temperature and pressure (STP) conditions (0^oC and 1 atm.) for uniformity and comparison with BMP test. It was observed that after 40 days, methane concentration in biogas reached 50% and this stage was considered the beginning of mature phase. When thermophilic condition prevailed, the daily biogas production increased significantly (Figure 4). Bouallagui et al. (2004) and Valdez-Vazqueza et al. (2005) found that biogas production rate in thermophilic temperature was higher than that from mesophilic condition This is because the thermophilic micro-flora have the capacity to use several sources of carbon than the mesophilic micro-flora (Converti et al., 1999). Cecchi et al. (2003) reported an unbalanced situation was observed for few days after shifting the operating condition from mesophilic to thermophilic in short period (within 48 hours). In this study, the gradual increase of temperature (2°C/day) did not exhibit negative effect on the process particularly on daily gas production.

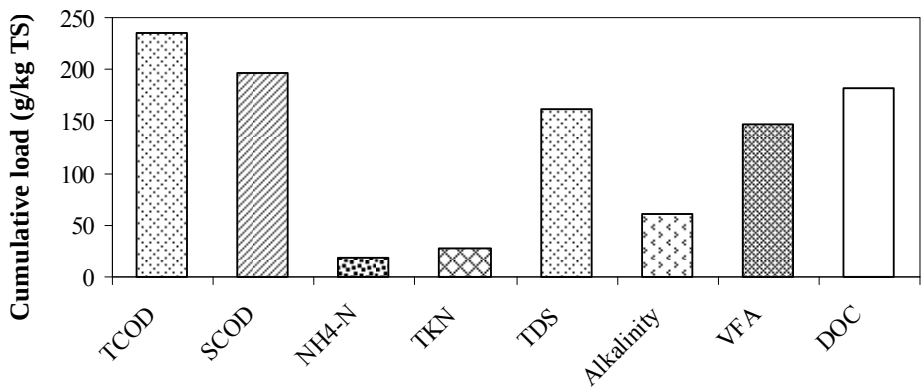


Figure 3 Cumulative pollutant load in leachate after pre-stage (R1)

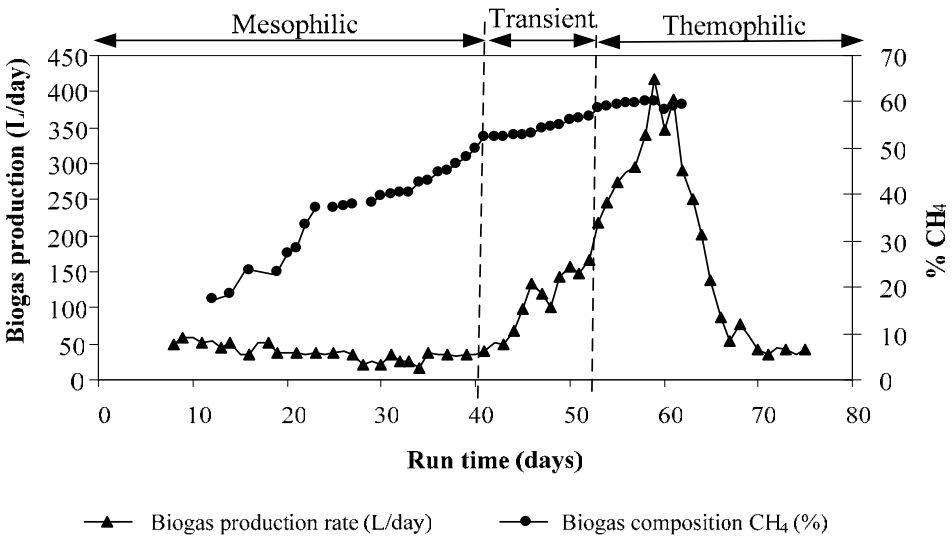


Figure 4 Daily biogas production and % methane in biogas with increasing temperature (R1)

3.2 Sequential Batch Anaerobic Digestion

The completion of each cycle operation was marked by exhaustion of biogas production. Leachate characteristics in terms of VFA concentration, is illustrated in Figure 5. The rate at which balanced condition ($CH_4 \geq 50\%$; pH $\geq$ 7) was reached in fresh waste reactors depends upon two factors: the rate at which the fresh waste reactor is sufficiently inoculated by stabilized reactor and the rate at which volatile acids produced in fresh waste reactor are flushed into leachate. The increase of leachate cross-recirculation rate resulted into more rapid degradation of VFA. VFA produced in fresh reactors are removed as a substrate to stabilized reactor which converted into biogas at the same time inoculates fresh reactor producing better contact with microorganisms. As observed, VFA decreased rapidly in Cycle III. It is worthwhile to note that the start-up period decreased with subsequent cycles.

Figure 6 presents the CH_4 composition at three consecutive cycles. The cumulative biogas production in Cycle I and II were 5927 L and 6669 L and this corresponds to specific biogas production of 324 L/kg VS and 396 L/kg VS, respectively. Enhanced cumulative biogas production of 7763 L was generated by Cycle III. This value corresponds to 418 L/kg of VS added with 80% VS reduction. Improved methane content was exhibited by Cycle III in which the highest methane value of 70% was obtained on day 19 and remained stable.

Methane yield at each cycle was calculated as the combined methane production from fresh and stabilized waste reactors. This yield is entirely attributed by the fresh waste bed, as the stabilized waste bed was exhausted of its methane-producing potential before the start of each cycle experiment. It was observed that daily biogas production with higher methane content (Figure 6 and Figure 7) is enhanced with consecutive cycle operation and increase of leachate cross-recirculation rate improves process efficiency and shortens digestion time. In Cycle 1, the daily biogas production was fluctuating and increase during premature phase indicating that fermentation of organic was the main reaction with higher percentage of carbon dioxide in the gas. Likewise Figure 8 presents the specific cumulative biogas production for 3 cycles. Cycle II and III produce higher biogas at short digestion period of 23 and 21 days, respectively. The first cycle was perhaps not as efficient as the subsequent cycles. The highest peak of daily biogas production of around 560 L was obtained by Cycle III. Moreover, methane concentration increased sharply and after 21 days of operation, improved biogas and methane yield of 418 L/kg VS and 240 L/kg VS was generated, respectively.

