THERMOPHILIC ANAEROBIC DIGESTION OF MUNICIPAL SOLID WASTE IN COMBINED PROCESS AND SEQUENTIAL STAGING

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Abstract

Anaerobic digestion is an attractive method for waste stabilization with the potential generation of biogas and stabilized waste residue. Development of a treatment process at short digestion period with maximum process efficiency is the objective of this research. This paper presents the optimization performance between the combined anaerobic digestion and sequential staging concept in thermophilic solid state batch system. The former involves enhanced pre-stage flushing with microaeration and inoculum addition in methane phase. The latter involves leachate cross-recirculation between the old and new reactors directly without conducting pre-stage operation. The optimized process for combined anaerobic digestion showed that reducing pre-stage operation with maximum removal of organics from waste bed is beneficial. Moreover, the sequential staging concept offers an improved process over the combined anaerobic digestion. Improved waste stabilization with 86% and 79% of mass and volume reduction was achieved, respectively. Higher methane yield of 334 L CH_4/kg VS with 86% VS reduction which is equivalent to 84% process efficiency was obtained.

Keywords: anaerobic digestion; solid waste; leachate; microaeration; biogas

Introduction

The triggering environmental problems linked to municipal solid waste landfills and its disposal, diminishing land resources and depletion of fossil fuels have fostered the need for biological pre-treatment of solid waste prior to landfill. The anaerobic digestion process is considered as innovative and attractive technology for waste stabilization with significant mass and volume reduction with the generation of valuable by products such as biogas and stabilized waste residue. This method is especially suitable for the waste characteristics in Asian region. According to Visvanathan et al. (2004), the solid waste composition in most Asian countries is highly biodegradable with high moisture content and mainly composed of food waste. This type of waste is neither appropriate for incineration for it requires high energy input to bring the waste to its ignition level, nor can be landfilled directly due to the associated negative impacts of landfilling. Direct landfilling of such waste creates nuisance owing to the generation of highly concentrated leachate, methane gas emission, and quick settlement of landfill due to waste decomposition that eventually affects the landfill stability. The appropriate alternative that can surpass these limitations is to subject the waste for biological (anaerobic) treatment process.

Anaerobic digestion technology encompasses wide spectrum of procedure types from wet to dry, from single-phase to multi-phase, from batch to continuous and within a variety of feedstock. The specific features of batch process includes simple design and process control, lower investment cost, small water consumption, etc. make them attractive for developing economies (Mata-Alvarez, 2003). The optimization process needs further investigation especially during the start-up stage in order to shorten the overall digestion duration with maximum process efficiency (Meisgeier et al. 2003). The biogas yield and production rate were at least as high in systems where the wastes were kept in their original solid state wherein it is not diluted with water (Baeten & Verstraete 1993, Oleszkiewicz & Poggi-Varaldo 1997, Spendlin & Stegmann 1998). Moreover, substrate particle size reduction enhances anaerobic digestion process in which higher yield of biogas and reduced digestion time were possible (Palmwoski & Muller 2000). Dayanthi et al. (2004) reported the significance of leaching and the generated leachate can be potentially used for cross recirculation. Furthermore, Nguyen (2004) described the importance of flushing and microaeration during pre-stage, pH adjustment and inoculum addition to start-up methanogenesis, and leachate percolation to enhance biogas production in combined anaerobic digestion process. Anaerobic digestion in batch sequential staging employs leachate cross-recirculation between new and stabilized reactor. This operation overcomes the associated problems with inoculation, mixing, and process instability. Thermophilic digester was considered as a reliable and accepted mode of fermentation which is more efficient in terms of biogas yield; retention time, loading rate, and pathogen kill (De Baer 2000).

This paper studied the combined anaerobic digestion process with the aim to optimize the overall digestion system under thermophilic condition and reduced pre-stage operation. Additionally, an attempt was taken to employ sequential staging concept by using a stabilized (old) reactor which underwent a combined anaerobic digestion process. Importantly, process evaluation between an optimized combined process and sequential staging concept were evaluated with the main objective of optimizing the process.

Methodology

Equipment

This study was performed in pilot scale, double-walled stainless steel anaerobic digesters with a total volume of 375 L. The designated volume for waste bed is 260 L, leaving the available headspace and bottom space for biogas generation and gravel support, respectively. The reactors were equipped with top removable cover for waste loading and unloading in each batch. 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.

Air compressor was used to provide aeration/microaeration. Microaeration (limited amount of oxygen supplied in anaerobic zone) could increase the hydrolysis rate thereby improving pre-stage performance. The operation of pumps and air compressor were controlled at certain rate and interval by flow meters and timers. The leachate recirculation system consists of the reactor's bottom outlet connected to leachate storage tank. The tank is equipped with pump and liquid distribution line up to the top inlet of the reactor. The sprinkler placed at 3 cm below the top cover, distributes the water throughout the waste surface. The flushed leachate is allowed to flow through the waste bed and collected to the same storage tank by gravitational force. The reactor is equipped with biogas sampling and biogas production measurement system. The biogas is measured by using a drum type gas meter.

Feedstock preparation and characterization

The substrate used was collected from Rangsit market in Bangkok, Thailand and mainly comprised of mixed vegetables waste. Fresh waste was manually sorted to remove bulky and inorganic fractions and was subjected to size reduction of less than 30 mm by using mechanical pulverizer. Representative waste sample was taken for solid analysis and was characterized to contain high moisture content (MC=90%), high volatile solids (VS=78%) and total solids (TS) of 10%. The shredded waste was loaded into the reactor together with bamboo cutlets (10% volume of loaded waste) as bulking agent. The purpose of adding bulking material was to create void space to facilitate the flow and distribution of flushing water and microaeration/aeration throughout the waste bed. At the end of the process, bamboo cutlets were separated from the digested waste and the waste was subjected for solid analysis.

Analytical methods

Solid waste analyses before and after digestion were determined in terms of MC, TS, and VS. Biochemical methane potential (BMP) test was conducted on fresh waste based on the method established by Hansen et al. (2004). Daily biogas composition was analysed by using gas chromatograph (GC 14A-SHIMADZU). Leachate in pre-stage and methane phase were analyzed for alkalinity, pH, dissolve organic carbon (DOC), volatile fatty acid (VFA), and ammonia nitrogen (NH_4-N) by following the analytical procedures of standard test methods in APHA et al. (1998).

Experimental set-up

This study was conducted in two runs. The first run employed a concept of combined anaerobic digestion process while the second run was performed by using sequential staging concept (Figure 1).

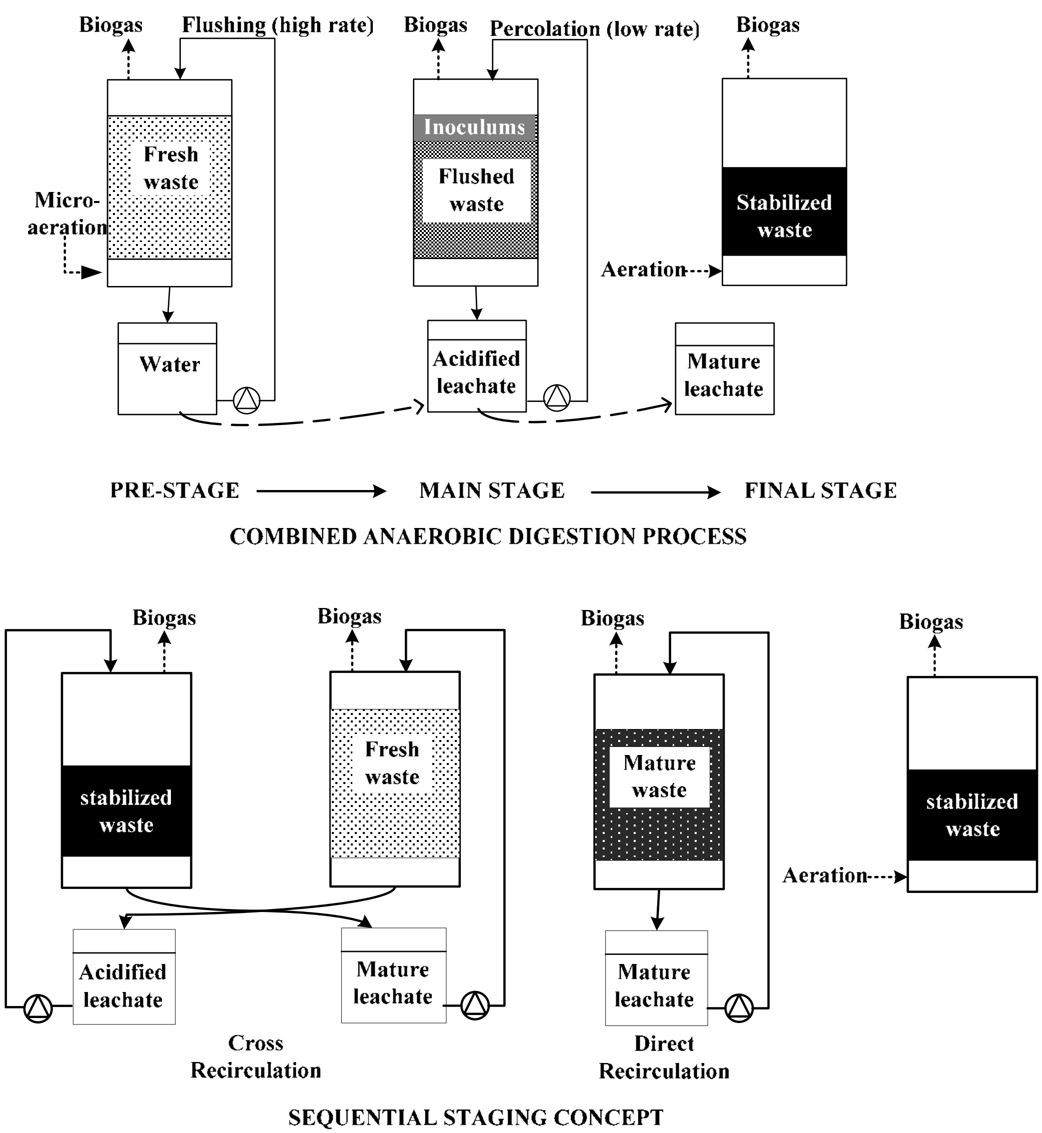

Fig. 1: Schematic diagram of combined and sequential staging anaerobic digestion process.

Combined process involves three stages and was conducted in single digester. The first stage involves an enhanced pre-stage operation (hydrolysis and acidification) with flushing and microaeration. The next stage was the methanization start-up which employed pH adjustment, inoculum addition, and mature leachate percolation. The system was allowed undisturbed while the biogas composition and production were constantly monitored. Active methanogenesis can be indicated when the methane content in biogas reached 50%. Then, acidified leachate percolation was started until the biogas production decrease and consecutive batches of acidified leachate was fed until the biogas production leveled off at low production rate. Acidified leachate percolation was practiced to promote biogas production and enhance methanogenic phase. Finally, after the waste was completely stabilized, aeration was applied to vent out the remaining biogas from the digester before unloading.

The concept of sequential staging was performed in Run 2. The stabilized (old) reactor which exhibited better performance from Run 1 was continuously operated and coupled with newly loaded reactor to perform sequential staging process. Leachate from nearly completed old bioreactor is recycled between new and old reactor providing moisture, inoculum, nutrient, substrate, and buffer necessary for methanogenic phase start-up. After start-up, the newly loaded reactor becomes methanogenic mature reactor and is maintained by recycling leachate upon itself (direct recirculation) (Chynoweth et al. 2003). The process was ended by providing aeration when the biogas produced decreased significantly.

Run 1

The effect of reduced pre-stage duration and reduced volume of flushing water in the overall process performance was evaluated. Two parallel reactors were utilized to perform Run 1 experiment. The pre-stage duration for reactor 1 was conducted for 5 days which used a total volume of 600 L of tap water. However, reactor 2 was operated for only 3 days with total volume of 360 L of flushing water. So that, after pre-stage operation, the total volume of flushing water used for each kg of waste were 3 L and 1.8 L for reactor 1 and 2, respectively. Figure 2 describes the operation involved in Run 1 and Run 2.

Initially, waste was loaded into the reactors to a compaction density of 630 kg m^{-3} together with bulking agent. Reactor 1 (R1) was opened twice for additional waste feeding of 30 kg and 20 kg of waste in day 2 and day 4, respectively. Since reactor 2 (R2) was operated for 3 days pre-stage duration, additional waste of 50 kg was fed in day 2, so that after pre-stage operation, the reactors contained a total of 200 kg of waste. The purpose of additional waste feeding was to utilize the available reactor's headspace due to waste settlement. Microaeration and flushing rate and interval were similar in both reactors. Microaeration (0.3 L kg^{-1} h^{-1}) was conducted for 2 h after 4 h of flushing. Flushing (1.5 L kg^{-1} h^{-1}) was conducted every 4 h.

After pre-stage operation, pH adjustment to 7.0 was conducted by using NaOH solution to buffer the system. Then, inoculum was added on top of hydrolyzed waste. Mixture of cow dung, stabilized/digested waste, and anaerobic sludge was used as seeding material which has been acclimatized to thermophilic condition, totally accounting for 18% VS of the loaded waste. Percolation was performed for two days to distribute inoculums throughout the waste bed. It was observed that R1 and R2 reached an active mathanonegenesis (CH_4=50%) on day 12 and 10, respectively; thereby acidified leachate percolation was started on the said day at a rate of 0.2 L min^{-1} for 4 h run and 4 h stop interval. At the end of the process, the reactors overall process performance was evaluated. It was found out that R2 performed well over R1 (Figure 3). Thus, R2 was continuously operated and used as old reactor in Run 2.

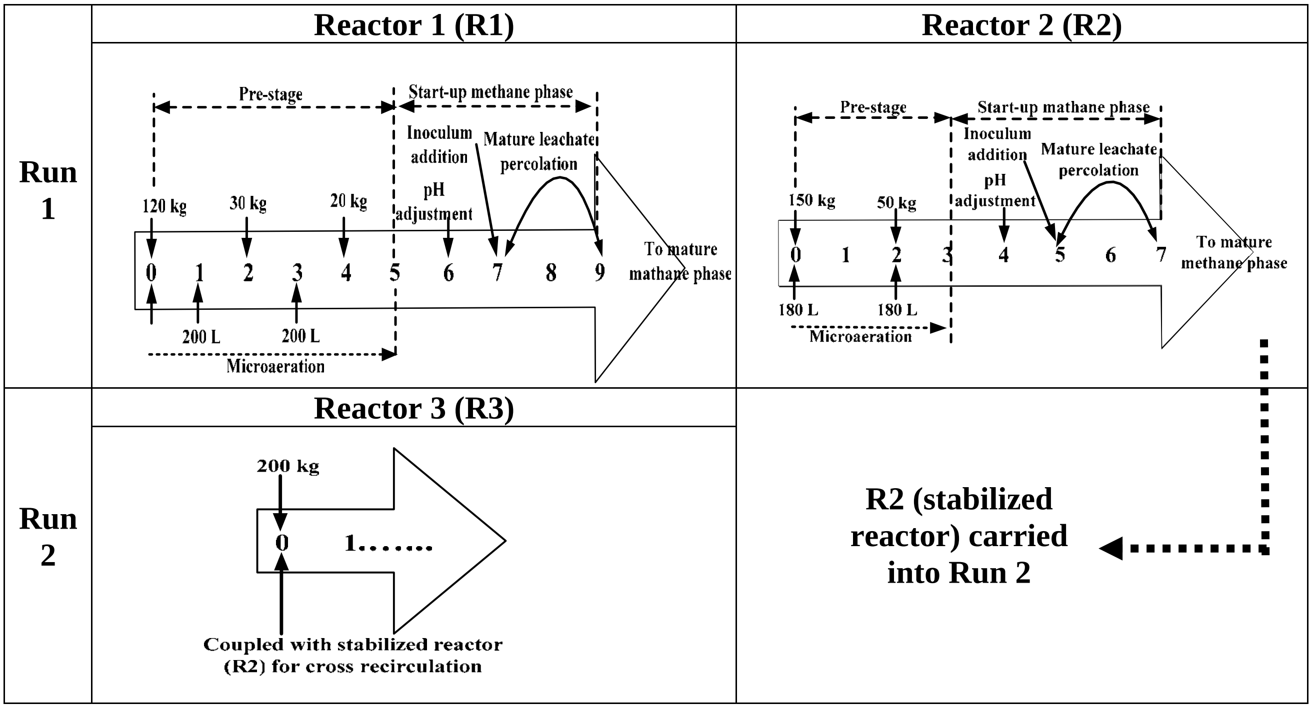

Fig. 2: Process mechanisms in Run 1 and Run 2.

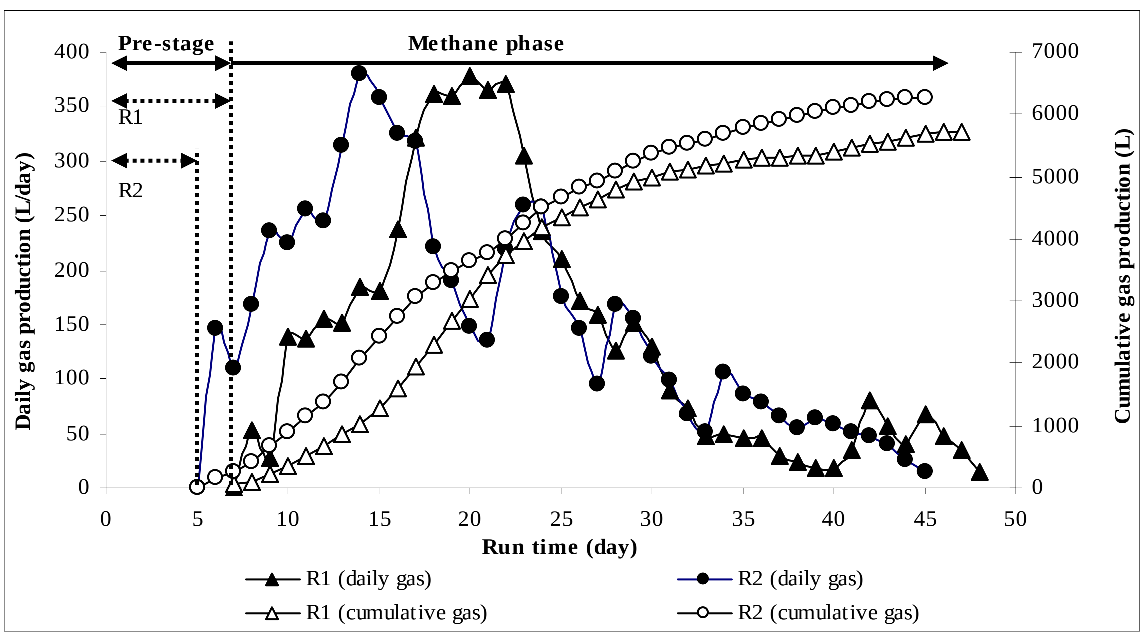

Fig. 3: Daily and cumulative gas production (Run 1).

Run 2

Anaerobic digestion in sequential staging process was performed in Run 2. R2 from Run 1 was operated continuously and used as old reactor. While, reactor 3 (R3) is loaded one time of 200 kg of waste and called as new reactor (Figure 2). R2 (old) and R3 (new) were coupled together for cross-recirculation by using mature leachate taken from previous run. The mature leachate used for cross recirculation at a rate of 3 L min^{-1} for 30 min daily. Cross-recirculation was ended when new reactor reached mature methane phase (pH=7.0 and CH_4=50%) and direct recirculation was performed until the digester biogas production leveled off.

Results and Discussions

Pre-stage

Figure 4 represents the results of Run 1 experiment during 5 and 3 days of pre-stage operation. The cumulative load indicates that flushing the waste for 3 days (1.8 L kg^{-1}) could generate comparable load as 5 days (3 L kg^{-1}) of flushing. Thus, flushing for short duration at reduced volume of water is attractive because more concentrated leachate can be obtained and that can be almost used for percolation during methane phase. It could be deduced that flushing for longer period with the use of high volume of water may washed out the necessary microorganisms and enzymes present, and the concentration of hydrolysates produced is relatively low. The same figure also exhibits the trend of hydrolysis and acidification performance. It was observed that alkalinity and pH behavior indicated that the system is in acidic medium. Higher amount of DOC (5.4 g L^{-1}) and VFA (11.4 g L^{-1}) were leached out during first day of pre-stage operation. With the flushing operation, the concentration of the said parameters reduced significantly after 5 days. The highest pollutant load of 189 g kg^{-1} TS and 336 g kg^{-1} TS for DOC and VFA was exhibited by R2 (after 3 days pre-stage operation), respectively. So that, after 3 days of operation the inhibiting products were sufficiently removed. In this regard, shortening pre-stage operation with lesser volume of flushing water showed a positive effect in enhancing pre-stage performance.

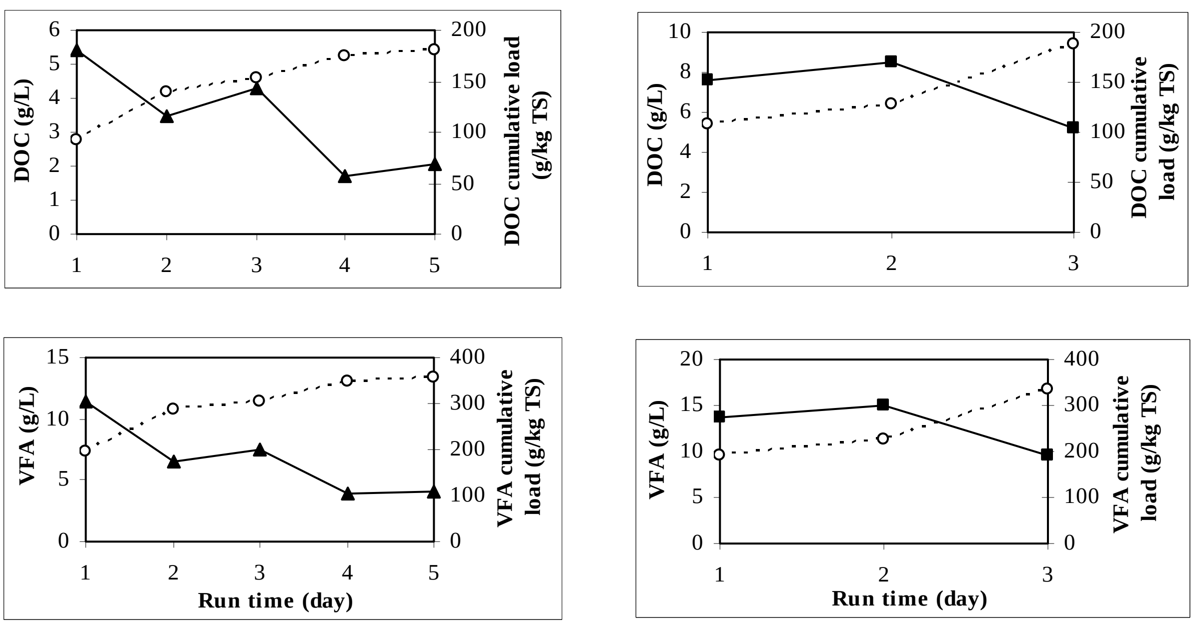

Fig. 4: Daily concentration and cumulative load of DOC and VFA in daily leachate (Run 1).

Methane phase

Figure 3 represents the performance variations in terms of daily and cumulative biogas production after pre-stage in Run 1. Rapid increase of biogas production was displayed by both reactors. The positive shift in methane phase performance observed from reduced pre-stage with lesser volume of flushing water provides added benefits. This includes shorter lag phase period, and higher biogas production which eventually resulted to reduced digestion duration. Lag phase period of 5 days (after pre-stage) was exhibited by both reactors. However, an active methane phase was obtained earlier by R2.