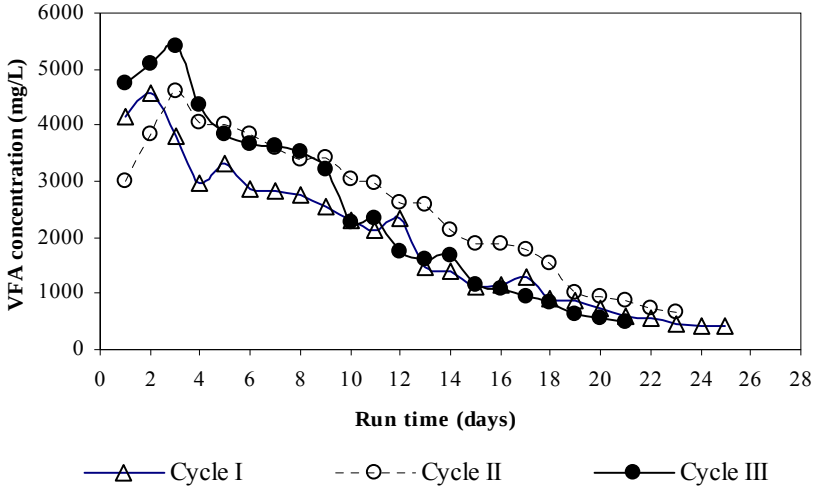


Figure 5 VFA concentration in fresh waste reactors in three cycles

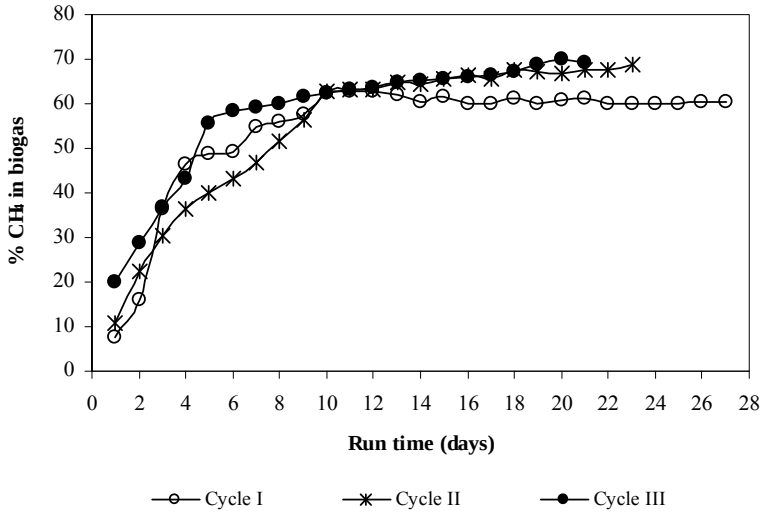


Figure 6 CH_4 composition in three cycles

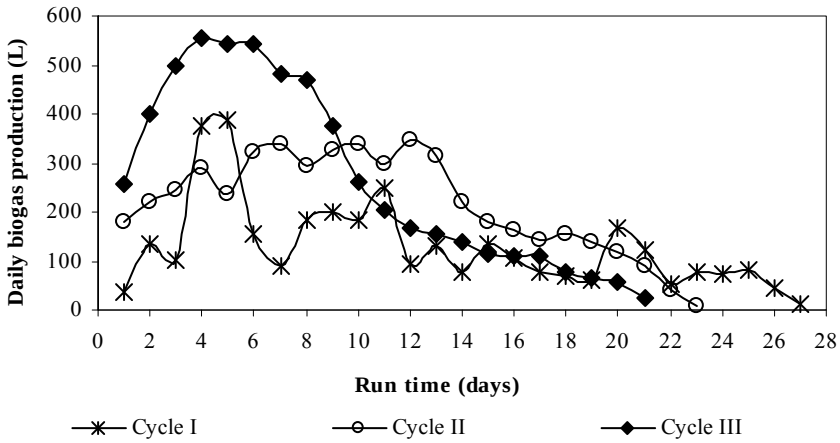


Figure 7 Daily biogas production in three cycles

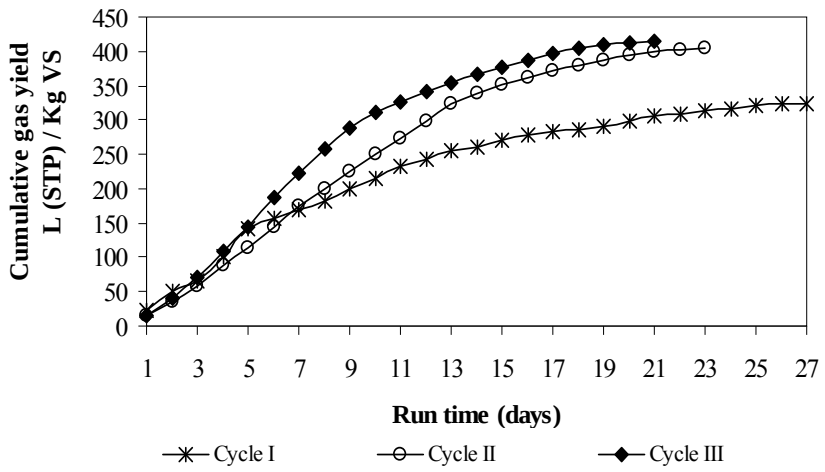


Figure 8 Specific cumulative biogas production in three cycle

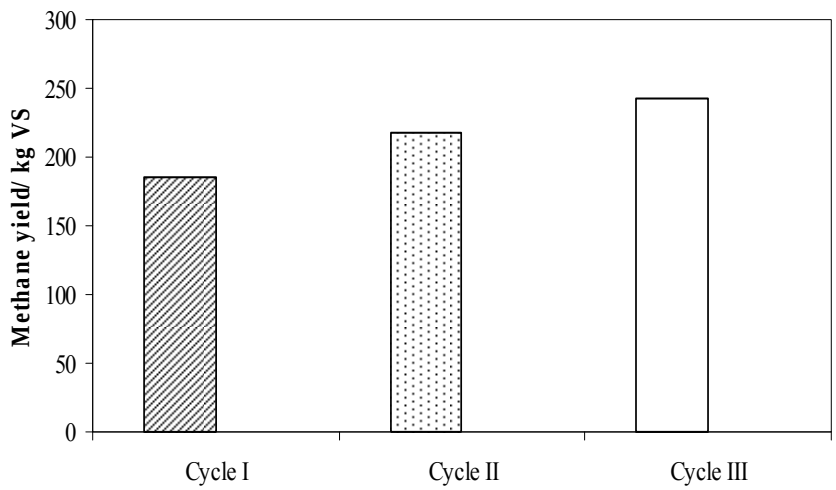


Figure 9 Specific methane production in three cycles

Therefore, this study shows that, within the flushing volume conducted, the degradation is a function of both kinetics and flushing rate. This experiment demonstrates higher degree of waste stabilization can be achieved as the recirculated rate increased with subsequent cycle operation which also generates high volume leachate as shown in Table 1. Mature leachate (from stabilized reactor) used for flushing the fresh waste reactor during sequencing staging operation does not only provide inoculum, nutrients, and moisture but also buffers the system to provide a favourable condition for the process. Moreover, increased flow rate may lead to less chance of short-circuiting thus providing more efficient inoculum distribution. Higher circulation rate also improves the inoculation of fresh reactor, allowing it to reach balanced condition more quickly. This finding is in line with the observation of Chugh et al. (1998) who reported that higher leachate recirculation rate; stable digester performance with increased biogas yield can be obtained.

The specific methane yield increases with subsequent cycle operation (Figure 9). Overall assessment results are summarized in Table 2. The early start-up of methanogenesis and increased methane production rates at higher leachate cross-recirculation rate could be due to increased flushing of waste bed and dilution of the inhibitory products leading to stable process performance. Although this study shows that the extent of waste decomposition improves with increase in moisture flow, the maximum volume of leachate that used for recirculation depends on the remaining volume after completion of digestion

process. Upon the commencement and completion of consecutive cycle operation, process instability was not detected.

Table 2 Overall sequential anaerobic digestion process assessments

Parameters	R1	Cycle I	Cycle II	Cycle III
Total volume of biogas (L)[1]	7226	5927	6669	7763
Total volume of methane (L)[1]	3956	3380	3672	4439
Biogas production /kg VS input (L)[1]	261	324	396	418
CH_4/kg VS (L)[1]	143	185	218	240
CH_4/kg VS (BMP assay) (L)[1]	294			
Process efficiency (%)	48.6	62.9	74.2	81.7

[1] Volume expressed at STP (0° C, 1 atm.)

4 Conclusion

An experimental investigation on pilot scale sequential batch anaerobic digestion process in three consecutive cycles under thermophilic condition was investigated. This paper evaluates the effect of increasing leachate cross-circulation rates at sequential cycles with cross-recirculation rate of 0.34, 0.46, and 0.58 m^3 leachate/m^3 of waste per day for Cycle I, II, and III respectively. This process showed increasing specific methane yield of 184, 217, and 239 L CH_4/kg VS which correspond to process efficiency of 63%, 74%, and 82% for Cycle I, II, and III respectively. The start-up period decreased from 7 days in Cycle I to 5 days in Cycle III. Higher recirculation rates enhanced biogas production but also shorten digestion period. Therefore, thermophilic sequential batch anaerobic digestion process along with several cycles and increased recirculation rate enhanced the organic solid waste which generates high biogas yield and high process efficiency.

5 Acknowledgement

The authors wish to convey their gratitude to the Swedish International Cooperation Development Agency (SIDA) for generously supporting the financial aspects of this research. This study is part of Sustainable Landfill Management in Asia under the Asian Regional Research Program on Environmental Technology (ARRPET).

References

APHA, AWWA, and WEF. (1998). Standard method for the examination of water and wastewater, 1995, 19th edition. Washington, D.C., USA. ISBN: 0-87553-235-7.

Bouallagui H., Haouari, O., Touhami, Y., Cheikh, B.R., Marouani, L., Hamdia, M.(2004). Effect of temperature on the performance of an anaerobic tubular reactor treating fruit and vegetable waste. Process Biochemistry 39:2143-2148.

Cecchi, F., Traverso, P., Pavan, P., Bolzonrlla D., Innocenti, L. (2003). Characteristics of the OFMSW and behavior of the anaerobic digestion process. In Mata-Alvarez, J. (Ed.) Biomethanization of the organic fraction of municipal solid wastes (pp.141-178.IWA Publishing. ISBN: 1- 900222 -14-0.

Chugh, S., Clarke, W., Pullammanappallil, P., and Rudolph, V. (1998). Effect of recirculated leachate volume on MSW degradation, Waste Management and Research, 16, 6: 564-573.

Chynoweth, D.P., Sifontes, J.R., and Teixeira, A.A. (2003). Sequential batch anaerobic composting of municipal and space mission waste and bioenergy crops. (Presented in ORBIT conference, Perth Australia). URL: http://www.agen.ufl.edu/~chyn/download/SebacORBIT.doc.

Chynoweth, D.P., Owens, J., O'Keefe, D., Earle, J.F., Bosch, G., Legrand, R. (1992). Sequential batch anaerobic composting of the organic fraction of municipal solid waste. Water Science and Technology, 25 (7): 327-339.

Converti, A., DelBorghi, A., Zilli, M., Arni S., DelBorghi M. (1999). Anaerobic digestion of the vegetable fraction of municipal refuses: mesophilic versus thermophilic conditions. Bioprocess Engineering, 21:371–6.

Edelmann, W., Baier, U., Ehgeli, H. (2004). Environmental aspects of anaerobic digestion of organic fraction of Municipal solid waste and of agricultural wastes. http://www.arbi.ch/LCA%20AD%20OFMSW.pdf.

Gerardi, M. (2003). The microbiology of anaerobic digesters. Jonh Wiley and Sons, Inc. New Jersey. ISBN: 0-471-20693-8.

Hansen, T.L., Schmidt, J.E., Angelidaki, I., Marca, E., Jansen, J.C., Mosbaek, H., and Christensen, T.H. (2004). Method for determination of methane potentials of solid organic waste. Waste Management, 24: 393-400.

Juanga, J.P. and Visvanathan, C. (2006). Thermophilic anaerobic digestion of municipal solid waste in combined process and sequential staging. Presented in the 6th international symposium on global renaissance by green energy revolution. Nagaoka, Japan.

Juanga, J.P. (2005). Optimizing dry anaerobic digestion of organic fraction of municipal solid waste. Asian Institute of Technology (AIT), Thailand, Master's thesis no. EV-05-11.

Nguyen, P.H.L., P. Kuruparan and C. Visvanathan, (2005). Anaerobic digestion of municipal solid waste as a treatment prior to landfill. Bioresource Technology, *In Press.*

Valdez-Vazqueza, I., Ríos-Leala, E., Esparza-Garcíaa F., Cecchi, F., Poggi-Varaldoa, H. M.(2005). Semi-continuous solid substrate anaerobic reactors for H_2 production from organic waste: Mesophilic versus thermophilic regime. International Journal of Hydrogen Energy, 30: 1383 – 1391.

Visvanathan C., Trankler, J., Joseph, K., Chiemchaisri, C., Basnayake, B.F.A., and Gongming, Z. (2004). Municipal solid waste management in Asia: Asian regional research program on environmental technology (ARRPET). Asian Institute of Technology publications. ISBN: 974-417-258-1.

Anaerobic Digestion of Municipal Solid Waste in Thermophilic Sequential Batch Process

R. Adhikari, J.P. Juanga, C. Visvanathan

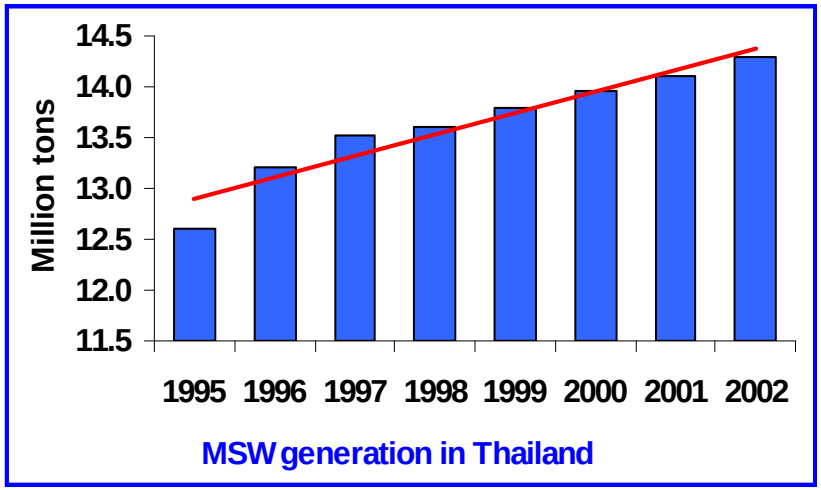
Environmental Engineering and Management Program

Asian Institute of Technology

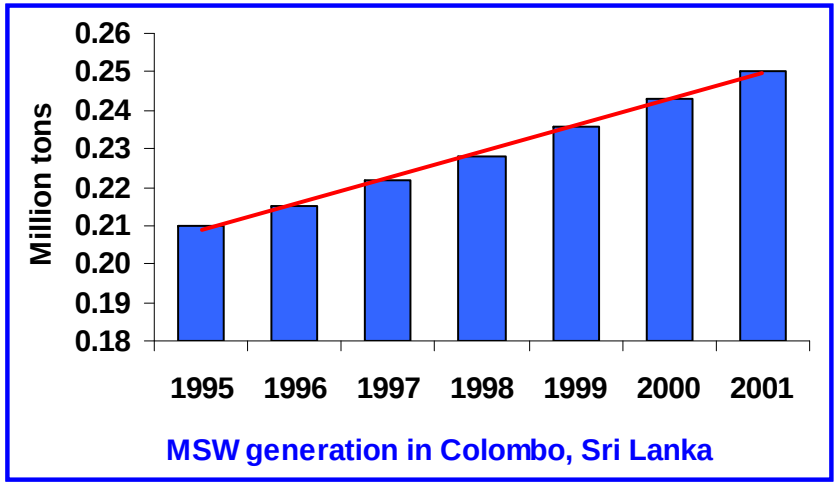
Thailand

September 13-15, 2006

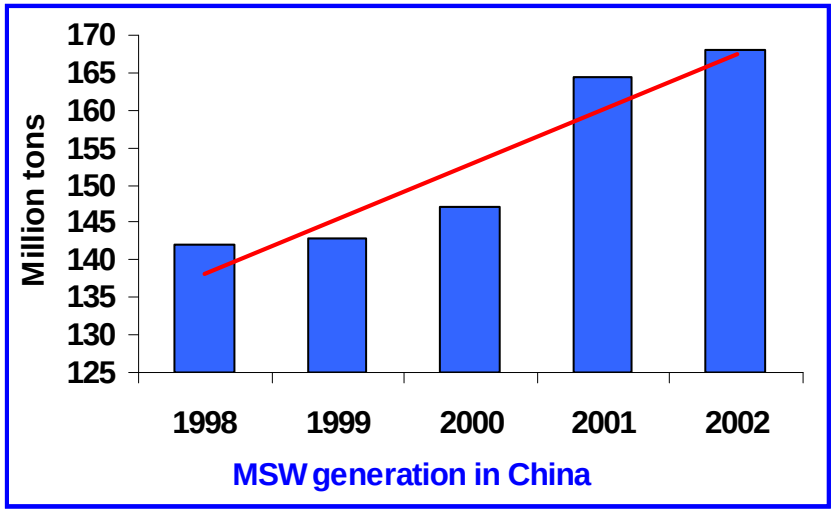
Increasing Trend of MSW Generation with Time



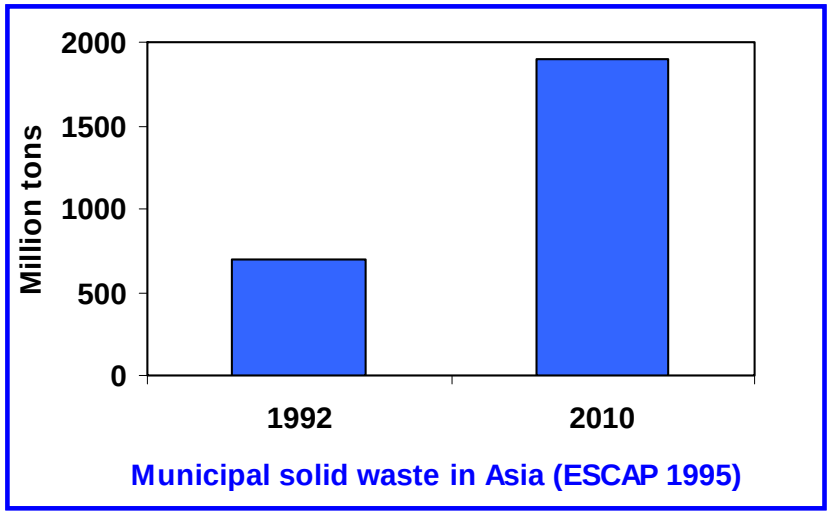
MSW generation in Thailand



MSW generation in Colombo, Sri Lanka



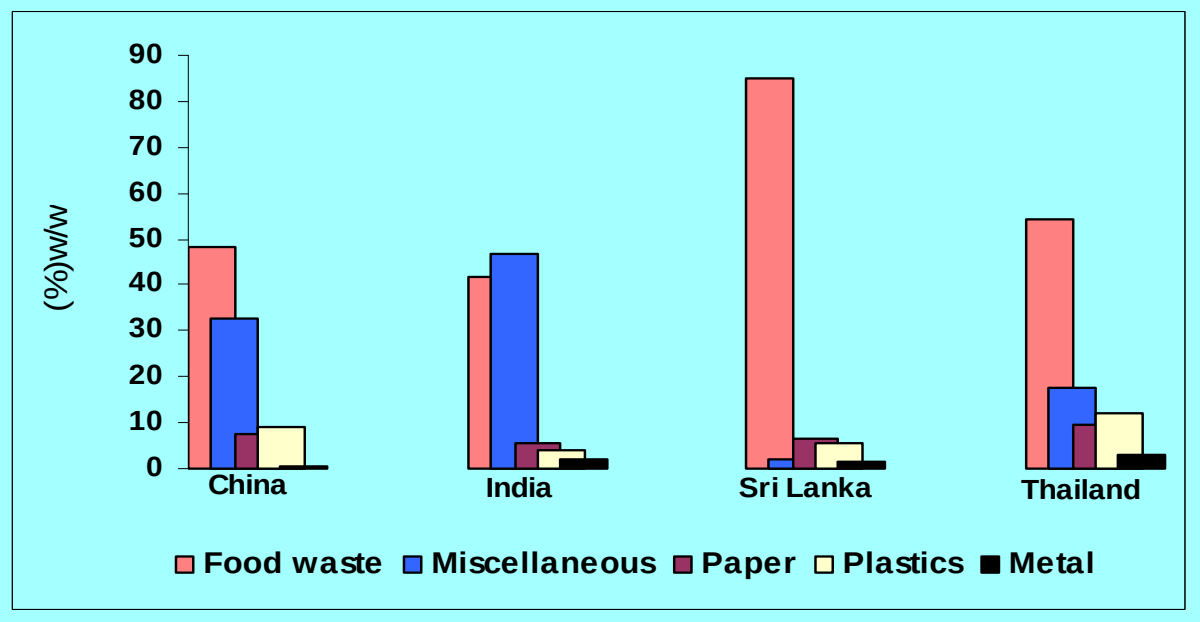
MSW generation in China



Municipal solid waste in Asia (ESCAP 1995)

Potential Waste Characteristics

✓ Higher amount of organic fraction

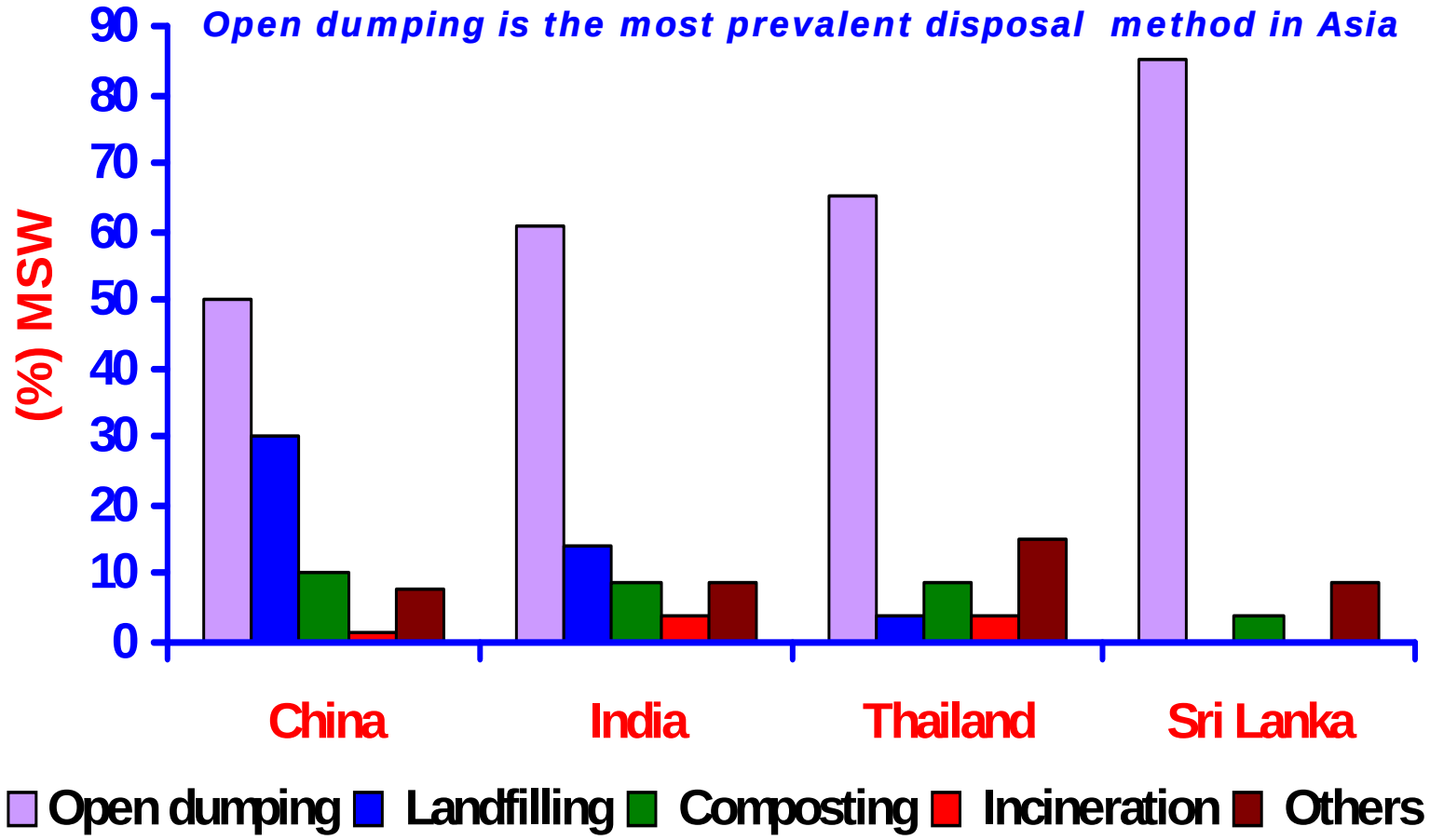


Municipality	Moisture (%)
In Thailand	
Hat Yai	57
Chonburi	59
Samutprakarn	65
Pattaya	70
In India	
Kolkata	40-45

✓ High moisture content

Need for treatment prior to landfill to stabilize the organic fraction as well as the long term emission control

Municipal Solid Waste Management in Asia



Open dumps: No precautionary measures for potential emissions (gas and leachate)

Open Dumpsites in Asia

Gohagoda (Sri Lanka)

Chennai (India)

Shanghai (P.R. China)