Moreover, an improved methane concentration was also observed. The commencement of acidified leachate percolation during mature methane phase, exhibits a rapid increase of biogas generation. This indicates that leachate percolation which causes leachate contact with the waste have a positive influence in the process (Warith et al. 2001). After 45 days of operation, a total of 5300 L (310 L kg TS^{-1}) and 6300 L (332 L kg TS^{-1}) of biogas were produced by R1 and R2, respectively. However, the operation of reactors can be stopped after 30 days because of insignificant increase of biogas. Generally, R2 operation was better than R1 not only in pre-stage but also in main stage. R2 operation was shorter and offers a number of advantages such as less volume of flushing water and higher biogas production with high methane content. Generally, it can be said that the digestion performance was stable.

In Run 2, it should be noted that R2 from run 1 was operated for 2 months before it was coupled with R3 (newly loaded). Importantly, pre-stage operation was not conducted in R3. Moreover, coupling the reactors directly without conducting pre-stage operation does not only inoculates the new reactor and removes organic acids but it could concentrate nutrients, inoculums, and buffer which are necessary for the rapid metabolism. Nevertheless, the sequential staging process could convert large fraction of organic matter into biogas. After the two reactors were coupled, an active methane phase was rapidly exhibited by new reactor (R3) when compared to previous run. It was observed that the methane concentration in both reactors increased and was stable to around 50% after 4 days of operation. Also, the pH of R3 started at 5.6 and rose to >6.5 after 4 days and this would indicate that the system was fully started up

The reactors (R2 and R3) were uncoupled and direct leachate recirculation on R3 commenced on day 10. During the commencement of direct recirculation, the pH remained above 7 and stabilized at a value of 7.7 during the entire run. The observed decreasing trend of DOC and VFA in leachate accompanied with the increase of biogas may indicate a balance system. The reduction of VFA or DOC concentration may be attributed to removal by leachate recycle and metabolism by a developing methanogenic microbe population. Moreover, the NH_4-N concentration did not increase significantly instead the concentration leveled off at 1 g L^{-1}. After 28 days of operation, a total of 6200 L of biogas that is equivalent to 334 L kg VS^{-1} was produced (Figure 5). The biogas generation leveled off after 25 days indicating that the conversion was more or less completed. The continued generation of VFA along with the biogas production with 50% CH_4, indicates that even though acidogenesis reaction is active during early days of operation, the methanogens population was able to establish and a balance process was achieved at early stage of operation. After 25 days of operation, biogas production did not further increase, instead it gradually drop. Thus, ending the process on day 25 seemed to be satisfactory.

Process efficiency

The methane yield in pilot scale digesters was compared to lab-scale BMP test to verify the process conversion efficiency. The methane yield was based from % VS destruction for it offers better representation in the actual process performance (Teixeira et al. 2004). BMP test of the fresh waste generates 400 L CH_4/kg VS. Table 1 represents the overall assessment of methane phase. Comparable result in terms of methane yield and methane conversion efficiency was exhibited by reactor 1 and 2 during run 1. However, more biogas can be produced by a reduced pre-stage in shorter time. In this regard, an improved methane generation, mass and volume reduction can be achieved by a reduced operation with less flushing water. However, among them, better result was displayed by reactor 3 (run 2). Improved digester performance in terms of waste stabilization was achieved. Nonetheless, the methane yield obtained is 334 L CH_4/kg VS which is equivalent to 84% process efficiency.

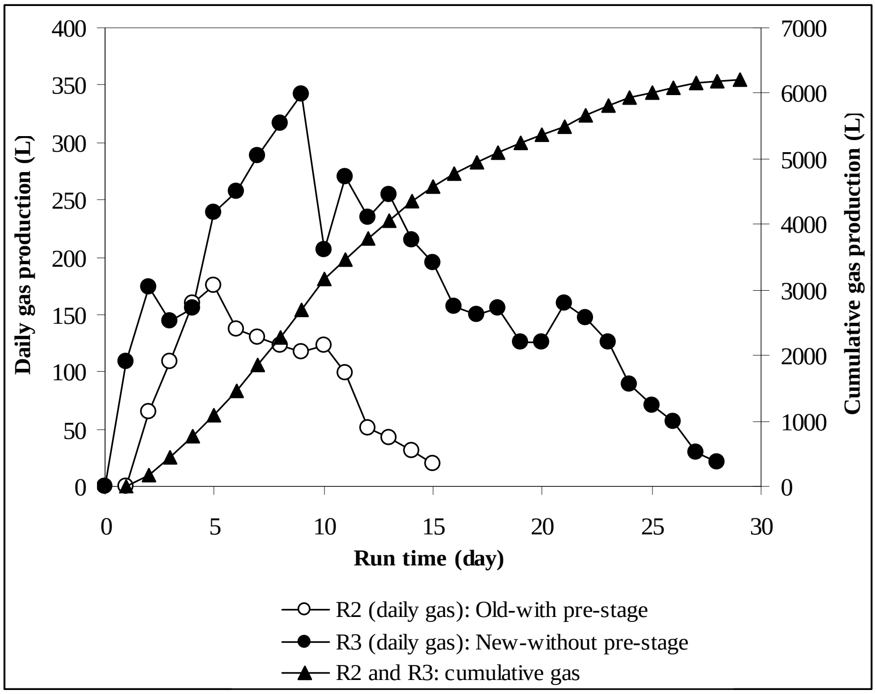

Fig. 5: Daily and cumulative biogas production of reactor 2 and 3 (Run 2).

Run no./ Reactor no.	% Mass reduction	% Volume reduction	% VS reduction	Methane yield (L CH_4/kg VS)	Process efficiency (%)
Run 1					
Reactor 1	74	58	71	320	80.0
Reactor 2	84	74	86	322	80.4
Run 2					
Reactor 3	86	79	86	334	83.5

Table 1: Overall assessment of methane phase.

Conclusions

The results showed that pre-stage flushing operation for 3 days (1.8 L kg^{-1}) is more preferable than 5 days (3 L kg^{-1}). Almost 44% of C from waste bed was removed into leachate with hydrolysis and acidification yield of 188 g C/kg TS and 337 g VFA/kg TS. This signifies that reducing pre-stage operation and volume of flushing water resulted to maximum removal of organics from waste bed is beneficial in optimizing the overall process in combined anaerobic digestion. Nevertheless, leachate cross-recirculation between the old and new reactors directly without conducting pre-stage operation optimizes the overall digestion process. The sequential staging concept offers an improved process over the combined anaerobic digestion. Improved waste stabilization with 86% and 79% of mass and volume reduction was achieved, respectively. Moreover, higher methane yield of 334 L CH_4/kg VS with 86% VS reduction which is equivalent to 84% process efficiency was obtained.

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Thermophilic Anaerobic Digestion of Municipal Solid Waste in Combined Process and Sequential Staging

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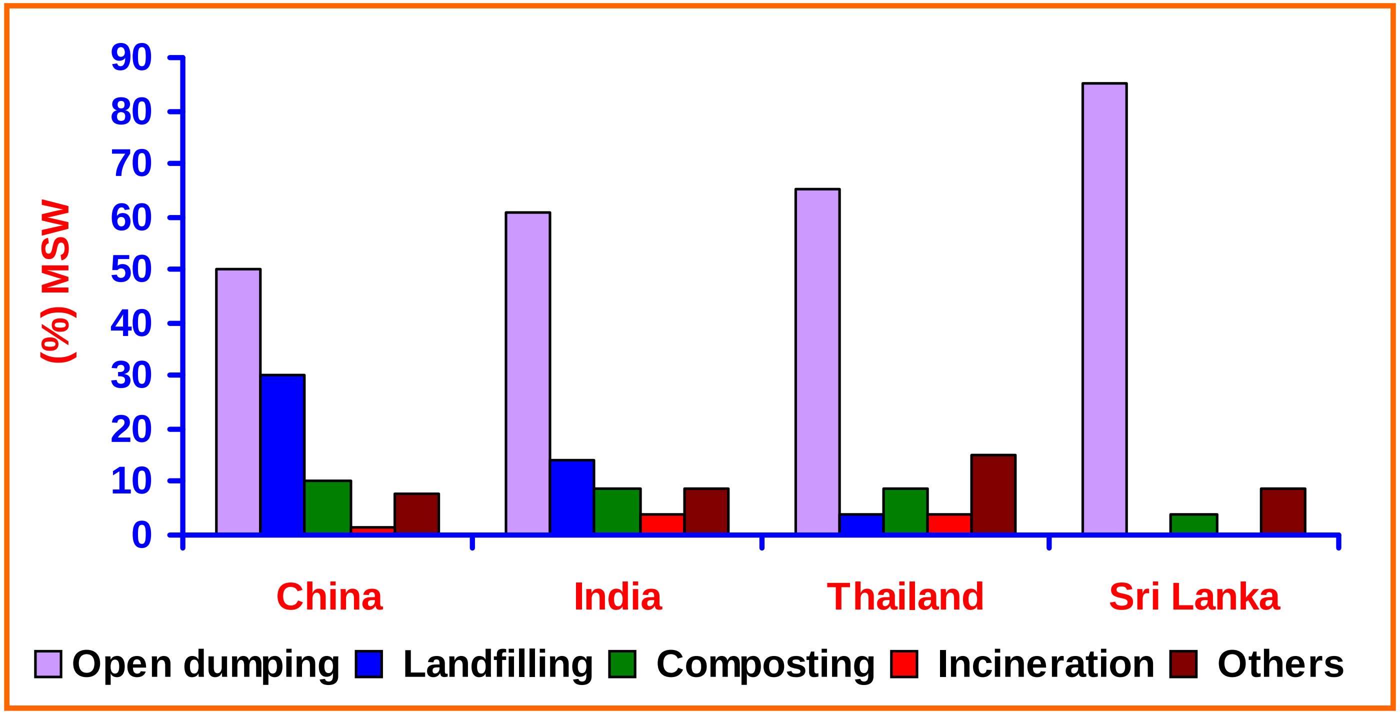
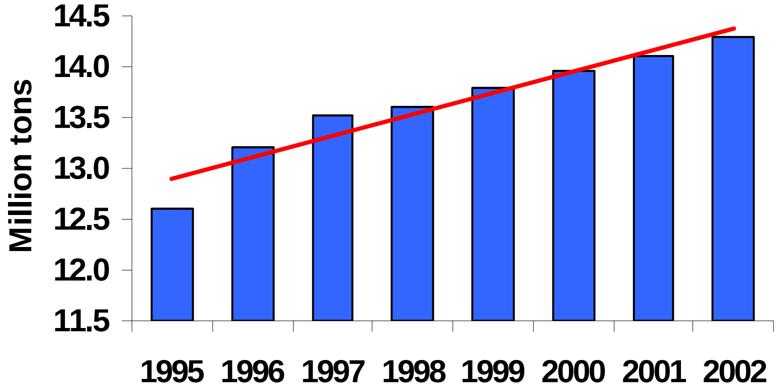
Overview of Municipal Solid Waste Management in Asia

Open dumping is the most prevalent method: more than 50 % of the waste is disposed in open dumps

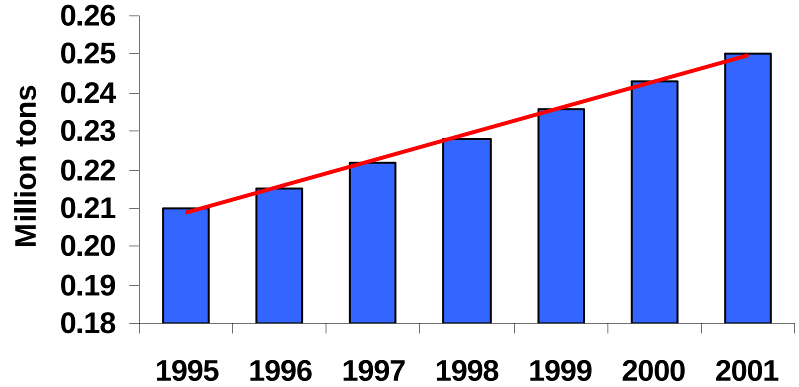


No precautionary measures for potential emissions (gas and leachate)