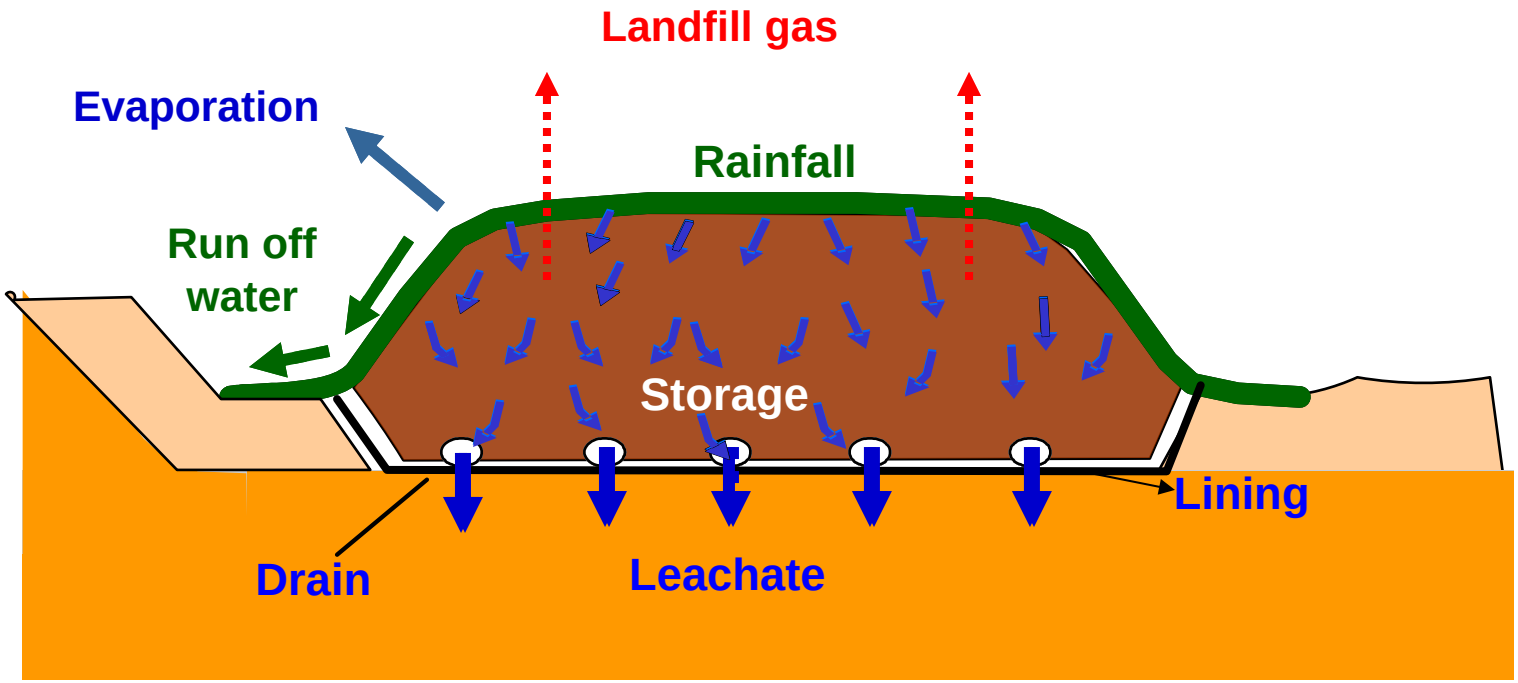
Nonthaburi (Thailand)

Landfill is far better than Open dump

However, direct landfilling of waste pose long term environmental problem

Landfill and associated problems

- Ultimate destination of waste residues
- Cheap, simple but unsustainable in long term
- Environmental concerns: Air, surface / ground water problems
- Landfills are indispensable component of integrated solid waste management



Problem Statement

- Old landfill sites are exceeding their capacities, new landfills are difficult to find!
- Mass/volume reduction of MSW → better utilization of space
- High organic fraction (>60%), high moisture content in Asian MSW
- Aerobic and anaerobic biological processes: two viable bio-technologies
- Stabilization of solid waste besides mass and volume reduction

Aerobic Composting

Odor problem, Less volume reduction

net energy user

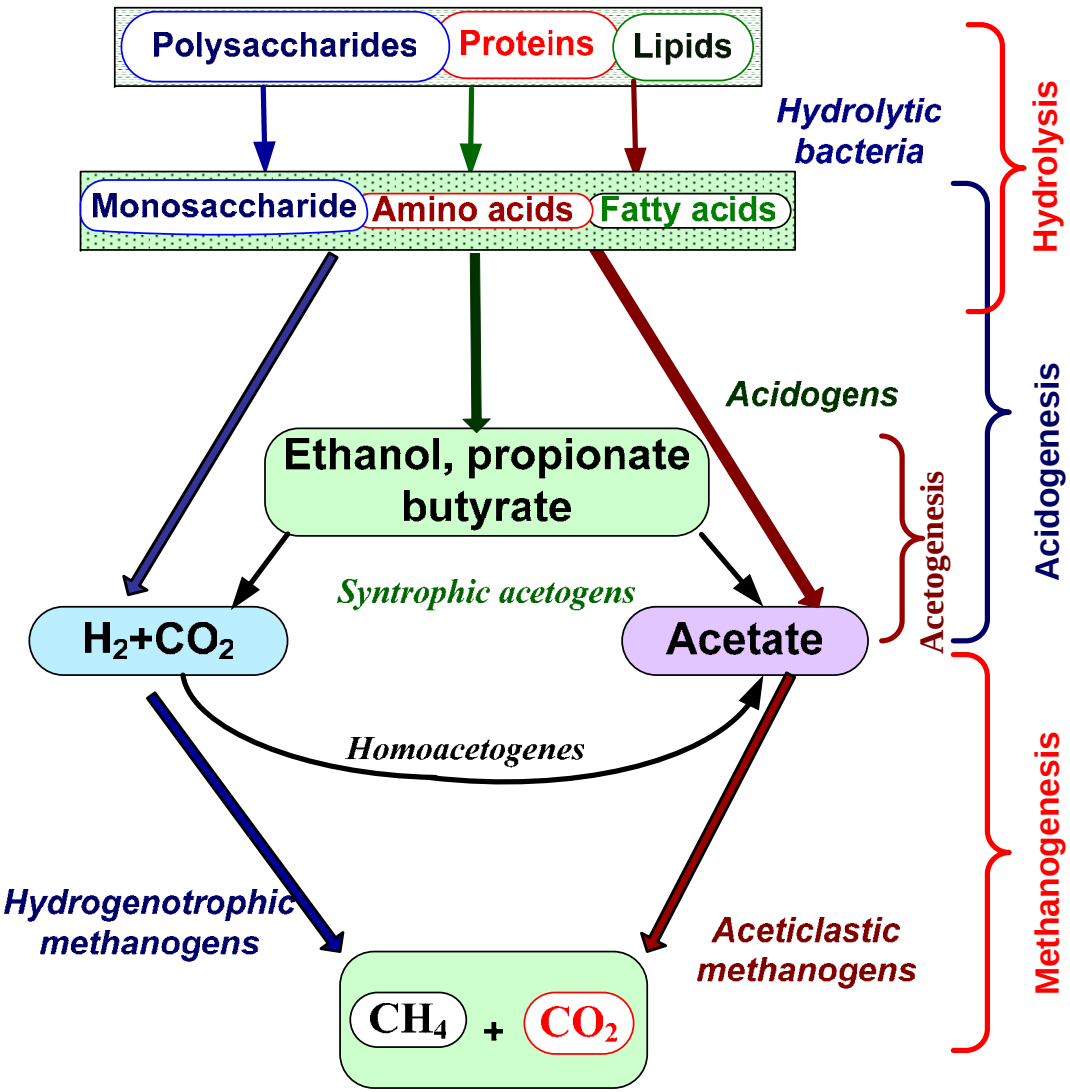
Anaerobic digestion

Less odor, more volume reduction

net energy producer

Anaerobic Digestion is an Environmentally benign!

Anaerobic Digestion: Fundamental Process

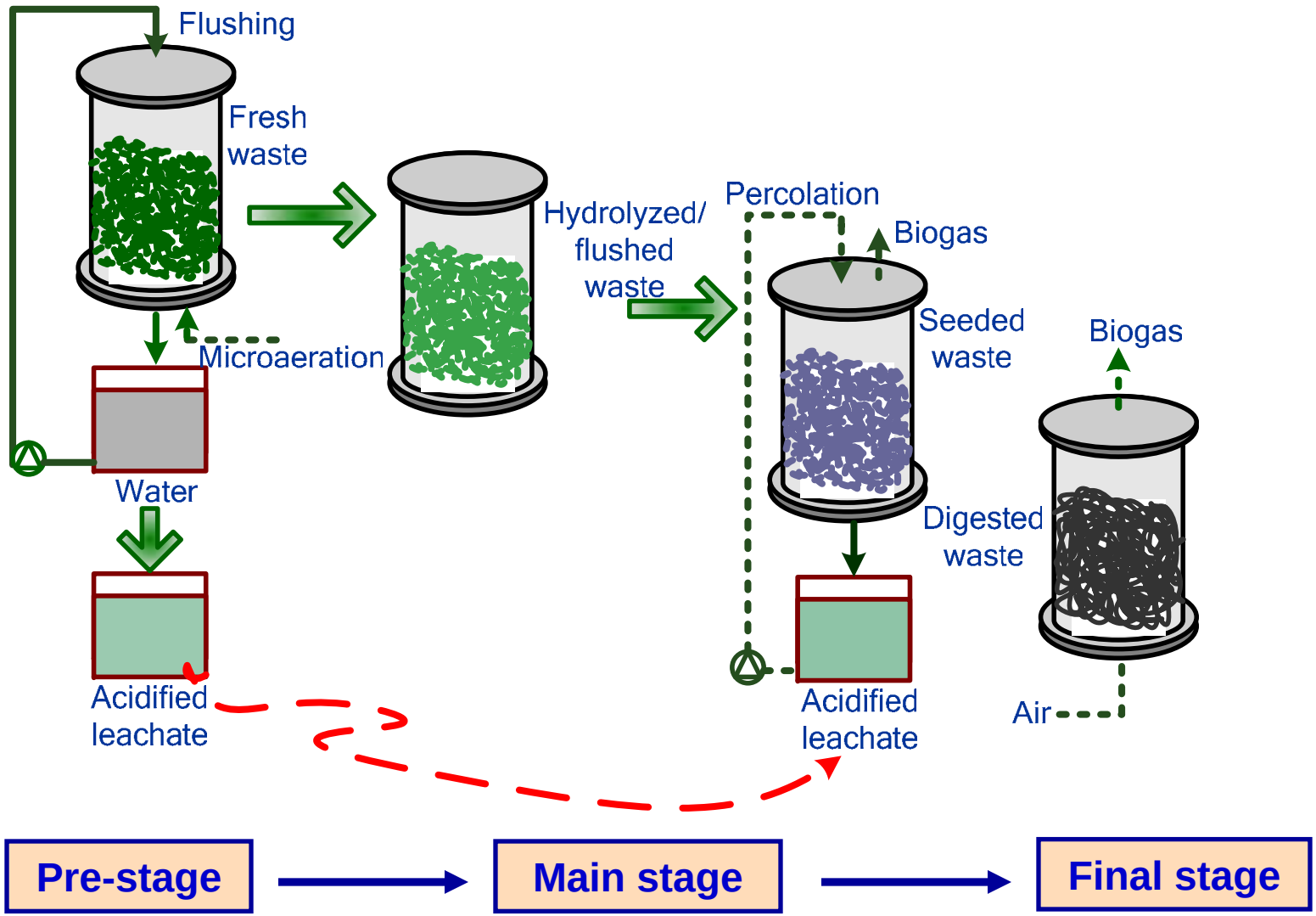


Study Objectives

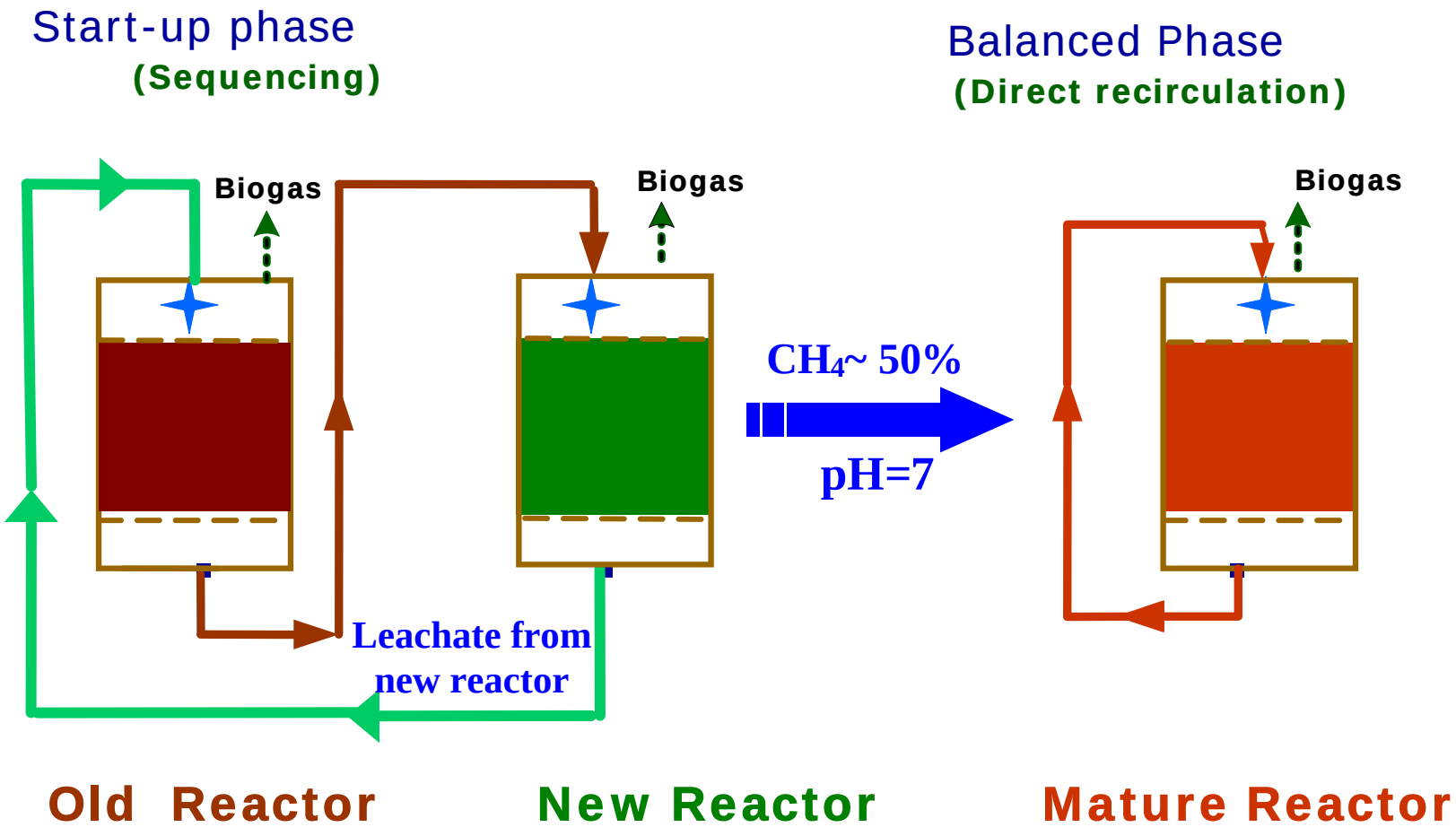
- To investigate the performance of sequential batch anaerobic digestion process at three consecutive sequential staging (cycles) under different leachate cross-recirculation rate at thermophilic condition

- To study and investigate the possibility of utilization of digestate waste for its economic value

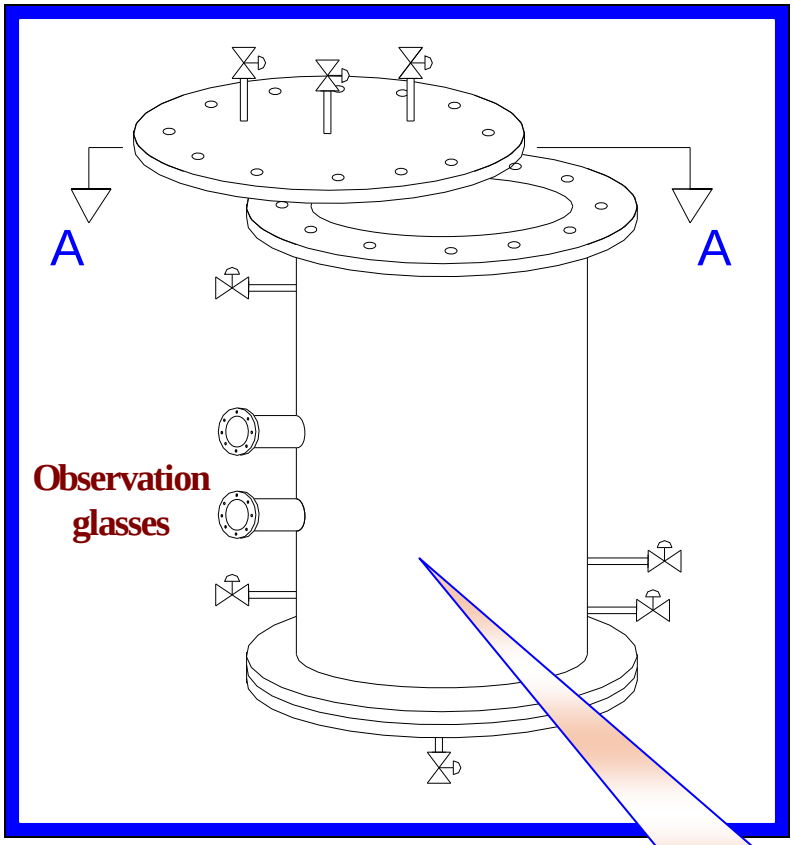
Concept of Combined Anaerobic Digestion Process

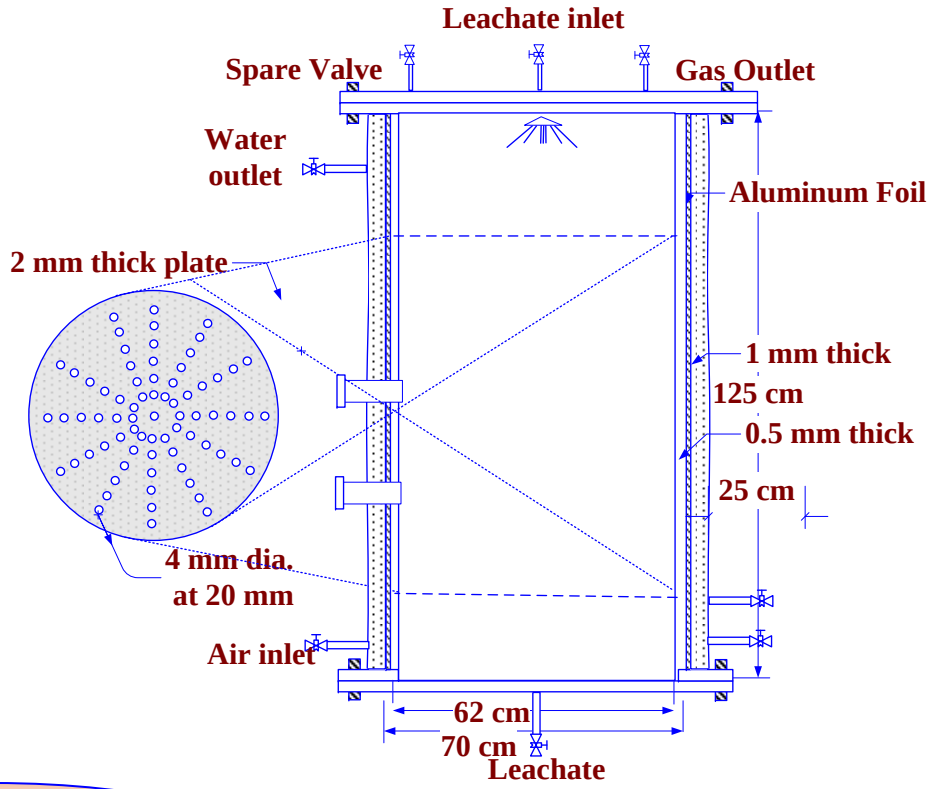


Concept of Sequential Staging Anaerobic Digestion Process



Reactor Configuration

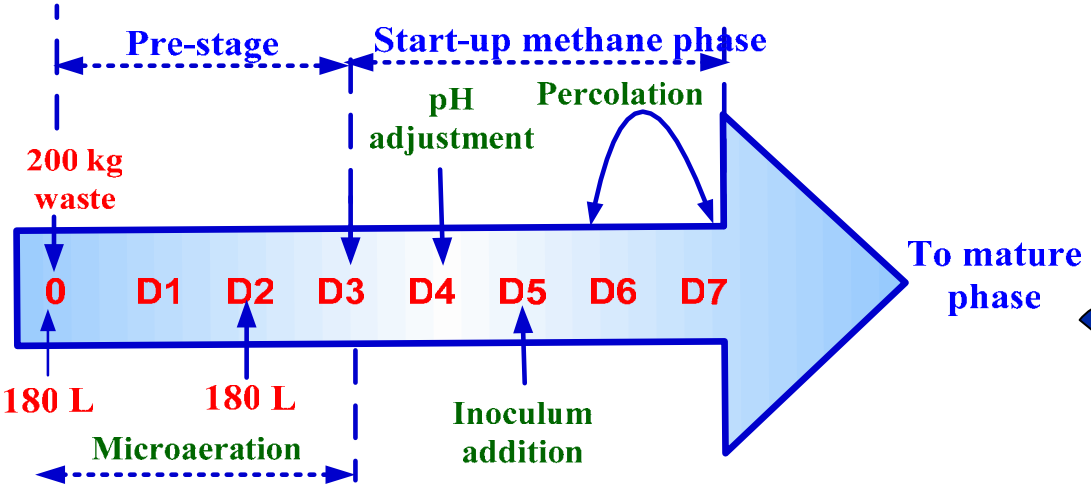




260 L Working volume

Stabilized Reactor Preparation

Combined digestion process



Pre-stage	Mesophilic (37°C)
Main stage	Transient (37°-55°C)
	Thermophilic (55°C)