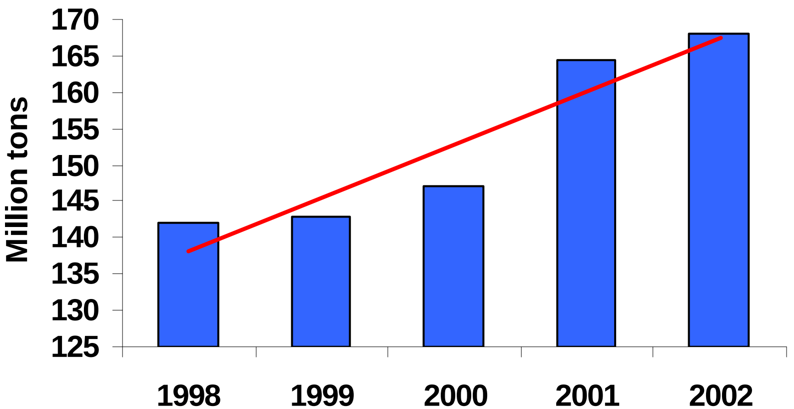
Increasing Trend of MSW Generation with Time



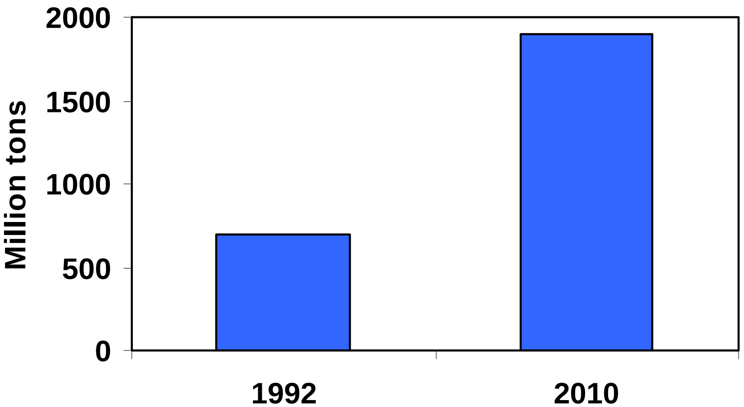
MSW generation in Thailand



MSW generation in Colombo, Sri Lanka



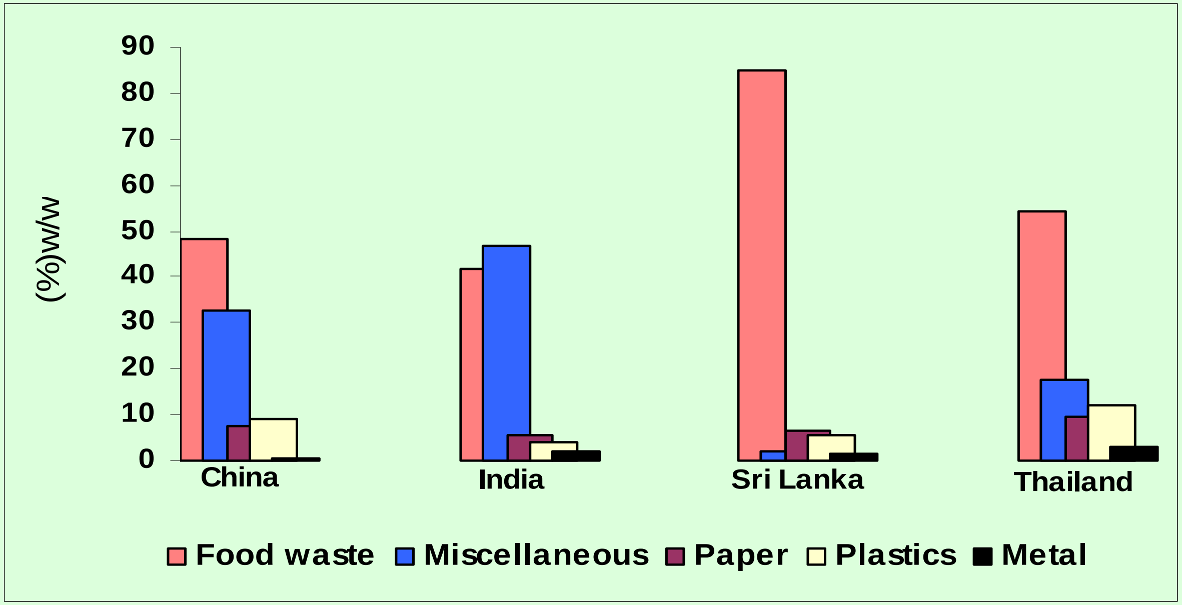
MSW generation in China



Municipal solid waste in Asia (ESCAP 1995)

Potential Waste Characteristics

✓ Higher amount of organic fraction



✓ High moisture content

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

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

Potential MSW Treatment Process

Mechanical Biological Treatment

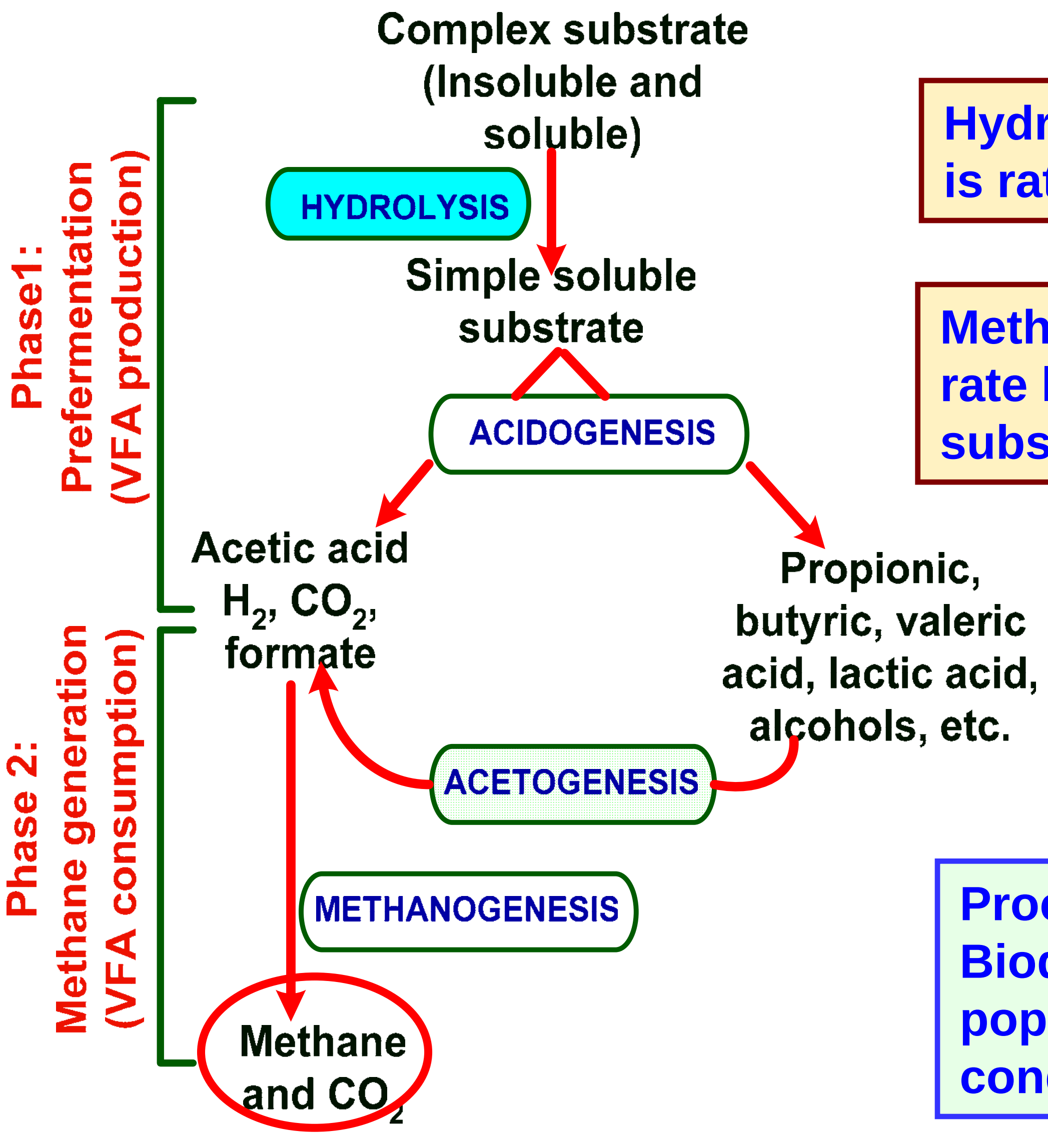
- **Composting technologies**
  - Need more space and time consuming
  - More energy & manpower required
  - O&M problems
  - Odor problems, high moisture content of waste
- **Anaerobic digestion**
  - Higher net power generation
  - Lesser plant area required for a continues operation
  - Greater volume reduction in MSW
  - Organic stabilization and pathogen reduction

Bio-methanization may be the attractive alternative in Asian countries where higher organic fraction exist

Introduction to Anaerobic Digestion

- **Potential technology for waste reduction and stabilization**
- **Attractive method for solid waste treatment prior to landfill**
  - Supports sustainable development
  - Reduction of significant emissions
  - Generation of useful byproducts: compost/biogas
  - Energy recovery from biogas for power generation

Overview of Anaerobic Digestion Process



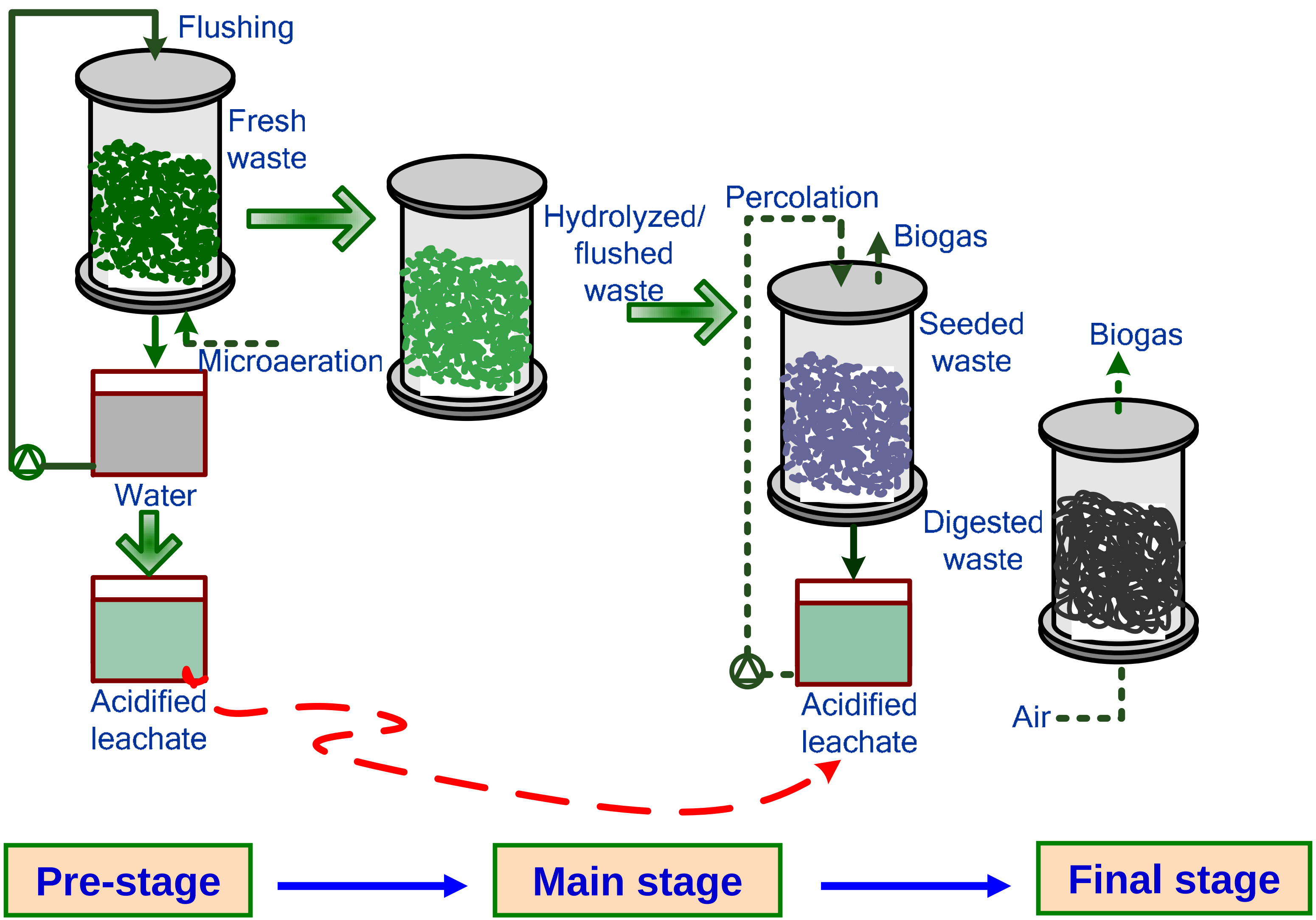
Adapted from Fox and Poland, 1994)