Stabilized reactor (Biogas exhausted)

Sequential staging process

Carried to Cycle I (Sequential staging)

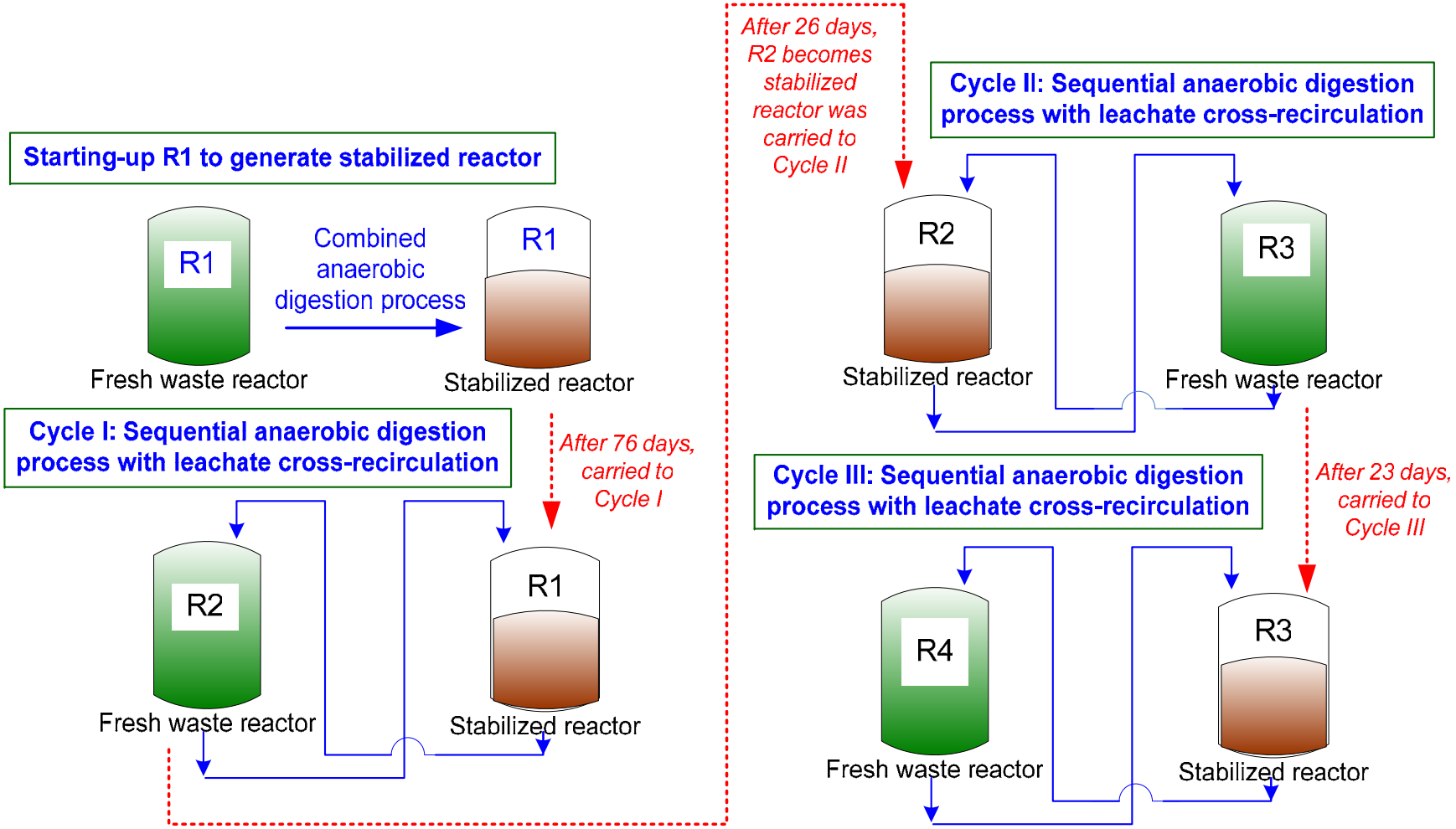
New reactor shifted to Stabilized reactor (Biogas exhausted)

Carried to Cycle II (Sequential staging)

New reactor shifted to Stabilized reactor (Biogas exhausted)

Carried to Cycle III (Sequential staging)

Preparation of Stabilized Reactor and the Sequencing Staging Operation at Three Cycles



Feedstock Preparation

Waste segregation

Shredding-Size reduction

Weighing of waste

Weighed waste ready for loading

Reactor loading

The Digestion System

Sequential Anaerobic Digestion: Process details

Operating condition:

Thermophilic (55°C); Particle size (30 mm)

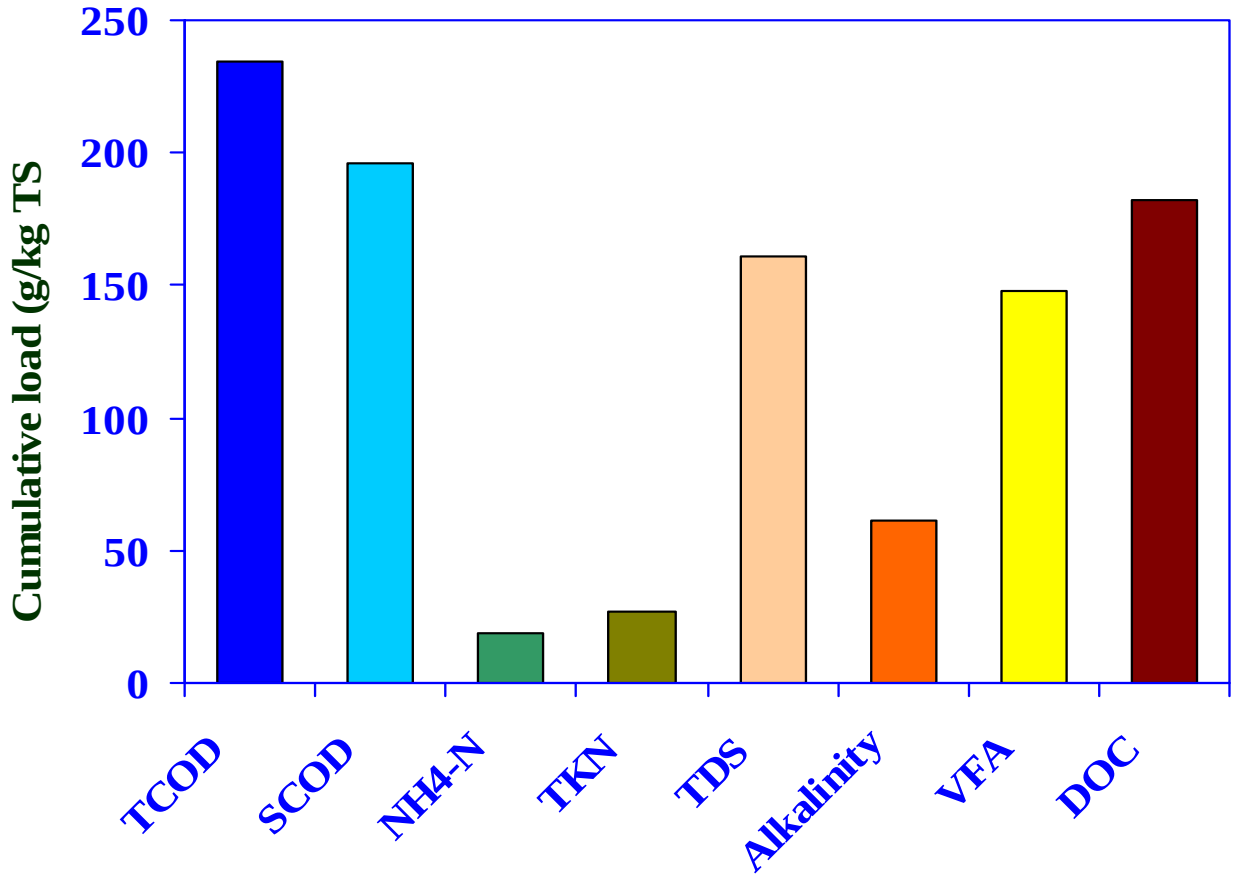
Operation	Volume of leachate used for cross-recirculation	Cross-recirculation rate
Cycle I	90 L	3 L/min (0.34m^3/m^3 waste. day)
Cycle II	120 L	4 L/min (0.34m^3/m^3 waste. day)
Cycle III	150 L	5 L/min (0.34m^3/m^3 waste. day)

Cycle I ➔ pH ~ 7; CH_4 ~ 50% (day 7)

Cycle II ➔ pH ~ 7 (day5); CH_4 ~ 50% (day7)

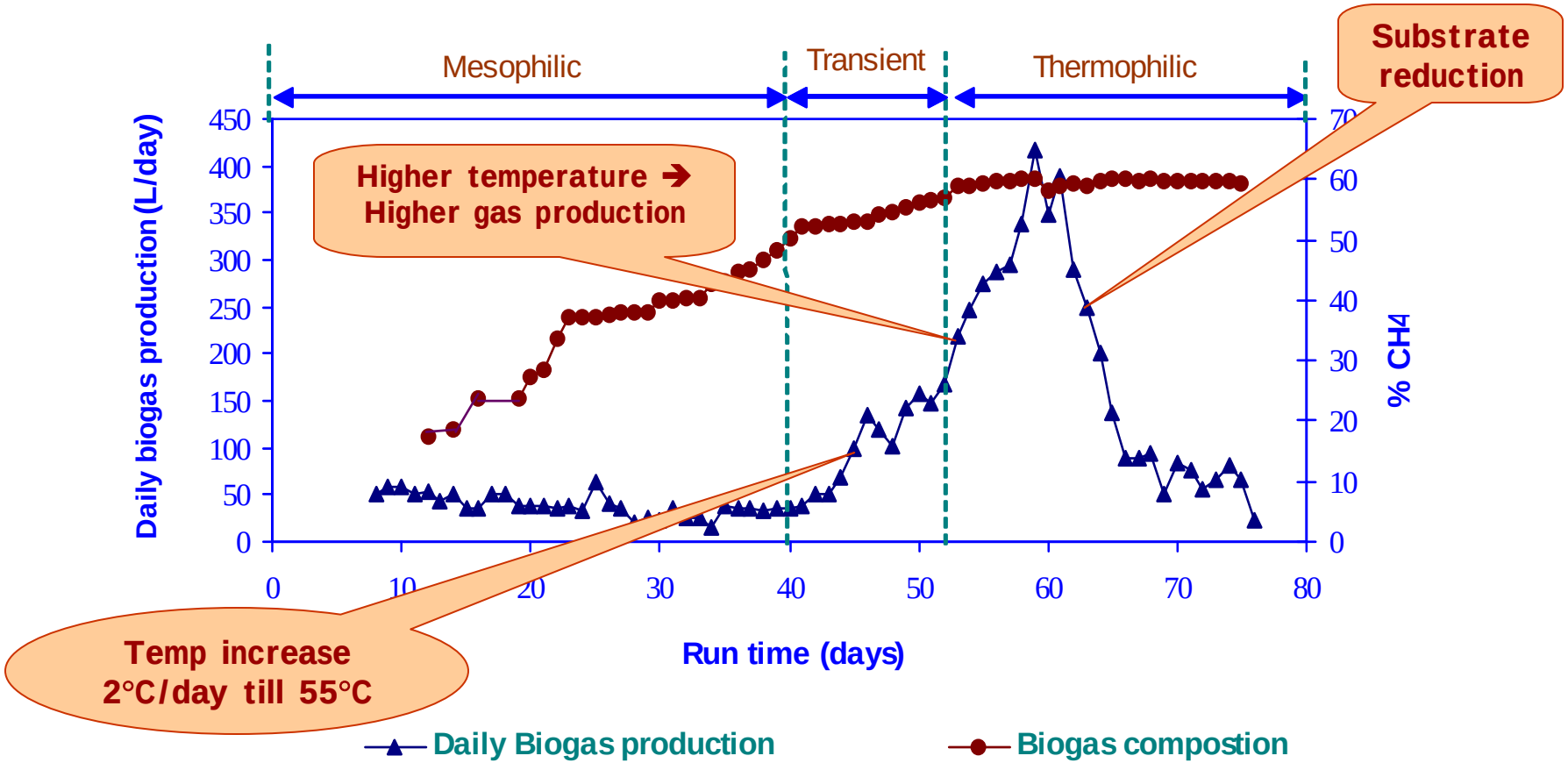
Cycle III ➔ pH ~ 7; CH_4 ~ 50% (day 5)

Results:
Pre-stage Pollutant Load Removal



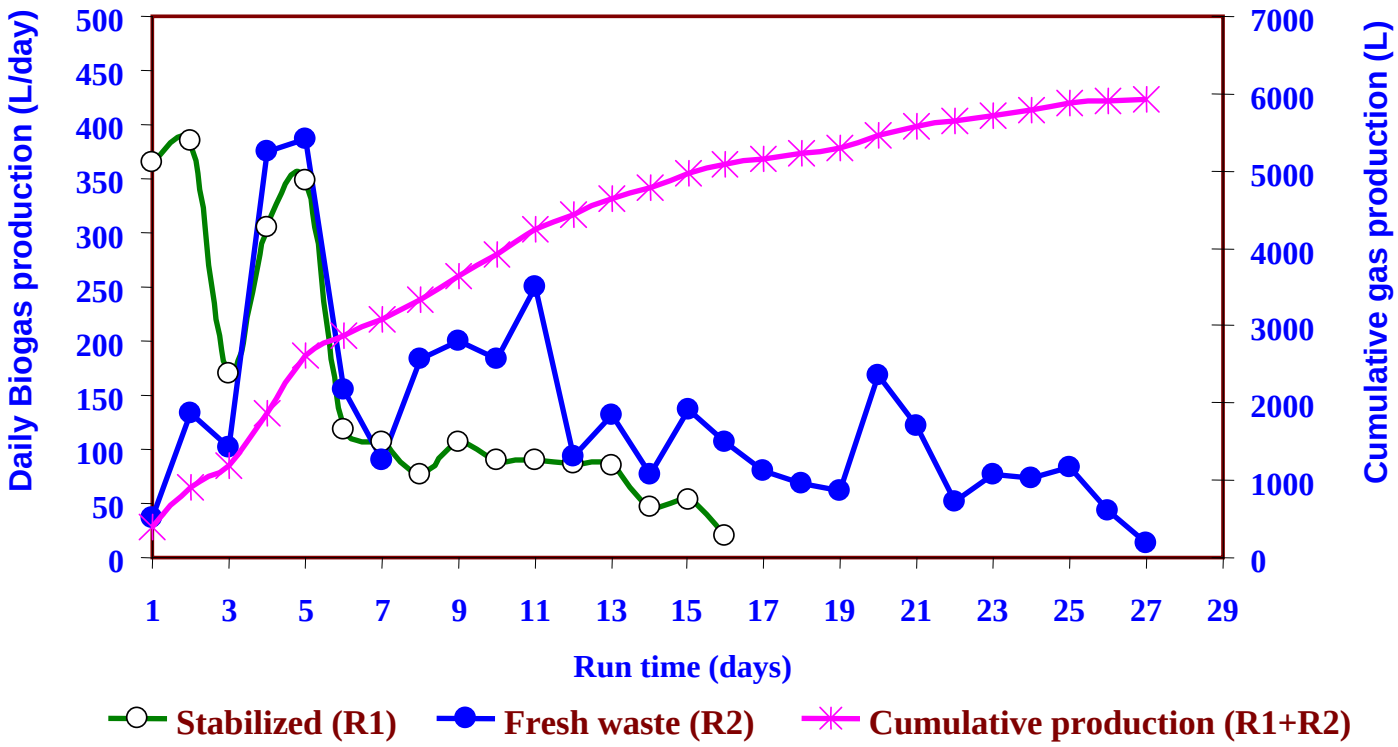
Pollutant load flushed after pre-stage of combined process:
234 g TCOD/kg TS,
161 g TDS/kg TS,

Results: Main Stage Biogas Generation



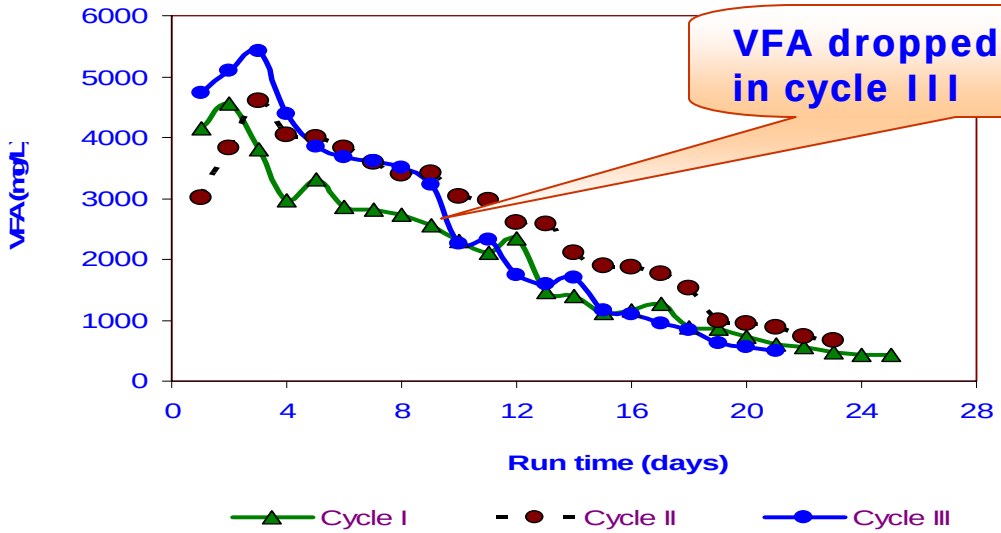
Long time inoculum acclimatization not necessary

Biogas generation: Cycle I



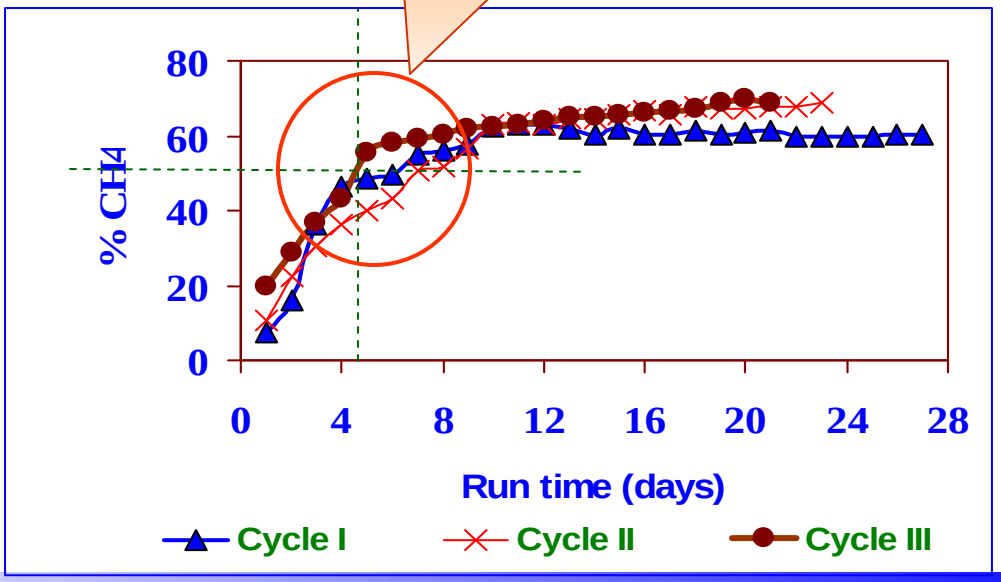
As the stabilized waste bed was exhausted of its methane-producing potential before the start of the experiment
➔ *Biogas production is attributed to fresh waste only*