Hydrolysis of particulate material is rate limiting-step

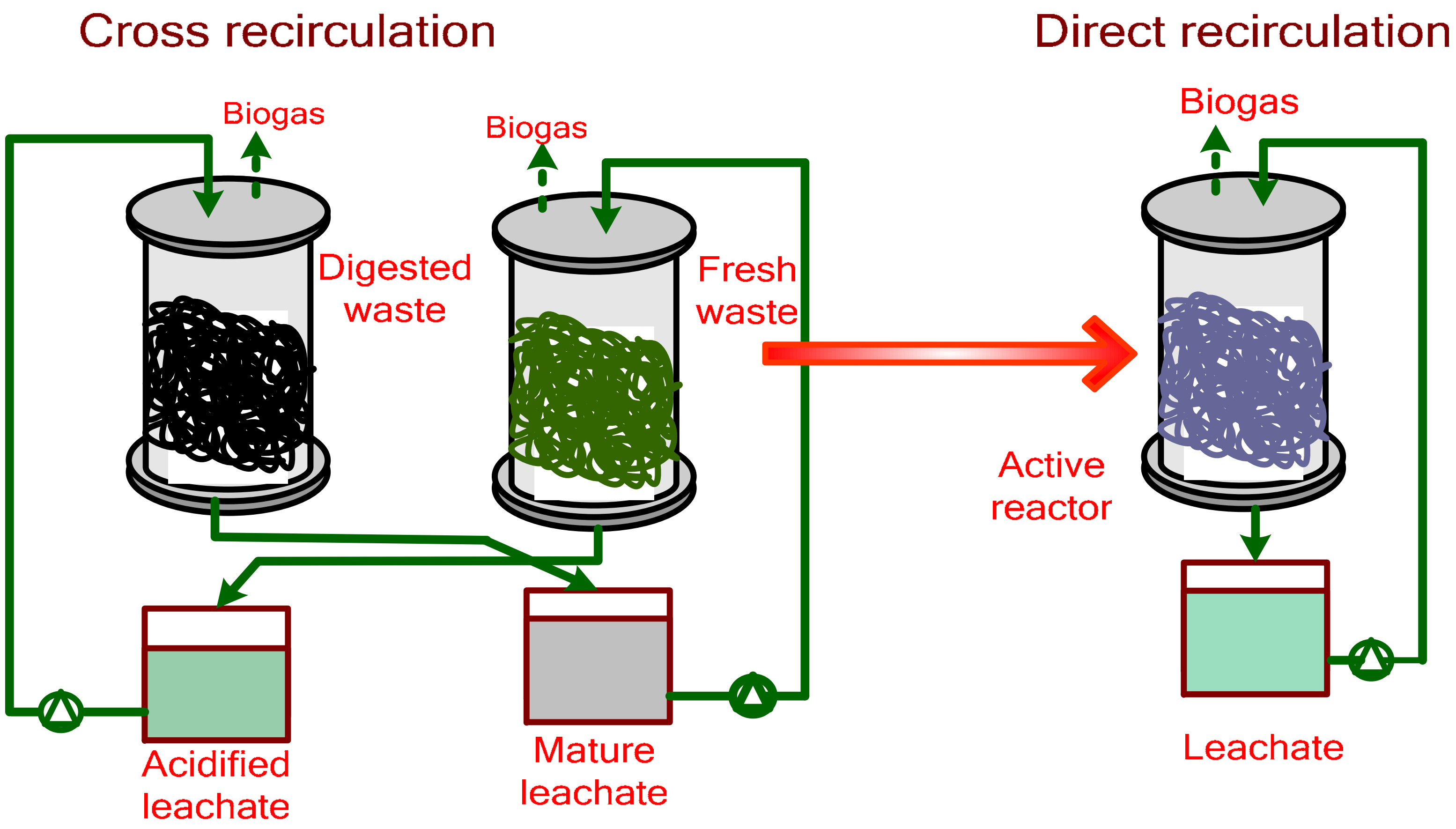
Methanogenesis is slowest and rate limiting due to inhibiting substance.

Process stability depends on: Biodegradability of feedstock, population of bacteria, growth conditions and the temperature

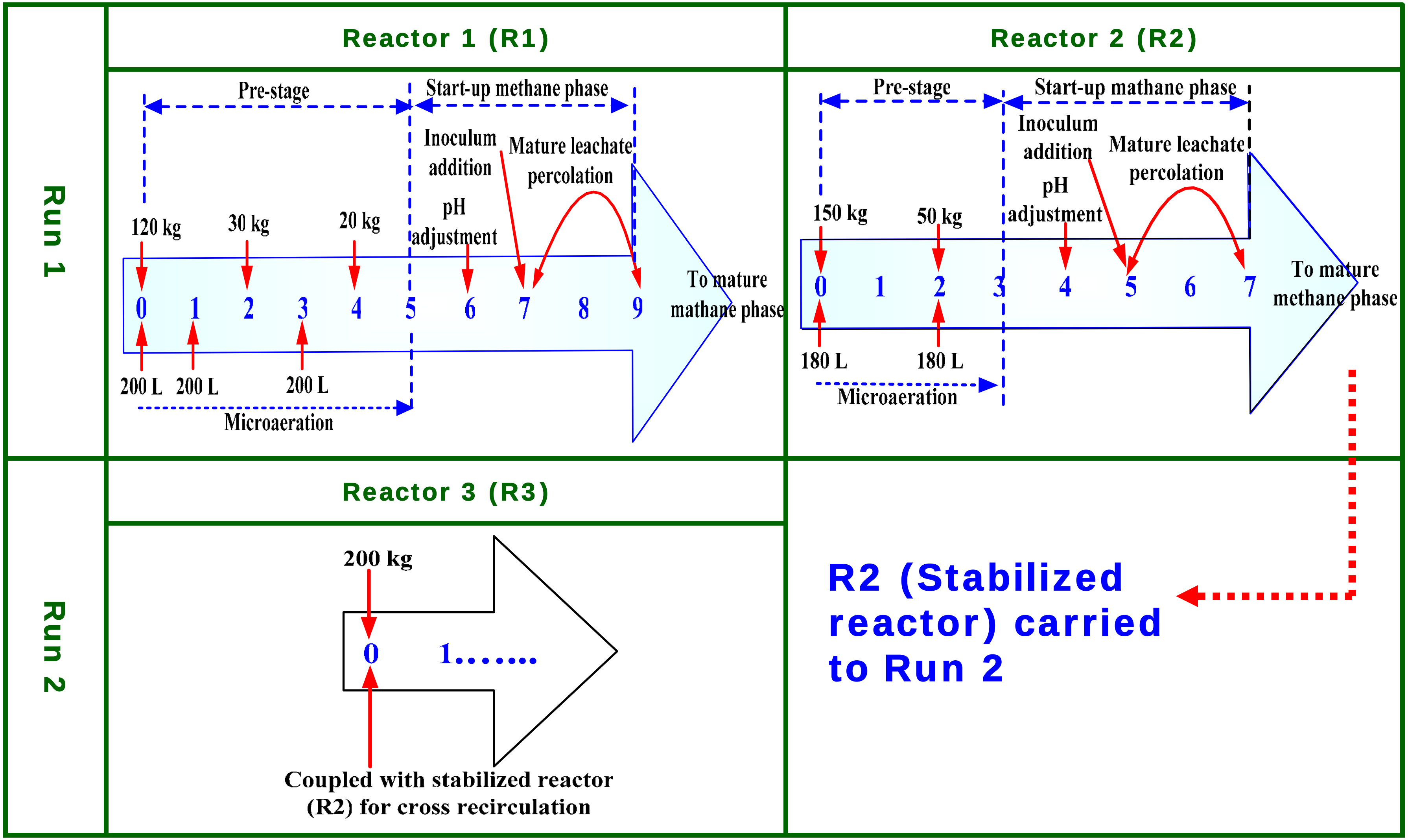
Concept of Combined Anaerobic Digestion Process



Concept of Sequential Staging Anaerobic Digestion Process



Detailed Experimental Set-up



Feedstock Preparation

Waste segregation

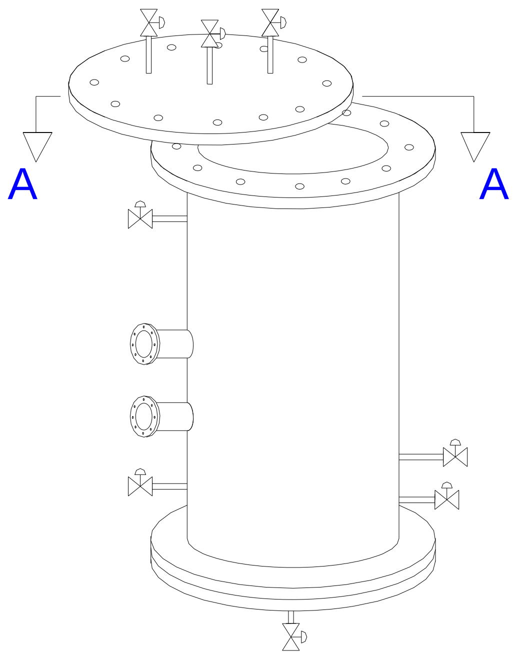
Shredding-Size reduction

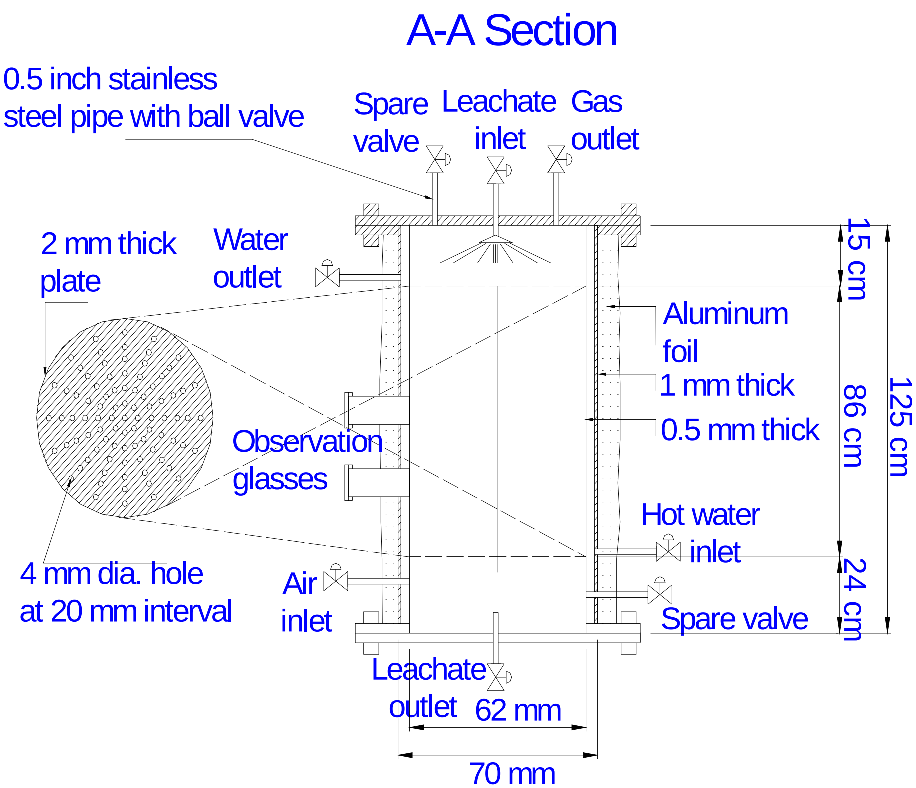
Weighing of waste

Weighted waste and bamboo cutlets ready for loading

Reactor loading

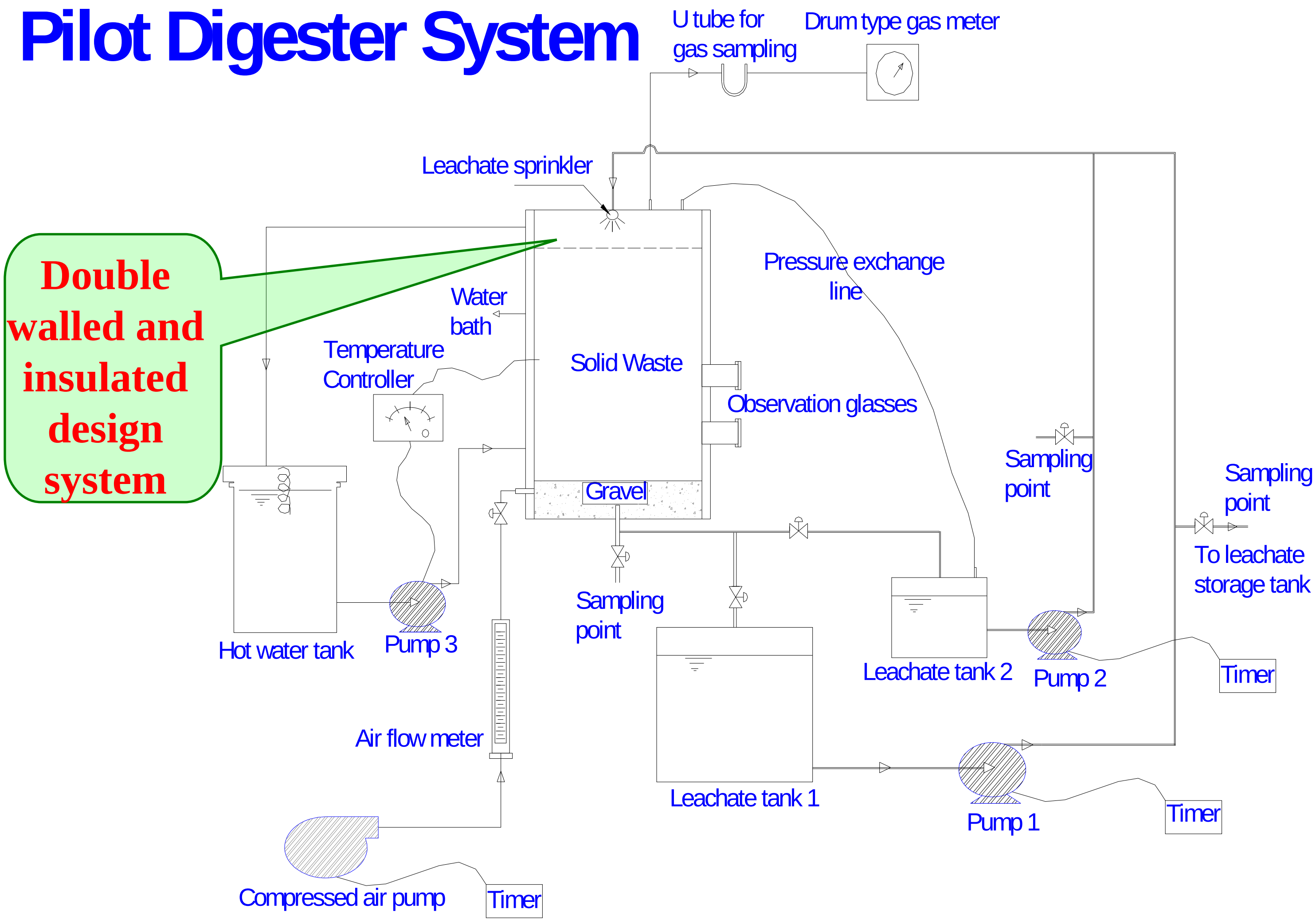
Digester design



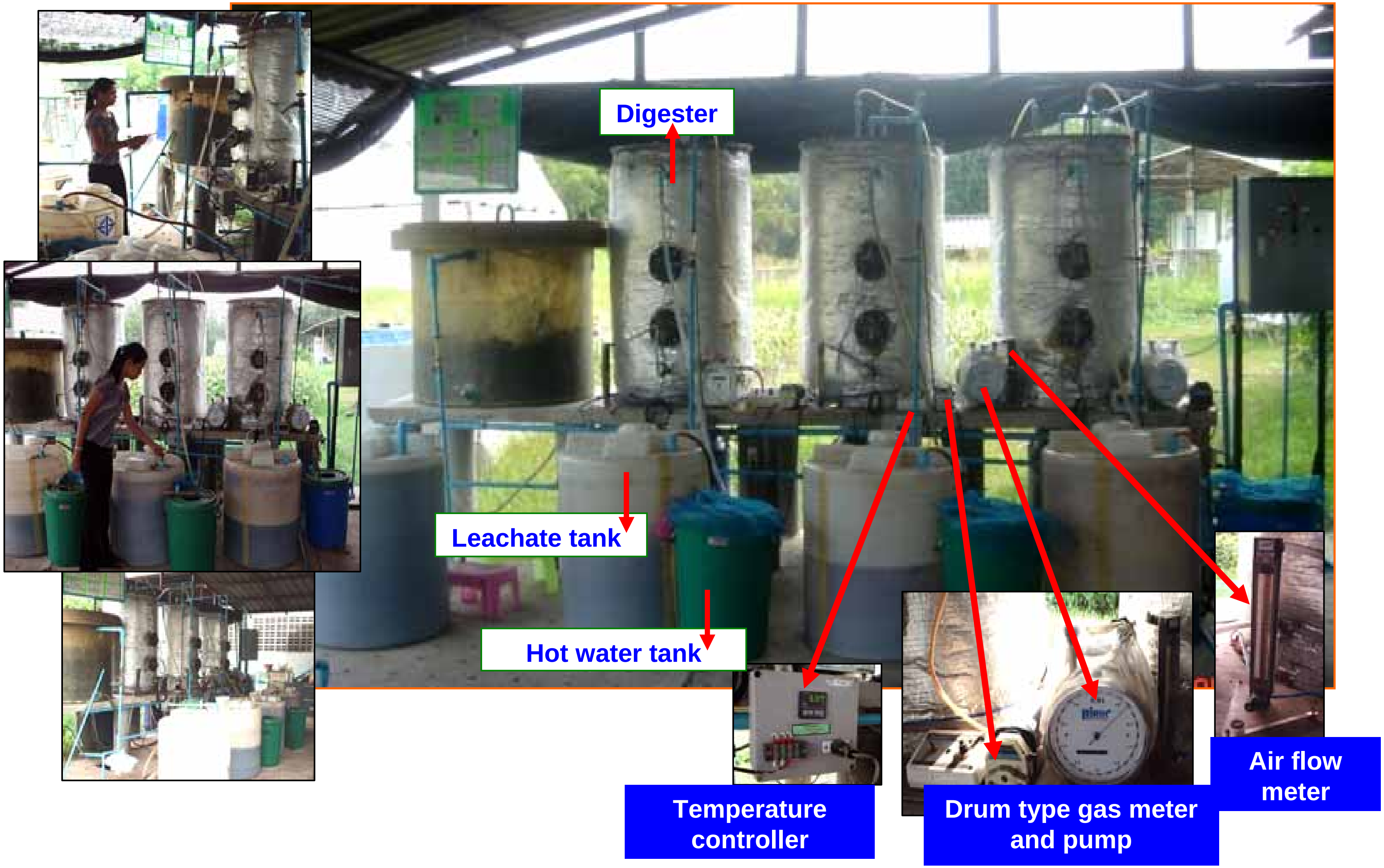


Opening reactor in 3D

Pilot Digester System

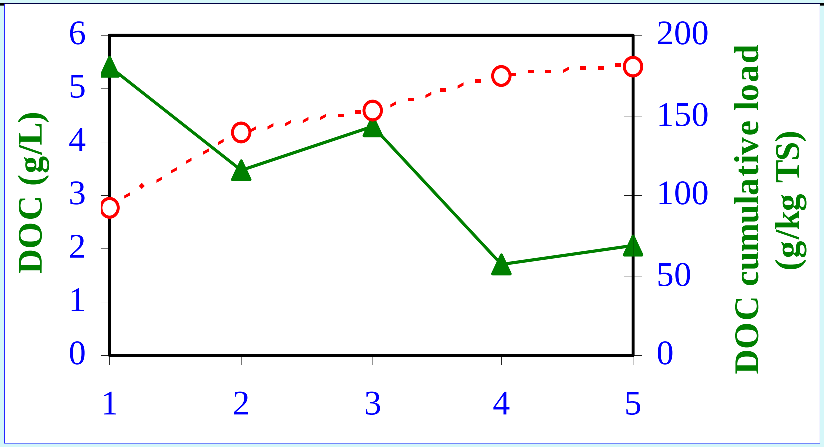


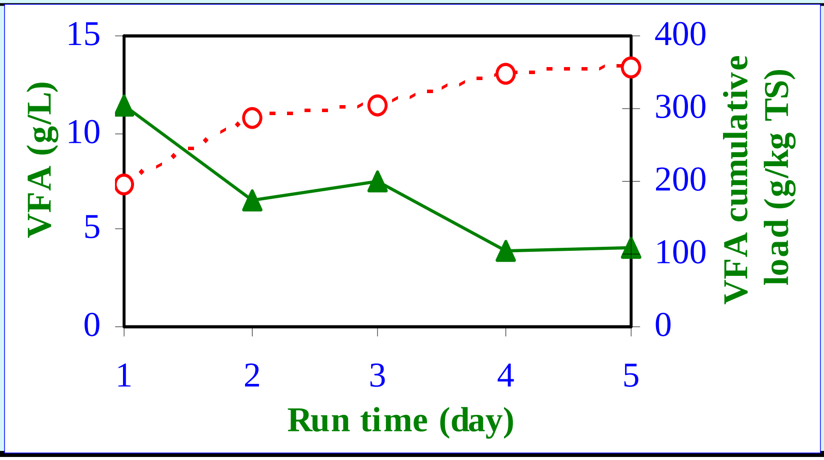
Anaerobic Digestion System