Sequential Staging Process Assessment



VFA dropped more rapidly in cycle III

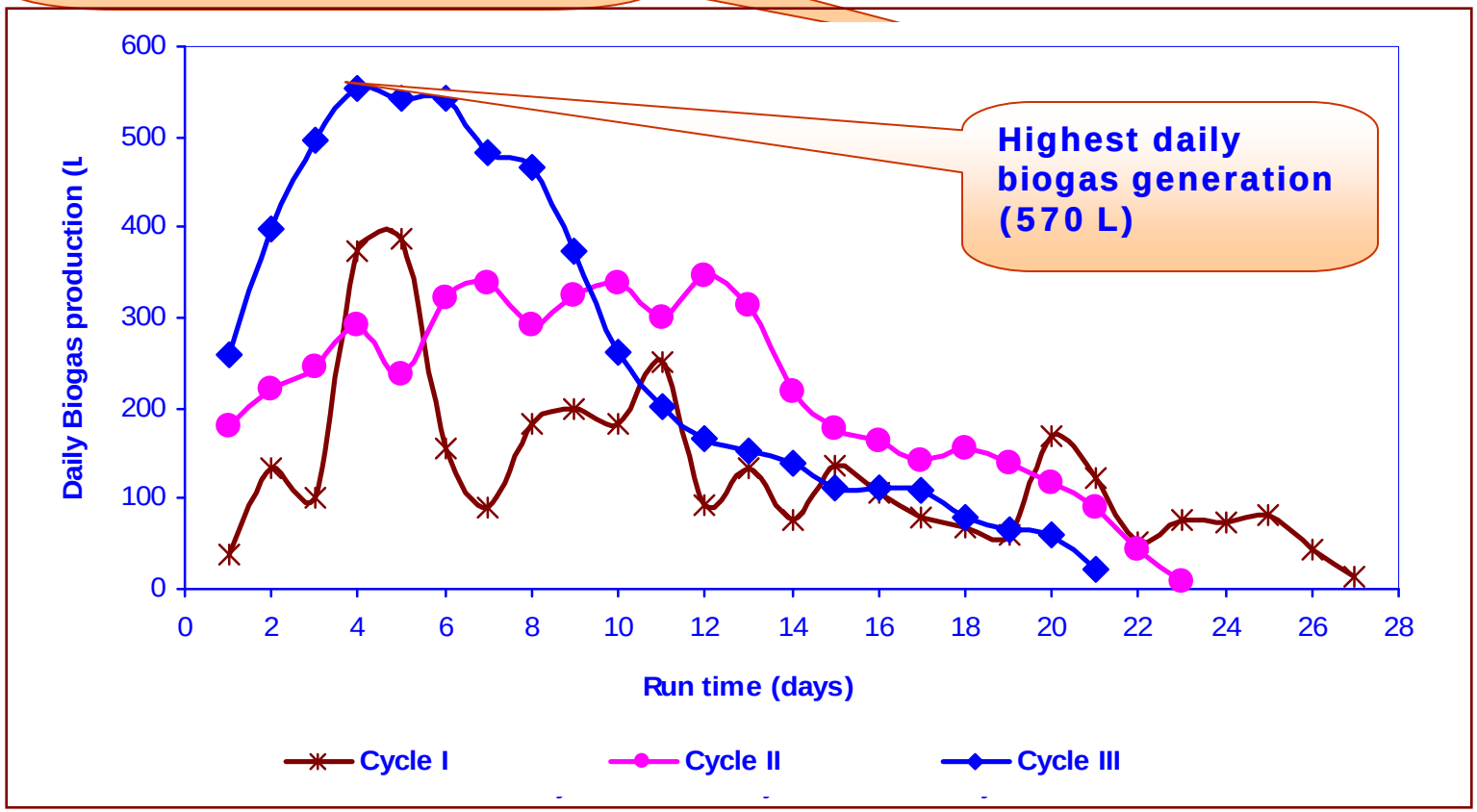
Fresh reactor remained coupled for 5 days in cycle III compared to 7 days for cycle I & II. Methane concentration increased faster



Increased leachate circulation rate stimulates methanogenesis activities

Sequential Staging Process Assessment

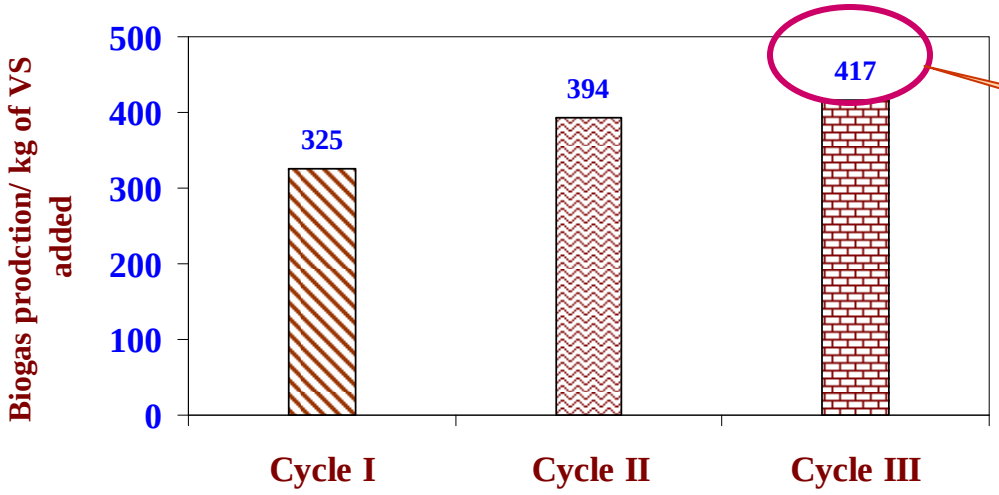
At day 21, Cycle III produced more gas than other cycles



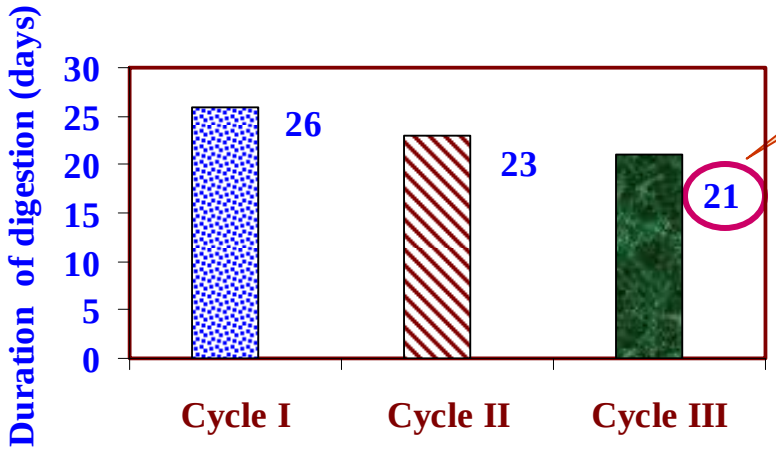
Highest daily biogas generation (570 L)

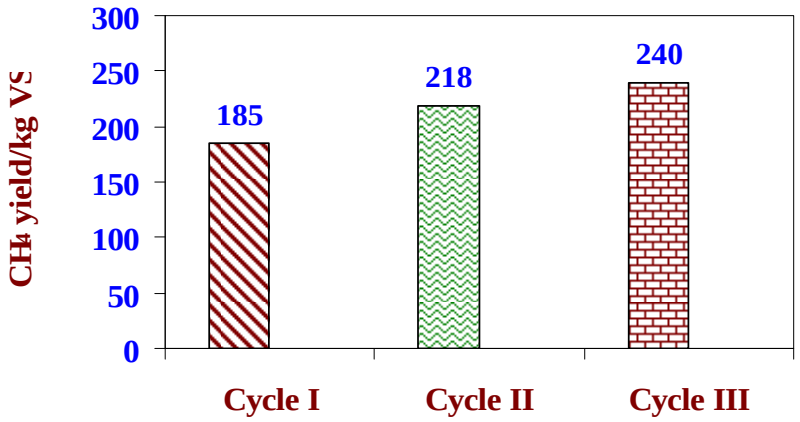
Within the flushing volume used, the degradation is a function of time and cross-recirculation rate

Sequential Staging Process Assessment

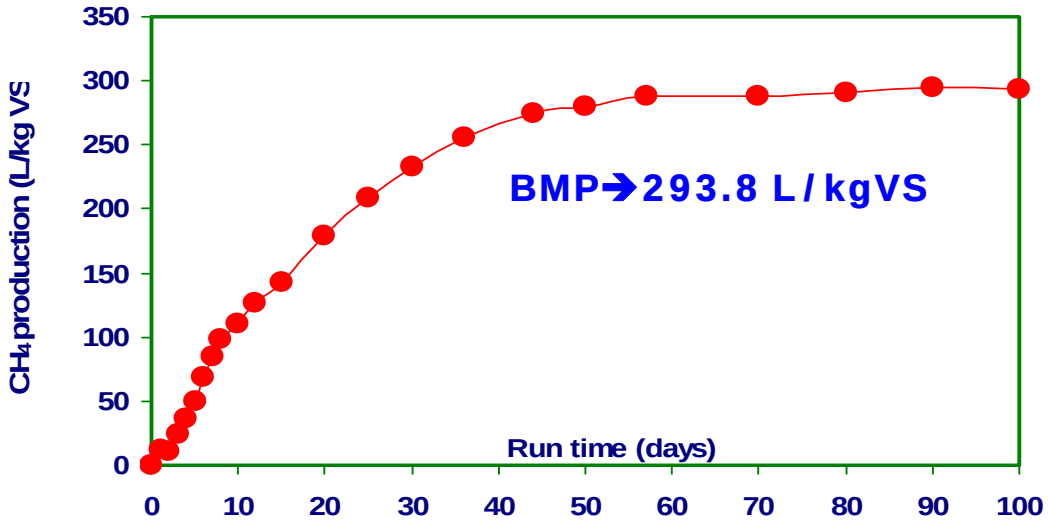


Not only biogas yield increased but digestion time was shortened to 21 days





Overall Process Assessment



Parameters	R1	Cycle I	Cycle II	Cycle III
Total volume of biogas (L)	7226	5927	6669	7763
Total volume of methane (L)	3956	3380	3672	4439
Biogas production/kg VS (L)	261	324	396	418
CH4/kg VS (L)	143	185	218	240
Process efficiency (%)	48.6	62.9	74.2	81.7
Duration (days)	76	26	23	21

Digestate Quality



Nutrients are intact

	Nutrients			TOC (%)
	N (%)	P (%)	K (%)	
Cycle III	2.26	0.57	0.6	10.6
Thai guideline	1.0	0.8	0.5	<20

Anaerobic digestion does not reduce nitrogen and phosphorus but keeps the value of nutrients intact for fertilizer

Heavy metals within limit

	Heavy metals							
	Cd	Cr	Cu	Pb	Hg	Ni	Zn	Mn
Cycle III	0.85	14.5	40	26.2	-	9.75	1.19	109
WHO	3	50	80	150	1	50	300	-

No cause of concern from Heavy metal contamination (below standards) of hand-sorted feedstock

Conclusions

- Initial reactor was operated well under an optimized combined anaerobic digestion process wherein considerable amount of pollutant load was removed after 3 days of pre-stage operation.
- Sequential staging process performed in three cycles eliminates the need for pH adjustment, inoculum addition, and pre-stage operation.
- Gradual temperature increment at a rate of 2°C was found satisfactory to bring the mesophilic condition to thermophilic. Biogas production increased at higher operating temperature (thermophilic).
- Higher leachate cross-circulation rate resulted into more rapid waste degradation with shorter digestion time at high methane yield and improved process efficiency (82%).
- The stabilized waste residue meets the Thai guideline as proposed by Land Development Department. Moreover, the heavy metals (Cd, Cr, Cu, Pb, Ni, Zn) contained in waste is below the WHO standard limits.

THANK YOU VERY MUCH...