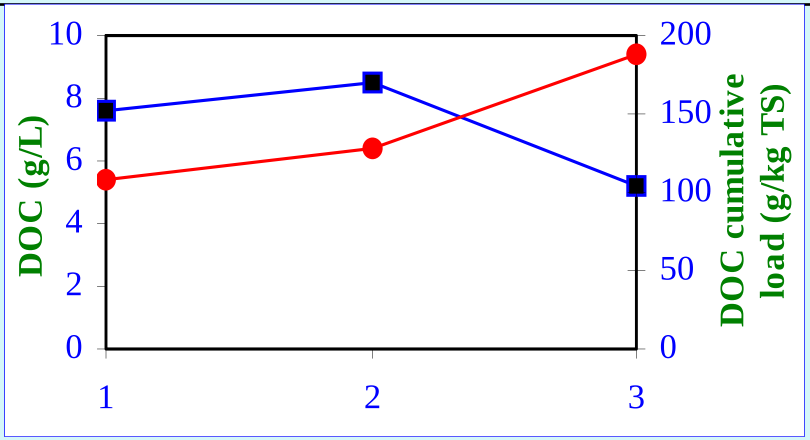
Pre-stage Performance: Run 1

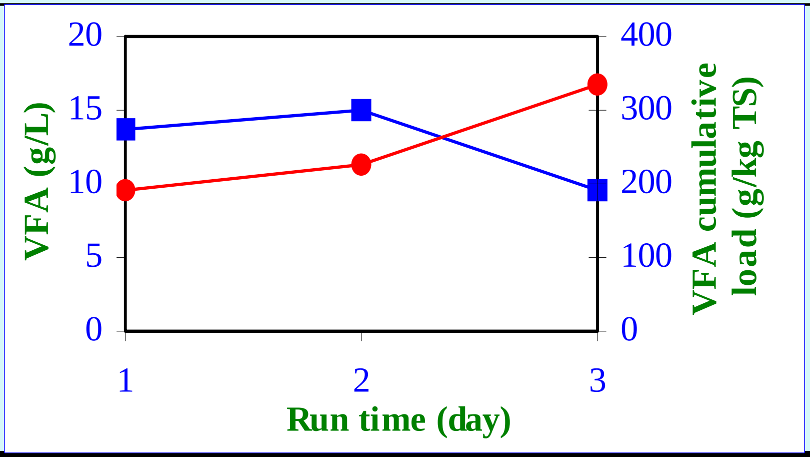
Reactor 1





Reactor 2

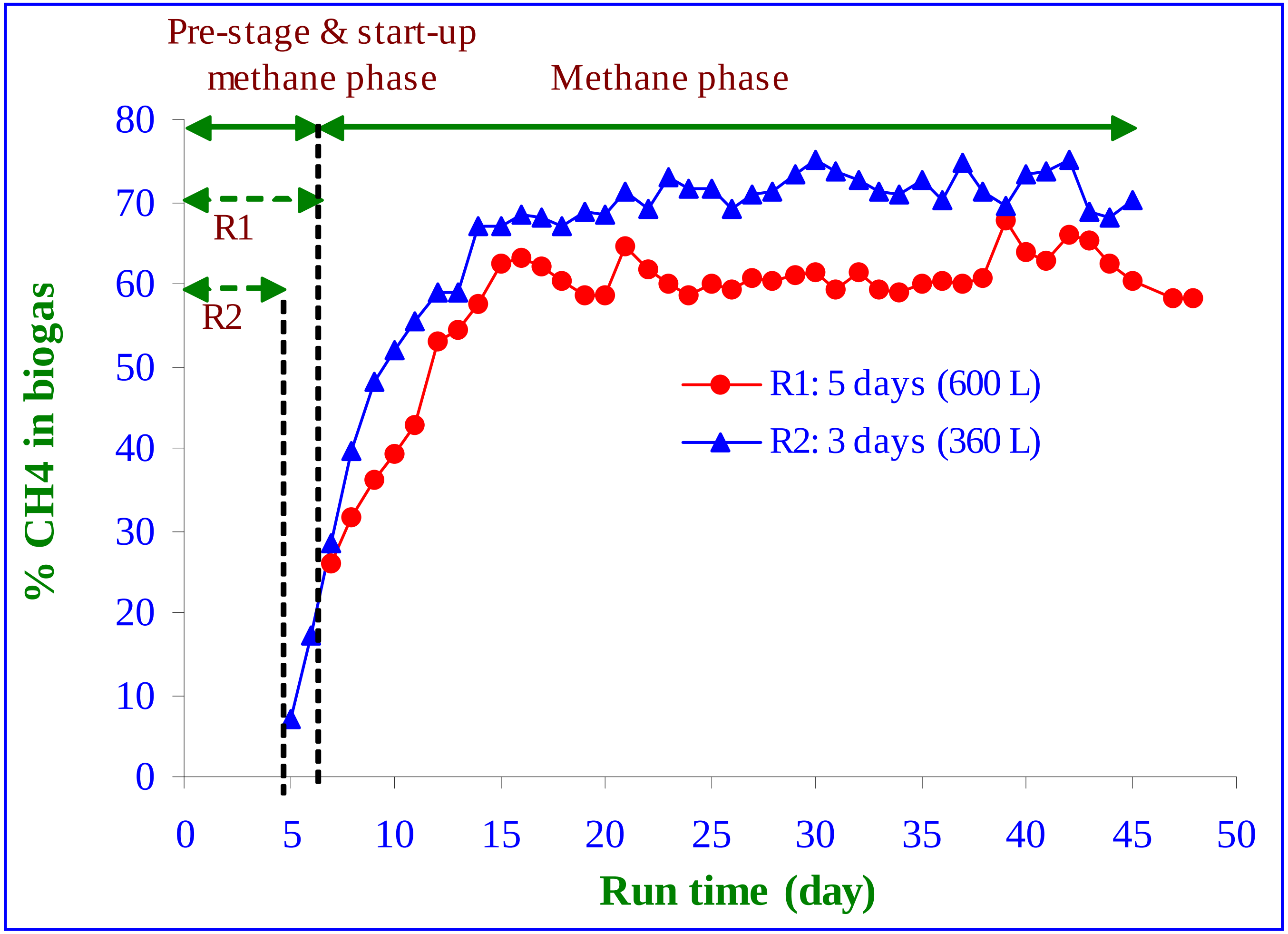




Shortening of pre-stage operation (3 days) with lesser volume of flushing water showed a positive effect in enhancing pre-stage performance

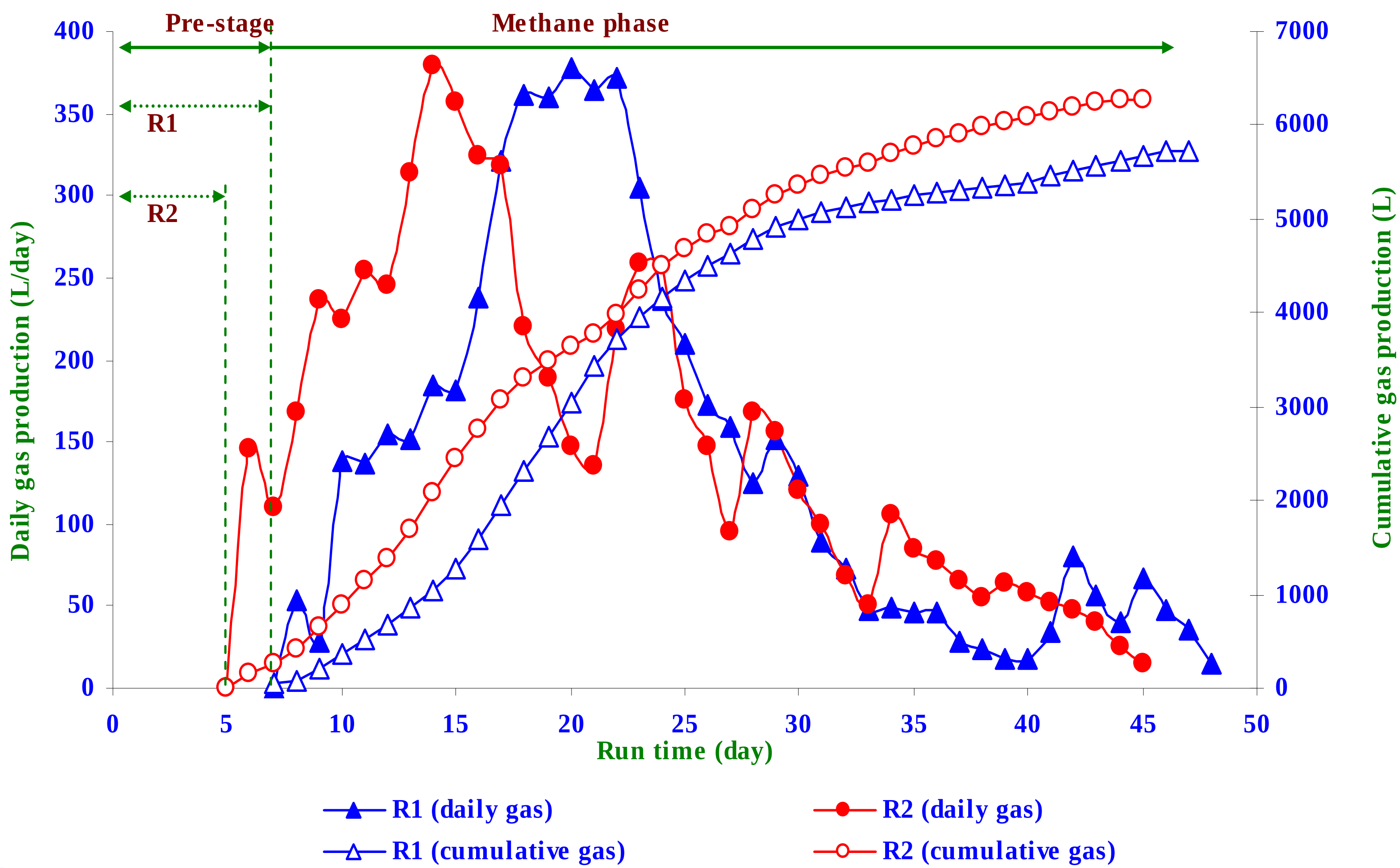
Methane Phase Performance (Run 1)

Reactor 2 (3 days, 360 L) showed higher methane concentration than Reactor 1 (5 days, 600L)



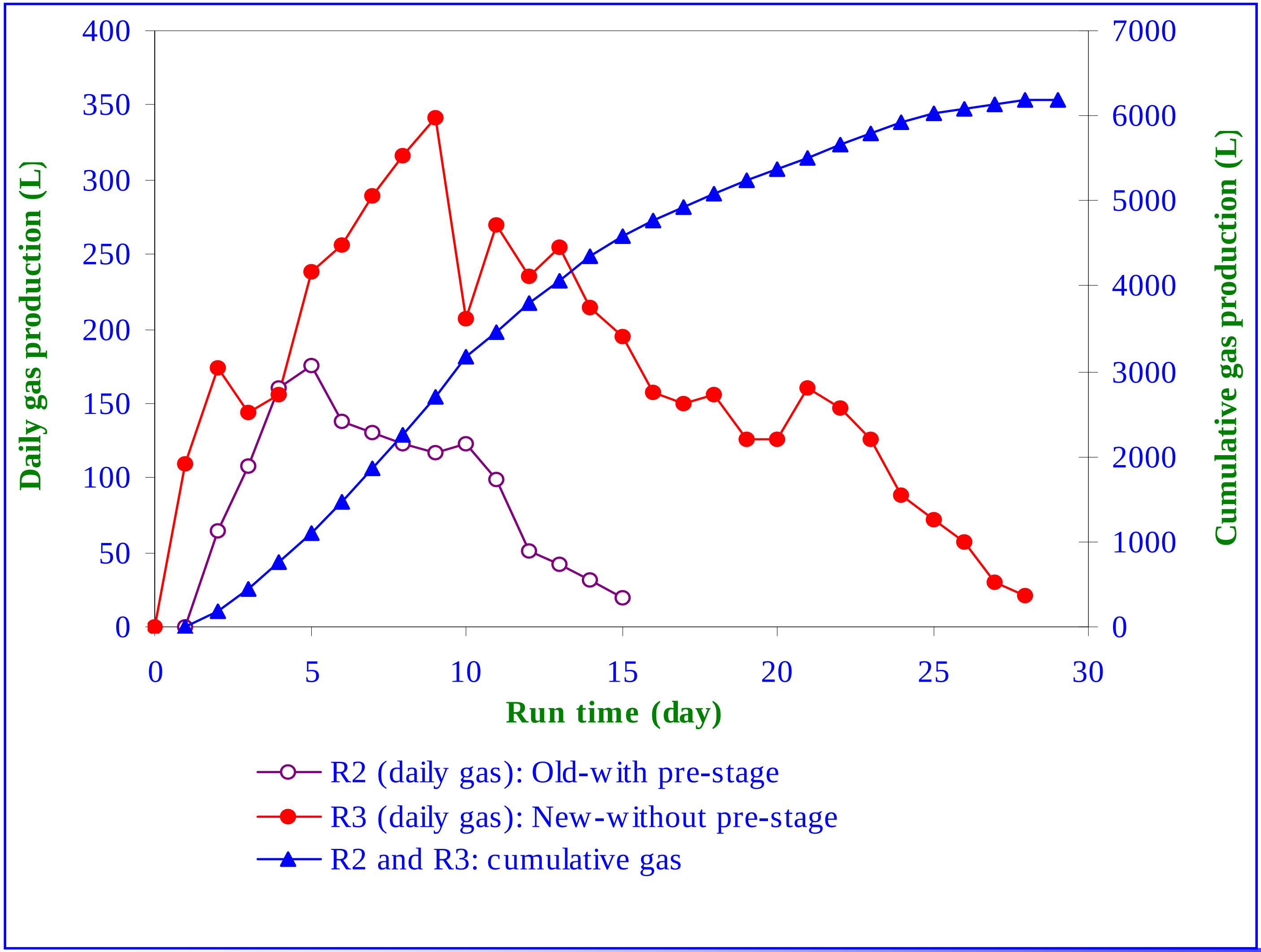
Methane Phase Performance (Run 1)

Reactor 2 showed enhanced biogas production

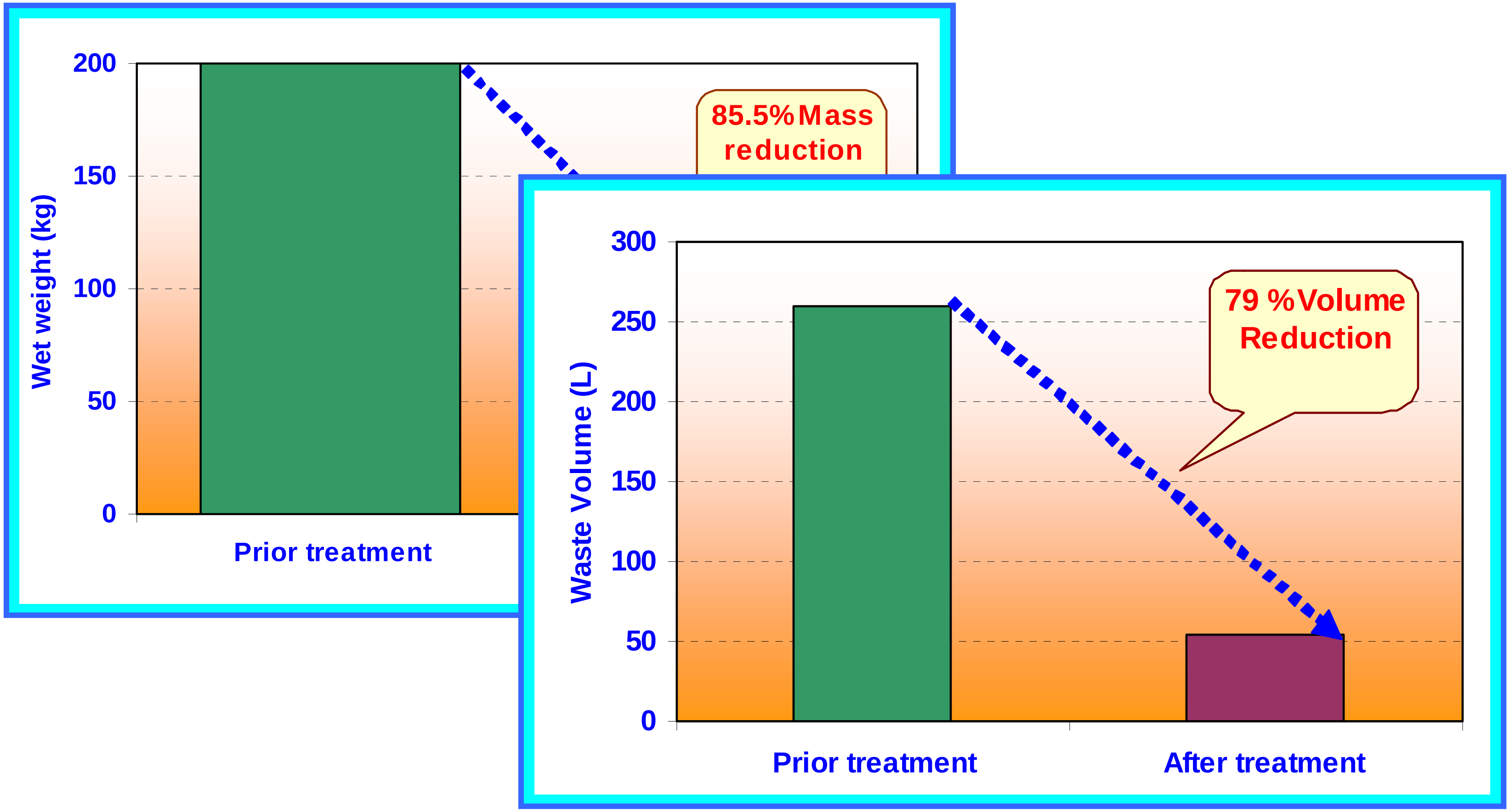


Methane Performance (Run 2)

After 28 days of operation, 6200 L of biogas produced (334 L kg VS^{-1})



Waste Stabilization Efficiency in Sequential Staging Anaerobic Digestion Process



Methane yield of 334 L CH4/kg VS with 86% VS reduction which is equivalent to 83.5% process efficiency was obtained

Process Efficiency Evaluation

Run no. / Reactor no.	% Mass reduction	% Volume reduction	% VS reduction	Methane yield (L CH_4 / kg VS)	Process efficiency (%)
Run 1 (Combined Process)					
Reactor 1	74	58	71	320	80.0
Reactor 2	84	74	86	322	80.4
Run 2 (Sequential Staging)					
Reactor 3	86	79	86	334	83.5

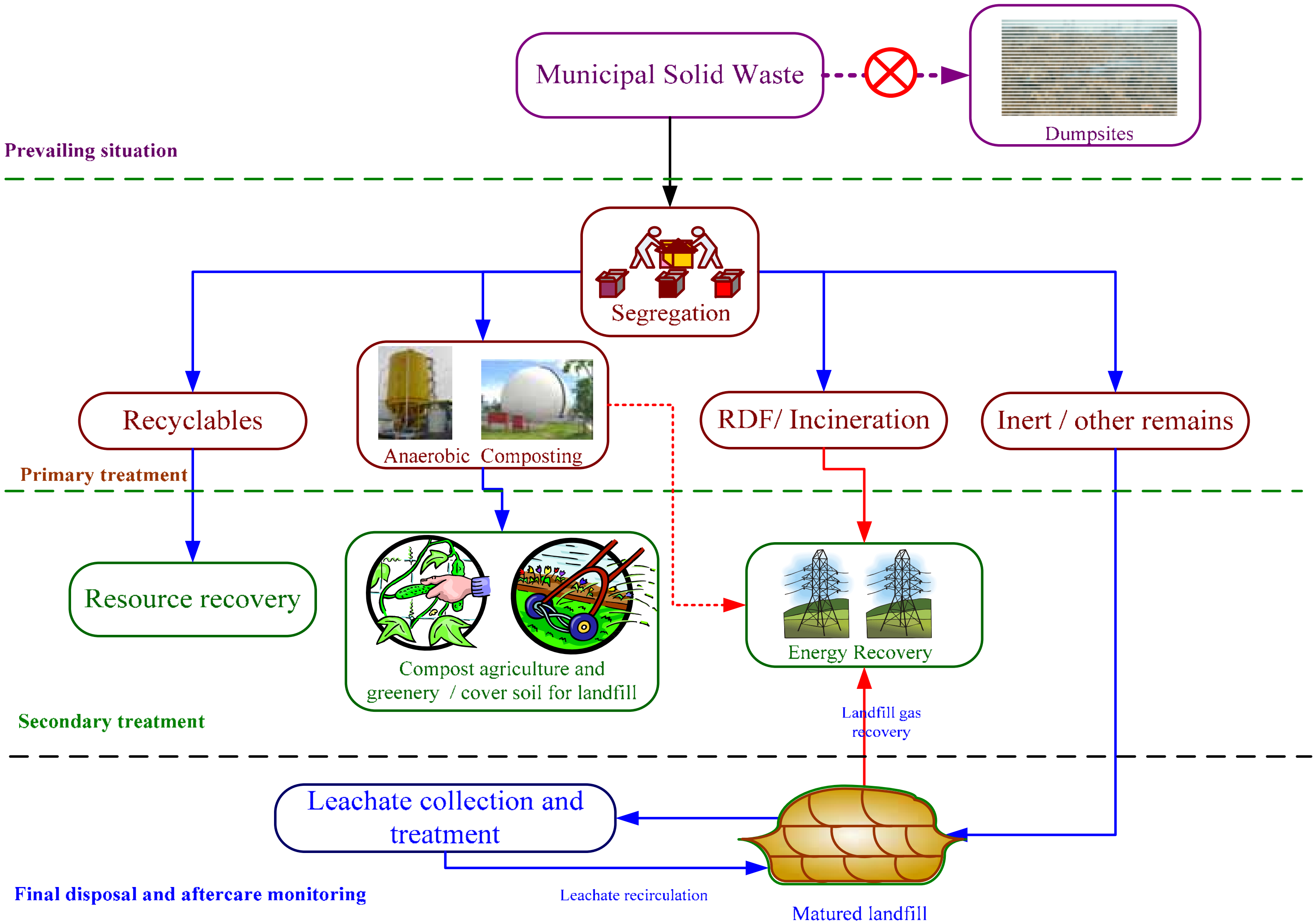
Shorter digestion period with enhanced waste stabilization was exhibited by sequential staging process

Conclusions

- **Combined Process**
  - ✓ Shorter flushing mechanism for 3 days (1.8 L/kg) showed beneficial effect over 5 days (3 L/kg)
  - ✓ Enhanced hydrolysis and acidification yield; 44 % of C from waste bed was removed into leachate
  - ✓ Reducing pre-stage operation and volume of flushing water enhances the overall combined process

- **Sequential staging**
  - ✓ Offers more improved process over the combined anaerobic digestion
  - ✓ Higher methane yield equivalent to 83.5% process efficiency can be obtained

Sustainable Solid Waste Management Approach



Rayong Waste to Energy Pilot Plant Project: Rayong, Thailand

A municipal solid waste treatment plant in Rayong Municipality using anaerobic digestion

Overview of the plant:

Waste materials: MSW, fruit-vegetable and fruit waste (FVFW), and night soil waste (NSW)

Plant design and capacity: 74 tons/day (6o tons of sorted MSW and FVFW, and 14 tons of NSW)

Process design: single-stage, wet continuous, completely mixed

Project's objective: production of electricity while the by-product (digestate) is to be used as soil conditioner or fertilizer.

Project's main philosophy: treat the waste immediately as received in the plant.

Rayong Waste to Energy and Fertilizer Plant

Front-end Treatment Plant

Bag-opener M/C in FET process

Drum Screen M/C in FET process

Magnetic Separator in FET Process

Post-hand Sorting Line in FET Process

Courtesy of: STFE Co., Ltd

Substrate Preparation in FET Process

Feed Preparation Tank in HLAD Process

Bioreactor (HLAD Tank) with cap. 2400 m^3

Dewatering Machine in Back-end Treatment Process

Courtesy of: STFE Co., Ltd

Thermal Dryer in
Back-end treatment Process

Gas Holder

Gas Engine to produce electricity in Biogas Utilization Process

Courtesy of: STFE Co., Ltd

Thermal Dryer in
Back-end treatment Process

Gas Holder

Gas Engine to produce electricity in Biogas Utilization Process

Courtesy of: STFE Co., Ltd

Thank you
very much…